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Microstructure and Meso-Mechanical Properties of Asphalt Mixture Modified by Rubber Powder under a Multi-Scale Effect

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Abstract: The applications of rubber-modified asphalt and its mixtures have received widespread attention due to the environmental and economic benefits of such materials. However, studies on the structural performance of rubber-powder-modified asphalt pavement are only concentrated on a certain scale, leading to research on the structural performance of pavement mostly focusing on mechanical responses at a macro scale. Therefore, the present study adopts the concept of multiscale research to analyze the viscoelasticity of high-dosage-modified asphalt and its mixtures at a microscopic scale from the perspective of meso-mechanical analysis. In this paper, to ensure the overall durability of a structure, the effective asphalt film thickness and coarse aggregate angularity index of the test material were measured first. The viscoelasticity of asphalt modified with rubber powder was then analyzed using a Brinell viscosity test, scanning electron microscopy (SEM), and a dynamic shear rheometer (DSR). We determined the optimal amount of rubber powder to be 30%. A universal testing machine was used to study the influence of different temperatures and loading frequencies on the viscoelastic properties of different asphalt mixtures. Research on the dynamic modulus found that the incorporation of rubber powder increases the elastic properties of the mixture such that the rubber-powder-modified asphalt mixture had a higher dynamic modulus. At the same time, the high-dosage-modified asphalt mixture was found to be closer to an elastomer under a low temperature and high frequency. At a high temperature and low frequency, the asphalt mixture changed into a viscoelastic body whose viscous properties were mainly affected by the asphalt binder. The addition of rubber powder changed the temperature sensitivity of the asphalt and then affected the viscoelastic properties of the asphalt mixture.

Keywords: rubber-powder-modified asphalt; multi-scale evaluation; viscoelasticity

1. Introduction

Intelligence, safety, and sustainability have become hotspots of transportation infrastructure research. Rubber asphalt technology promotes the green development, recycling development, and low-carbon development of transportation in compliance with recycling and reduction in the 3R environmental protection guidelines [1,2]. At the same time, the present study found that compared to ordinary asphalt-mixture pavement, roads paved with rubber-powder-modified asphalt technology offer a longer service life, lower maintenance costs, and higher driving safety and can also greatly reduce noise while driving [3]. As a three-phase system composed of an aggregate, asphalt slurry, and voids, asphalt mixtures are easily affected by factors such as vehicle load and external temperature changes and also have dynamic characteristics. Therefore, rheological research on the temperature and stress dependence of rubber-powder-modified asphalt and related mixtures is one of the most important research directions of rubber-powder-modified asphalt materials.



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). Research on waste-rubber powder originated in the United Kingdom [4]. Canada began research on rubber-powder-modified asphalt technology in the 1970s and gradually applied this technology to the construction of actual road projects [5]. Current research on rubber-powder-modified asphalt mainly involves using the wet method to complete the process of asphalt modification. In this method, rubber powder is mixed with asphalt, and then the rubber powder particles are evenly mixed into the asphalt to ensure that the powder fully combines with the asphalt and completes the chemical reaction [6]. Finally, the rubber-powder-modified asphalt is mixed with the aggregate at a high temperature. Ghavibazoo et al. [7] observed that due to the expansion of rubber powder particles, the free space of rubber particles in the asphalt was reduced, which caused a significant increase in the internal viscosity of the rubber-asphalt system. Peilong Li et al. [8] found that physical and chemical reactions coexist in this process and that the adsorption of light components of asphalt by rubber powder is an important factor in asphalt modification.

The wet method involves adding rubber powder into the process of asphalt heating through high-speed mixing and shearing such that the rubber powder and asphalt fully combine with each other to achieve full modification. The modified asphalt produced by this method can give full play to the modified effects of the rubber powder in addition to offering better performance. However, the high temperature required by the wetrubber asphalt process can easily aggravate the short-term aging of the asphalt and further affect modification of the asphalt. Thus, many scholars have carried out research on warm-mix rubber asphalt in response to this problem. Hainian Wang et al. [9] conducted rheological analyses on various types of warm-mix rubber-modified asphalt. The authors found that the warm-mixing agent had a significant effect on reducing the viscosity of the rubber asphalt and also improved the storage stability of the wet rubber asphalt. Xin Yu et al. [10] used a series of physical and chemical analysis methods to evaluate the influence of chemical warm-mix agents on the microscopic characteristics of rubber asphalt and correlated the results with macroscopic rheological properties. Leng Zhen et al. [11] investigated the interactions between different components of asphalt binders collectively modified with crumb rubber and warm-mix additives and found that the warm-mix agent accelerated the dissolution of the rubber powder in the base asphalt. Huayang Yu et al. [12] found that adding a liquid chemical warm-mixing agent in advance could reduce the reaction temperature of the rubber powder asphalt by at least 16 °C without affecting the rheological properties of the warm-mix rubber asphalt.

Along with the further development of research, many experts and scholars have carried out compatibility studies to solve the problems of the poor storage stability and easy segregation of wet-rubber asphalt. Han et al. [13] used a covalent grafting reaction to graft octadecyl amine (ODA) onto the surface of waste-rubber powder (WRP) to obtain an ODA-WRP modifier and noted that mixing SBS-modified (Styrenebutadiene-styrene block copolymer modifier) asphalt with ODA-WRP could improve the viscosity, stability, and plasticity of asphalt. Jiang Miao Yu et al. [14] modified rubber asphalt with nanoclay to improve the storage stability of the rubber asphalt. Through an X-ray diffraction (XRD) analysis of the nanoclay, changes in the gap distance of the nanoclay layer were observed, and the mechanism was studied. Yu et al. [15] noted that the surface activity of rubber particles increased after micro-radiation, which improve the stability and viscoelasticity of the modified asphalt. Xue et al. [16] activated rubber powder via chemical grafting to improve the stability and rheology of the asphalt.

Building on research into the rheological properties of rubber asphalt, domestic and foreign experts and scholars have researched the viscoelastic properties of rubber asphalt mixtures. Zeiada et al. [17] used viscoelastic continuous-damage models to compare traditional, polymer, and rubber asphalt mixtures and established damage characteristic curves for the three mixtures. Bai et al. [18] studied the random viscoelastic constitutive model and concluded that the model can not only approximate the probability distribution of the random strain responses of the material but also quantitatively evaluate the influence of the rubber powder modifier on the mechanical properties of the material. Kazem Jadidi

et al. [19] used the non-destructive ultrasound measurement technique and determined that the decreased integrated response for specimens with binders containing crumb rubber was less than the response among those without crumb rubber. This difference was due to the increased elastic recovery of crumb rubber in the binder. Yu Lei et al. [20] using uniaxial compression dynamic modulus tests to test related indicators at four different test temperatures and nine different load frequencies. Tang Hengshan [21] used an asphalt mixture performance tester (AMPT) to test the dynamic modulus of a rubber asphalt mixture to draw a master curve of the dynamic modulus. Punyaslok Rath et al. [22] combined new fracture testing methods with detailed image analysis techniques (SEM). These tests suggested that adding rubber decreased the cracking resistance of the mixes.

Qishi Li et al. [23] explored the influences of Sasobit/ESO on the rheological properties of SBRMA; the results indicated that the Sasobit/ESO composite not only enhanced the thermal cracking resistance of the SBRMA mixture but also enhanced the high-and low-temperature performance of SBRMA concurrently; moreover, the reduced short-term aging temperature afforded by Sasobit/ESO can help mitigate the adverse impacts of aging on the performance of SBRMA.

In summary, although significant research has been conducted on the viscoelasticity of rubber-powder-modified asphalt and asphalt mixtures, these studies mainly focused on the same scale, with fewer considering a multi-scale joint analysis of the performance of rubber-powder-modified asphalt mixtures. Therefore, the present work adopts the concept of a multi-scale study to analyze the performance of high-dosage-modified asphalt and its mixtures. We used the electron microscope scanning method to explore the microscopic appearance of the rubber-powder-modified asphalt, and the durability of the asphalt pavement modified by rubber powder was analyzed based on the effective asphalt film thickness. From the perspective of meso-mechanical analysis, a dynamic shear rheological test was carried out to analyze the rheological properties of rubberpowder-modified asphalt. A universal testing machine was used to study the influence of different temperatures and loading frequencies on the viscoelastic properties of different asphalt mixtures.

2. Materials

2.1. Aggregates

The angular property of an aggregate refers to the prominent degree of the edges and corners on the surfaces of mineral particles. Good angular properties can give an aggregate strong locking abilities when the road surface is formed, thus improving the overall strength and anti-deformation ability of the road surface. The aggregate is first treated with equivalent ellipticity to minimize the impact of the contour shape on the quantization of the angular quality while retaining the particle contour characteristics. The equivalent ellipse and convex surfaces of the particles are shown in Figure 1. According to Equation (1), the angular properties of aggregates are weighted by area:

$$A^{-} = \frac{\sum Y_i \times A_i}{\sum A_i} \tag{1}$$

where A^- is the area weighted value of the rough aggregate angular index, Y_i is the angularity index of the *i*-th particle in the aggregate sample, and A_i is the area of the particle from a top–down view.

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Figure 1. Schematic diagram of the particle equivalent ellipse and convex surface.

To determine the abrasion resistance of the coarse aggregate, the limestone aggregate was worn 0, 200, 500, 700, and 1000 times using a Los Angeles attrition apparatus (Zhongstron Measurement and Control Technology Co., Ltd., Tianjin, China). The abrasion test was carried out according to the coarse aggregate abrasion test of Highway Engineering Aggregate Test Specification (JTG E42-2005, Highway Research Institute of the Ministry of Communications, Beijing, China). The abrasion results are shown in Figure 2. The Image-pro image processing software was used to identify the aggregates. The basic parameters of the particles, such as the area, circumference, and long and short axes, were measured by the software, and the file for particle outline data was exported at the same time, as shown in Figure 3.

Convex surface



Figure 2. Changes in the angularity of aggregates.





It can be seen from the test results that as the amount of wear increases, the angularity of each particle size in the aggregate gradually decreases. The reason for this result is that as the amount of wear increases, the edges and corners of the coarse aggregate surface are gradually worn away, making the aggregate increasingly smooth. At the same time, when considering 500 repetitions of abrasion as the boundary, the large-diameter stones in the early stage are more likely to break and wear during the collisions with each other but tend to be stable in the later stages.

2.2. Asphalt Binder

A waste tire with a ratio of styrene-butadiene rubber to natural rubber of 3:7 was used as the raw material to prepare rubber-powder-modified asphalt. The coarse powder of the waste tire was subjected to chemical pretreatment and then finely crushed to obtain waste-rubber powder with a fineness of 60 mesh. The rubber powder produced in this way featured smooth edges and corners, no obvious tearing, and small concave and convex surfaces; therefore, this rubber offered a large specific surface area, high levels of activity, and better performance.

In this study, the wet method was used to produce modified asphalt with rubber powder in a laboratory. As the rubber powder particles were sufficiently small, the traditional process of grinding rubber powder was omitted in the production process. In the production process for waste-rubber-modified asphalt, each index was strictly controlled in this study. In the process of drying rubber powder in the beginning stage, the drying temperature was set to 110 °C to ensure that the rubber powder was fully dried, and the heating temperature of the base asphalt was 180 °C. In the process of stirring, in order to speed up the reaction and ensure the full effect of the desulfurization reaction from rubber-powder swelling, the stirring temperature was set to 190–220 °C, and the stirring time was set to at least 45 min. After the waste-rubber powder was evenly distributed, the matrix asphalt was modified through swelling and desulfurization.

The amount of rubber powder affected the absorption degree of light oil during swelling. An excess amount of rubber powder will make the rubber absorb excess light components, thereby increasing asphalt viscosity. Too low a dosage of rubber powder will reduce the modification effects of high and low temperature performance. Therefore, in this study, modified asphalt was prepared using matrix asphalt, and the content of rubber powder was 25%, 30%, and 35% (25%, 30%, and 35% of bitumen mass). SBS-modified asphalt with an SBS content of 4.0% was selected for the comparative study to test the penetration, softening point, and ductility of the asphalt. A Brookfield viscometer was used to determine the apparent kinematic viscosity of the asphalt. The technical parameters are shown in Table 1.

Item	Penetration Degree/0.1 mm	Softening Point/°C	Ductility/cm	Brinell Viscosity/Pa·× s	Standard Method
70#matrix asphalt	61	49.8	66.9	0.424	
SBS-modified asphalt	56	68.5	32	1.325	
25% Rubber-powder-modified asphalt	61.8	71.6	12.9	2.162	JTG E20-2011
30% Rubber-powder-modified asphalt	56.7	78.9	15.7	2.887	
35% Rubber-powder-modified asphalt	51.2	79.2	17.5	3.921	

 Table 1. Basic indications of asphalt.

With an increase in rubber-powder content, the high-temperature performance was improved, which was embodied by the increase of the softening point. Due to the existence of rubber powder particles in the modified asphalt, the low temperature ductility improved with an increase in the rubber-powder content. At the same time, the viscosity of the asphalt reflected the resistance of the asphalt to flow and shear deformation. Here, the higher the viscosity was, the greater the resistant to shear deformation, and the less likely shear failure would occur at a high temperature. Thus, the resistance of asphalt to flow shear deformation increased with an increase in rubber-powder content. However, in an actual test, excess rubber-powder content will make the asphalt too viscous. Therefore, the rubber-powder content should not be too high. We determined that the optimal amount of rubber powder is 30%.

3. Characterization and Performance Testing

The properties of the rubber-modified asphalt and asphalt mixture were then analyzed using the multi-scale research concept. In this system, asphalt acts as a binder to bond the aggregate into a whole, thus providing the required structural strength. Therefore, we analyzed the microstructures of rubber-modified asphalt with different contents from a microscopic point of view. In this study, the effective asphalt film thickness of the rubber-powder-modified asphalt mixture was analyzed to ensure the mixture's overall durability. A dynamic shear rheometer (The AR1500ex shear rheometer produced by the TA company, Boston, MA, USA) was, moreover, used to measure the rheological parameters of the asphalt. Dynamic modulus tests (Rambo Think Material Testing Co., LTD, Shenzhen, Guangdong Province, China) were carried out on different asphalt mixtures to determine the dynamic moduli and phase angles at different temperatures and frequencies so as to explore the dynamic viscoelastic properties of the asphalt mixtures modified by rubber powder.

3.1. Characteristic Test at a Micro Scale

We carried out the microstructural analysis of rubber-powder-modified asphalt and its mixtures from a microscopic point of view. The surface of the sample was scanned with the electron beam of a scanning electron microscope (SEM) (SIGMA 300 scanning electron microscope produced by the Carle Carl Zeiss Company, Obercohen, Germany) to obtain a high-resolution image of the sample surface, which was then used to identify the surface structure of the sample and analyze the microstructure of the rubber-powder-modified asphalt. We then determined the asphalt film thickness of the rubber-powder-modified asphalt mixture and used the electron-microscope-scanning method to compare and correct the asphalt film thickness. The experimental design is shown in Table 2.

Project	Technical Indicator	Standard Method	Test Material	Test Conditions
Micro-Structural Analysis	SEM electroscope scanning test	JB/T 6842-93	Rubber-powder- modified asphalt (25%, 30%, 35% rubber-powder content)	The sample was frozen and brittle-fractured, and then the fracture surface was etched with a solvent We calculated the
	Asphalt film thickness	JTG E20-2011	Stone Mastic Asphalt with a maximum dimension of aggregates of 13 mm (30% rubber-powder content)	thickness of the asphalt film based on the effective asphalt content determined using the centrifugal separation method (correcting for the scanning electron microscope)

Table 2. Micro-scale characteristic test scheme.

3.2. Meso-Mechanical Analysis

3.2.1. Dynamic Shear Rheological Test Methods (DSR)

To explore the influence of rubber powder on the high temperature rheological properties of asphalt, a dynamic shear rheometer (TA company, Boston, MA, USA) was used to scan the asphalt at different feed frequencies and temperatures. Linear viscoelastic parameters such as the complex shear modulus (G*) and rutting factor (G*/sin δ) were obtained in the experiment. Among them, the complex shear modulus (G*) reflected the fatigue resistance of the asphalt. The larger the complex shear modulus (G*) is, the better the fatigue resistance will be. The rutting factor (G*/sin δ) represents the asphalt's resistance to deformation, where the larger the rutting factor (G*/sin δ), the stronger the material's resistance to deformation. The tests used 25 mm diameter parallel-plate geometry with a 1 mm gap and 8 mm diameter parallel geometry with a 2 mm gap, and temperatures set in 5 steps ranging from 46 to 70 °C according to the PG (Peformance Grade) ratings. The specific test scheme is shown in Table 3.

Table 3. Dynamic shear rheological test scheme.

Test Item	Temperature/°C	Temperature Step/°C	Frequency /Hz	Loading Method	Standard Method
Frequency sweeping Temperature scanning	46–70 46–70	6 6	0.1–25 0.1–25	sine wave	JTG E20-2011

3.2.2. Dynamic Modulus Test Design

To study the dynamic viscoelasticity of the rubber-powder-modified asphalt mixture, dynamic modulus tests were carried out at 5, 10, 20, 40, and 50 °C under unconfined conditions. Axial compressive stress of the offset sine wave or half normal vector wave was applied to the specimen at a certain loading frequency. The specific test scheme is shown in Table 4. We then calculated the dynamic modulus ($|E^*|$) and phase angle (φ) of the rubber-powder-modified asphalt mixture based on the test data. The phase angle (φ) was the main manifestation of the unsynchronized strain and stress of the viscoelastic materials under alternating loads, as determined by the viscoelastic mechanical properties of the asphalt mixture. The phase angle (φ) depended on the molecular structure of the viscoelastic material, as well as the temperature and frequency of the load.

Table 4. Repetitions of loading under various load frequencies.

Frequency/Hz	Number of Repetitions /Times	Frequency/Hz	Number of Repetitions /Times
25	200	1	20
10	200	0.5	15
5	100	0.1	15

4. Results

4.1. Microscopic Properties

4.1.1. Scanning Electron Microscope (SEM)

The microscopic morphology of the rubber-powder-modified asphalt with different rubber-powder contents is shown in Figure 4.



Figure 4. Scanning electron microscope images of asphalt modified with different dosages of rubber powder: (**a**) 25% rubber-powder content (560 times); (**b**) 30% rubber-powder content (520 times); (**c**) 35% rubber-powder content (640 times); (**d**) 25% rubber-powder content (55 times); (**e**) 30% rubber-powder content (39 times); (**f**) 35% rubber-powder content (50 times).

It can be seen from Figure 4a–c that the rubber-powder-modified asphalt containing 25% rubber powder had a larger dispersion unit after etching, and the size was not uniform. White rubber powder particles distributed on the surface (about 30 microns or less in size) can also be observed. The surface of the rubber-powder-modified asphalt containing 30% rubber powder illustrates the relatively uniform distribution of white particles. Dense particle distribution can be observed on the surface of the rubber-powder-modified asphalt containing 35% rubber powder. The particle sizes of these particles were about 40 microns or less, with different diameters.

The SEM electron microscope images in Figure 4 clearly show the distribution and development of waste-rubber powder in the asphalt. The waste-rubber powder showed good compatibility with the asphalt and was evenly dispersed. Uniform colloidal material was formed in the asphalt. The majority of the surface of the waste-rubber powder was dissolved and swelled by the light components in the asphalt, and a small number of light components penetrated into the waste-rubber powder. This occurred because after the rubber powder and modified asphalt were mixed under high-temperature conditions, the waste-rubber powder particles absorbed the light components in the modified asphalt and then dissolved and swelled. Meanwhile, a gel film layer also formed on the surface of the crumb rubber particles, thereby producing a better connection between the powder particles. The swelled volume of the waste-rubber powder particles reached 20% to 30% of the cementitious material's volume, thereby forming a semi-solid continuous phase system with large viscosity. The waste-rubber-powder particles exhibited both adsorption and filling functions, improving the viscoelasticity of the asphalt colloid to achieve a modification effect.

4.1.2. Asphalt Film Thickness

To meet the performance required by the overall structure, such as rut resistance, crack resistance, and water damage resistance, the aggregate must be bonded with enough asphalt to form a stable structure, and the asphalt adhering to the aggregate surface must reach a certain thickness to ensure overall durability. Therefore, the asphalt film thickness of the asphalt mixture with 30% rubber-powder content was determined by a test. First, six specimens numbered 1-6 were centrifuged to determine the available asphalt content of each sample. At the same time, according to the research data, the relative density of the asphalt was 1.03. The change in the effective asphalt film thickness with an increase in time under different experimental environments was then calculated, and the thickness of the asphalt film was compared and corrected using a scanning electron microscope. Figure 5 shows images of the asphalt mixture at different magnifications. The revised calculation results of the effective asphalt film thickness are provided in Table 5.





Figure 5. Asphalt mixture images at different magnifications: (a) magnified 3000 times; (b) magnified 50,000 times.

Effective Pitch Film Thickness/µm		Tin	ne/h	
Specimen Number	0	2	4	7
1	251	240	225	221
2	251	226	167	140
3	251	204	134	89
4	251	182	76	31
5	251	189	130	74
6	251	173	131	52

It can be seen from Figure 6 that the asphalt film thickness of the rubber-powdermodified asphalt mixture gradually decreased over time. The higher the temperature was, the faster the thickness of the asphalt film decreased. With an increase in humidity, the thickness of the asphalt film decreased slightly, but the change was not obvious, indicating that the influence of temperature on the thickness of the asphalt film over a relatively short period of time was much greater than the influence of humidity.



Figure 6. Asphalt film thickness under different test conditions: (**a**) asphalt film thickness under different humidity levels; (**b**) asphalt film thickness at different temperatures.

(a)

The asphalt film thickness of the specimen in the simulated outdoor environment was also measured, and the results are shown in Figure 7.

(b)



Figure 7. Simulated changes in asphalt thickness in an outdoor environment.

It can be seen from Figure 7 that the asphalt film thickness of the asphalt mixture decreased rapidly over the first 8 days to 61.8% of the initial value and then decreased slowly.

4.2. Meso-Mechanical Analysis

4.2.1. Rheological Properties

The content of rubber powder affected the degree of absorption of light oils during the swelling of the rubber powder. Rubber-powder content that is too high or too low can affect the performance of the asphalt and mixture [24]. Based on the above test results, we selected 30% rubber-powder content. The rubber-powder-modified asphalt and SBSmodified asphalt were then tested to study the dynamic viscoelastic properties of the two asphalts. The changes in the complex moduli and rutting factors of the two asphalts at different temperatures and frequencies were analyzed, and the high-temperature stability of the rubber-powder-modified asphalt binder was evaluated. The results are shown in Figures 8 and 9.



Figure 8. The variation curve of the complex moduli of different asphalts with frequencies: (**a**) rubber-powder-modified asphalt; (**b**) SBS-modified asphalt.



Figure 9. The variation curve of different asphalt rutting factors with frequency: (**a**) rubber-powder-modified asphalt; (**b**) SBS-modified asphalt.

It can be seen from Figure 8 that at low temperatures, due to continuous loading and unloading, the internal structure of the asphalt changed, resulting in a loss of the modulus, which made the complex modulus smaller. Therefore, when the temperature was 46 °C, the asphalt complex modulus first became larger and then decreased as the frequency increased. Asphalt is a viscoelastic substance whose deformation is divided into elastic deformation and permanent deformation. Elastic deformation can be restored, but permanent deformation cannot be restored. When the frequency increases, the action time becomes shorter, and the deformation decreases, making the complex mode larger. Therefore, when the temperature is in the range of 52 to 70 °C, the asphalt complex modulus is positively correlated with frequency. When the frequency is constant, the complex modulus is negatively related to temperature, and the decrease range is the largest (46 to 52 °C). The results show that the complex modulus of the rubber-powder-modified asphalt was higher than that of the SBS-modified asphalt, indicating that the incorporation of rubber powder improved the anti-deformation ability of the asphalt.

Figure 9 shows that when the temperature is 46 °C, with an increase in loading frequency, the rutting factor increases first and then decreases; when the temperature is in the range of 52 to 70 °C, the rutting factor is positively correlated with frequency and negatively correlated with temperature. Under the same test conditions, the rutting factor of rubber-powder-modified asphalt is higher. As the rutting coefficient increases, the ability to resist deformation is, therefore, enhanced, showing extremely high-temperature stability.

4.2.2. Analysis of Dynamic Viscoelastic Characteristics

• Dynamic Modulus

This test prioritized the effects of the test temperature and test frequency on the dynamic modulus. Three sets of parallel tests were carried out on the rubber-powder-modified asphalt mixture and SBS-modified asphalt mixture at different loading frequencies and different temperatures. The dynamic modulus results are shown in Figures 10 and 11.



Figure 10. Relationship between the dynamic moduli and loading frequencies of different asphalt mixtures: (**a**) rubber-powder-modified asphalt mixture; (**b**) SBS-modified asphalt mixture.



Figure 11. Relationship between the dynamic moduli and temperatures of different asphalt mixtures: (**a**) rubber-powder-modified asphalt mixture; (**b**) SBS-modified asphalt mixture.

Figure 10 shows that the dynamic moduli of the two asphalt mixtures was positively correlated with the loading frequency. This result is due to the viscoelastic characteristics of

the asphalt. However, with a further increase in loading frequency, the dynamic modulus rate of increase decreases and then gradually flattens out. This occurs because the response of the asphalt mixture to the load has a lagging process. Under the action of the load, the mixture will neither fully compress instantaneously when loaded nor will it instantaneously rebound completely when unloaded; thus, the strain is small. In reality, the mixture has a more obvious strength and modulus than those under a static load. Again, as the loading frequency gradually increases, the hysteresis of the load response becomes more obvious, which is manifested as a further increase in the strength and modulus.

As shown in Figure 11, when the frequency is constant, the dynamic modulus values of the two asphalt mixtures decrease as the test temperature increases. The higher the temperature is, the smaller the dynamic modulus of the asphalt mixture will become, which varies based on the loading frequency. When the temperature is 5 °C, the dynamic modulus of the asphalt mixture reached 7000 to 19,000 MPa. At this time, the asphalt mixture was closer to a linear elastic body, and the amount of deformation under the load was extremely small. As a long-term effect, the asphalt mixture would be prone to cracking under such a load. Here, as the temperature increases, the viscosity effect of the asphalt mixture also gradually increases. Asphalt pavement is prone to significant permanent deformation under heavy loads. Thus, the dynamic modulus value can be used to measure the high-temperature stability of asphalt pavement.

• Phase Angle

An important indicator for the viscoelasticity of asphalt mixtures is the phase angle. A change in the phase angle is mainly reflected by an increase or decrease in the internal friction resistance of the mixture. As the temperature and frequency change, the internal frictional resistance will also change accordingly [25]. The relationship between the phase angles, frequencies, and temperatures of the two asphalt mixtures is shown in Figures 12 and 13.



Figure 12. The relationship between the phase angle and loading frequency: (**a**) rubber-powder-modified asphalt mixture; (**b**) SBS-modified asphalt mixture.



Figure 13. Relationship between the phase angle and temperature of different asphalt mixtures: (**a**) rubber-powder-modified asphalt mixture; (**b**) SBS-modified asphalt mixture.

As shown in Figure 12, when the temperature is low, the phase angle will be negatively correlated with the loading frequency. The asphalt binder in the asphalt mixture plays a large role at low temperatures. At this time, the asphalt mixture is mainly characterized by elasticity. As the frequency increases, the mixture's viscosity decreases, and the elasticity increases. The higher the frequency is, the active the polymer chain segment, the lower the performance, the larger the phase angle at low temperature and low frequency, the smaller the phase angle at low temperature and high frequency. When the temperature is 40 °C and above, the main factor that determines the viscoelastic properties of the asphalt mixture at a high temperature and low frequency will be the embedding effect of the mineral skeleton. Moreover, the phase angle increases with an increase in frequency. As the asphalt binder becomes soft at high temperature and low frequency, the bonding and lubrication between mineral aggregates are weakened. Under normal circum-stances, mineral materials are elastic materials. Under low frequency loads, mineral materials with greater internal friction resistance the phase angle of is approximately zero. When the load frequency increases, the hysteresis effect is significant and the phase angle increases.

As shown in Figure 13, at low frequencies, with an increase in temperature, the phase angle increases in the early stage and then decreases, reaching a peak at 20 °C. In the case of a medium frequency, the change law of the phase angle with temperature also increases first and then decreases, and the peak of the phase angle appears later than that under a low frequency. Under a high frequency, the phase angle of the asphalt mixture increases with an increase in temperature, primarily because the asphalt mixture is close to the viscous material at low frequencies, and the viscosity of the binder continues to decrease as the temperature rises. When the temperature reaches a certain fixed value, the influence of the binder on viscosity can be ignored, but the mineral skeleton plays a leading role. The higher the temperature becomes, the more obvious the skeleton effect of the mineral material will be. The final result is that the phase angle first increases and then decreases with the temperature. When the temperature is lower at a medium frequency, the viscosity characteristics of the material are difficult to observe. As the temperature increases, viscosity gradually increases and eventually shows a similar pattern to that under low frequencies, except that the peak lag of the phase angle appears. Materials at high frequencies mainly exhibit elastic properties, and the proportion of viscous components increases as the temperature rises, and finally appears as the material the phase angle increases continuously as the temperature increases.

Based on the dynamic modulus test, the dynamic modulus of the rubber-powdermodified asphalt mixture was higher than that of the SBS-modified asphalt mixture along with a higher dynamic modulus, which showed stronger anti-rutting performance. Based on a comparison of the phase-angle test results, we found that at low temperatures, the rubber-powder-modified asphalt mixture featured a relatively large phase angle, exhibited elasticity, provided greater ductility for low temperature deformation, and offered strong anti-cracking abilities. At high temperatures, the rubber-powder-modified asphalt mixture had a significantly smaller phase angle, strong deformation recovery abilities, and reduced permanent deformation, which resulted in better high-temperature stability.

5. Conclusions

In this study, a multi-scale analysis method was used to explore the performance of modified asphalt and its mixture with high content of rubber powder. At a microscopic scale, the electron-microscope-scanning method was used to explore the microscopic appearance of the rubber-powder-modified asphalt, and the durability of the rubber-powder-modified asphalt pavement was analyzed through effective asphalt-film-thickness analysis. From the perspective of the meso-mechanical analysis, a DSR (dynamic shear rheological) test was carried out to analyze the rheological properties of the rubber-powder-modified asphalt, and the dynamic modulus test was used to analyze the dynamic viscoelasticity of the mixture. The conclusions are as follows:

- 1. Experimental studies have found that due to the interference of rubber powder particles, there are certain limitations when using condition indicators such as ductility, penetration, and the softening point to evaluate the performance of rubber asphalt. Therefore, it is recommended to combine the viscosity index and scanning electron microscope results when analyzing the performance of rubber-modified asphalt from a multi-scale perspective.
- 2. Based on the scanning electron microscopy analysis, the asphalt absorbed light components during the expansion process and formed a gel film on the surface of the rubber powder particles, thereby improving the high-temperature performance and viscoelasticity of the asphalt. With an increase in rubber-powder content, the particle size first decreased and then increased, indicating that the swelling rate of the asphalt first increased to an extreme value and then decreased with an increase in the rubber-powder content. Combining the scanning results of the electron microscope with those of Brookfield viscosity, the softening point and ductility index analysis showed that the best amount of rubber powder is 30%.
- 3. The effective asphalt film thickness of the rubber-powder-modified asphalt mixture was calculated using a centrifugal separation test, and the asphalt film thickness was compared and corrected via the scanning electron microscope method. Multi-scale combined analysis methods were used to verify the bonding strength of the adhesive. At the same time, we found that the use of digital image processing technology can better characterize the angularity of coarse aggregates. Then, we analyzed the impact of the macroscopic properties of the angularity of the aggregates on the performance of the asphalt mixture.
- 4. The DSR test showed that after continuous loading and unloading, the rubber-powder-modified asphalt had a higher complex modulus, thereby affording better fatigue resistance. Compared with the SBS-modified asphalt, the rutting factor of the rubber-powder-modified asphalt was increased by 10.3–19.3%, indicating that the high-temperature resistance and permanent deformation abilities of the asphalt were improved after adding the rubber powder.
- 5. The dynamic modulus of the rubber-modified asphalt mixture was negatively related to temperature. When the temperature was high (40 °C), the dynamic modulus difference of each loading frequency was very small. At this time, the viscosity effect of the asphalt mixture gradually increased, and the asphalt pavement was prone to a greater degree of permanent deformation when the load continued to increase. Therefore, the dynamic modulus was found to be very representative as an index for the high-temperature stability of asphalt pavement.
- 6. The temperature turning point for the phase angle of the high-dosage rubber-powdermodified asphalt mixture was 40 °C. At a low temperature and high frequency, the

asphalt mixture was closer to an elastomer, with its elastic properties mainly contributed by aggregate. At this time, the phase angle of the asphalt mixture decreased with an increase in frequency. At a high temperature and low frequency, the asphalt mixture transformed into a viscous elastomer. Then, the viscosity proportion of the mixture increased; the mixture's viscosity property was mainly affected by the asphalt binder. The addition of rubber powder changed the temperature sensitivity of the asphalt and then affected the viscoelastic properties of the asphalt mixture.

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