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Study on High and Low Temperature Performance of Mineral Powder Modified Rubber Asphalt Mortar

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Citation: Liu, W.; Zhang, C.; Li, L.; Wang, L.; Wang, L.; Pu, C.; Yang, G. Study on High and Low Temperature Performance of Mineral Powder Modified Rubber Asphalt Mortar. *Coatings* **2023**, *13*, 791. https://doi.org/10.3390/coatings13040791

Academic Editors: Valeria Vignali and Manuel Miguel Jordan-Vidal

Received: 22 March 2023
Revised: 7 April 2023
Accepted: 16 April 2023
Published: 19 April 2023

Abstract: With the increase of coal mining in China, a large amount of waste coal gangue is produced. How to reuse waste coal gangue is an important research direction. The research results showed that the improvement of base asphalt mortar by coal gangue powder could improve the performance of matrix asphalt, however, search of rubber asphalt mortar modified by coal gangue powder is rarely reported. High and low-temperature performance is the critical performance of asphalt mortar. So the limestone powder modified base asphalt mortar (LPMBAM), limestone powder modified rubber asphalt mortar (LPMRAM), and coal gangue powder modified rubber asphalt mortar (CGPMRAM) are prepared, the high and low-temperature performance of asphalt mortar are analyzed by cone penetration tests and bending beam rheological tests (BBR). The results show that the cone penetration of asphalt mortar decreases with the increase of the filler-asphalt ratio and the decrease of the temperature. The shear strength and the stiffness modulus increase with the rise in the filler-asphalt ratio and the decrease in temperature. At the same filler-asphalt ratio and temperature, the order of cone penetration is CGPMRAM < LPMRAM < LPMBAM, and the order of shear strength is CGPMRAM > LPMRAM > LPMBAM, so the high-temperature performance of CGPMRAM is better than that of LPMRAM, much better than LPMBAM, the order of stiffness modulus is LPMRAM < CGPMRAM < LPMBAM so the low-temperature performance of LPMRAM and CGPMRAM is better than that of LPMBAM. By the double linear model, the optimum filler-asphalt ratio is determined to be 0.44~0.46 for LPMRAM and 0.42~0.43 for CGPMRAM. Microscopic tests show that the surface of coal gangue powder is rougher than that of limestone powder. The content of active oxides such as SiO_2 and Al_2O_3 in coal gangue is about 7.8 times that of limestone powder. These physical and chemical properties make coal gangue powder able to adsorb rubber asphalt better and improve the high-temperature performance of CGPMRAM while slightly worsening the low-temperature performance of CGPMRAM but still better than LPMBAM.

Keywords: coal gangue powder; rubber asphalt; filler-asphalt ratio; double linear model; microstructure

1. Introduction

Coal gangue is a kind of solid waste produced in coal mining, generally stored in a stacking manner. China's stockpile has reached 7 billion tons with a growth rate of 1.5 billion t/a. These coal gangue not only occupy the land but because it contains heavy metals that can also lead to groundwater pollution and emissions of toxic gases. Currently, there is some research on the recycling of waste coal gangue, such as the preparation of wastewater treatment materials, the production of impermeable cement, and the filling of roadbeds [1–5]. In recent years, with the development of China's economy, many highways have been built and expanded every year. Many pavements have transverse and longitudinal cracks, rutting, and other diseases due to the external environment and driving load, which have not reached the expected service life [6–11]. The increase in the number of vehicles and vehicle load also put forward higher requirements for pavement performance. Therefore, how to use waste coal gangue is an important research direction.

Grinding waste tires into powder and adding a certain proportion to the base asphalt to make rubber asphalt can improve its road performance. In practical engineering, asphalt pavement, with other good physical and mechanical properties, is still easy to rut in high-temperature environment and easy to crack in low-temperature environment, which significantly affects the use of the highway, so it is necessary to study the high and low-temperature performance of asphalt mixture. Zhao [12] found that rubber asphalt's high and low-temperature performance is better than base asphalt's, and the water stability is improved. In addition, it can reduce noise pollution and has good economic benefits. Wang [13] studied the influence of the fineness and content of rubber powder on the performance of asphalt through experiments. Considering the indexes of softening point, penetration, and viscosity, the optimal mesh is finally determined to be 40–60 mesh, and the content is 17%. Inorganic particle powder modified asphalt is a crucial field of modified asphalt research. Tan [14] found that hydrated lime and calcium carbonate can improve the force required to separate the asphalt or asphalt mortar from the slate and the splitting strength ratio before and after freezing and thawing the asphalt mixture. Jia et al. [15] found that the surface structure of lime and cement particles is more complex than limestone powder, the fatigue performance of lime and cement asphalt mortar is better than that of stone powder asphalt mortar, and the decrease of inorganic powder particle size will further improve the fatigue performance. Yao and Gao [16] found that the asphalt mixture with Bayer red mud as the filler has the best temperature stability. The deformation, rutting, and low-temperature crack resistance are improved. Coal gangue powder shows a rich structure and large specific surface area.

Furthermore, Coal gangue powder contains many active oxides, such as SiO_2 and Al_2O_3. These physicochemical properties promote the acid-base reaction between asphalt and filler. Feng, Wu, Wang et al. [17–20] used coal gangue powder to improve asphalt mixture and found that it can improve the road performance of asphalt mixture.

In summary, many researchers have studied the powder modified asphalt mixture. However, there are few reports on using coal gangue powder to modify rubber asphalt. This paper selects limestone powder and coal gangue powder to alter the base asphalt and rubber asphalt with 20% rubber powder. Through the cone penetration test and bending beam rheological test, the influence of mineral powder on the high-temperature and low-temperature performance of asphalt mortar is analyzed. The double linear model is adopted to determine the optimal filler-asphalt ratio range.

2. Materials

The 70# base asphalt, rubber asphalt with 20% rubber powder, and limestone powder used in the test are all taken from a highway project under construction in China. Table 1 lists three index tests of base and rubber asphalt. The coal gangue was taken from Datong, Shanxi Province. After mechanical crushing and grinding, passing through 0.075 mm of sieve, the two kinds of ore powder were ready for the tests. As shown in Figure 1, the physical diagram of two kinds of mineral powder, and Table 2 is the technical performance of mineral powder.

Table 1. Three leading indicators of asphalt.

Indexes	70# Base Asphalt	15% Rubber Asphalt	20% Rubber Asphalt	25% Rubber Asphalt
Softening point (°C)	48.5	61.9	67	75.7
Needle penetration (mm) (25 °C)	44.1	44.1	41.9	40.5
Ductility (cm) (5 °C)	7.4	7.4	6.7	6.2

(**a**)

(**b**)

Figure 1. Sample of limestone powder and coal gangue powder: (**a**) Limestone powder; (**b**) Coal gangue powder.

Table 2. Technical performance indicators of mineral powders.

Technical Performance	Apparent Density (g/cm^3)	Hydrophilic Coefficient	Particle (<0.075 mm) Content (%)
Limestone powder	2.74	0.83	98
Coal gangue powder	2.27	0.77	100

3. Preparation of Rubber Asphalt Mortar

Referring to the research of Wei, Xu et al. [21,22] and actual test operation, it is found that it is challenging to mix when the filler-asphalt ratio reaches 0.8 for the mineral powder-modified rubber asphalt. Therefore, the filler-asphalt ratio is 0.1~0.7, and the test groups are three kinds of rubber asphalt, limestone powder modified base asphalt mortar (LPMBAM), limestone powder modified rubber asphalt mortar (LPMRAM), and coal gangue powder modified rubber asphalt mortar (CGPMRAM). Among them, LPMBAM is the control group. The fabrication of the experimental samples is as follows.

First, put the rubber asphalt into the oven, set the oven temperature to 185 °C (base asphalt needs 155 °C), and the heating time at one hour. After completely melting the asphalt, pour it into the container and weigh its mass.

At the same time, to prevent the temperature decrease of rubber asphalt, the mineral powder needs to be dried in an oven at 105 ± 5 °C for 0.5 h to reduce the temperature difference between the rubber asphalt and the powder. The quality of the corresponding mineral powder is calculated according to the ratio of powder to asphalt.

Then the dried mineral powder should be mixed with asphalt and heated in an electric furnace. Control the temperature at 180 ± 5 °C (base asphalt needs 150 ± 5 °C), control the stirring rate at 1000 r/min, and the mixing time is 0.5 h. During the mixing process, it is necessary to keep the stirrer blade's position in the middle of the mortar and as close to the vortex position as possible when adding the mineral powder so that the mixing mortar can be more evenly. When the filler-asphalt ratio reaches 0.4, as the amount of mineral powder is significant, the mortar is prone to aggregation when the powder is added in one-time, so the powder should be evenly added three times to avoid clumping asphalt mastic, as shown in Figure 2.

(**a**) (**b**)

Figure 2. The mixing process of the mortar and powder: (**a**) Heating by electric furnace; (**b**) Mixing by stirrer.

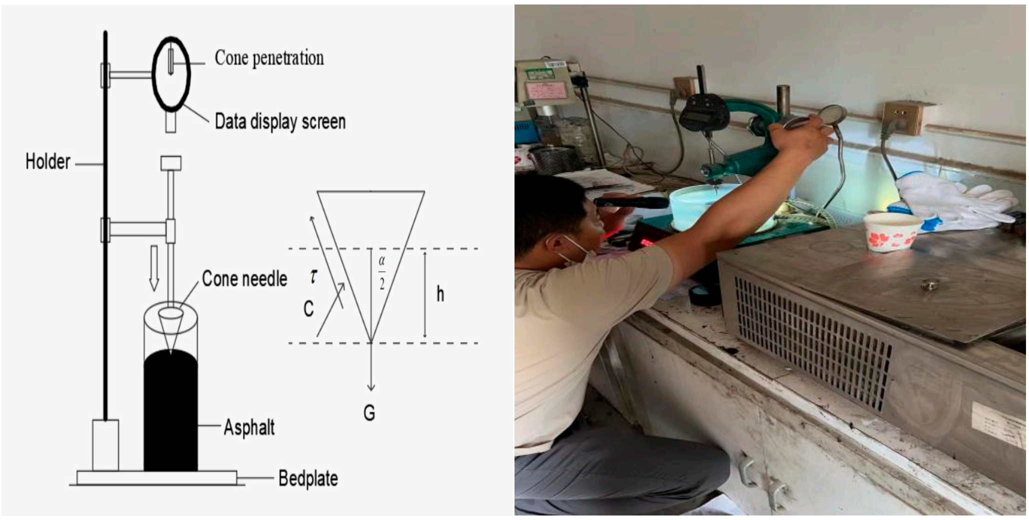
4. Test Instruments and Methods

4.1. Cone Penetration Test

Penetration is one of the main indexes to measure asphalt's hardness, consistency, and shear resistance. The addition of mineral powder makes the asphalt mortar thicker. It greatly improves the shear resistance, which causes difficulty for the needle to penetrate and a large dispersion of test results. Therefore, the shear resistance of asphalt mortar should be measured by the cone penetration test (Wuxi City Petroleum Instrument Equipment Co., Ltd., Wuxi, China) [23,24], and the cone needle replaces the long needle commonly used in the penetration meter, it is made of stainless steel with a cone angle of 30°, and its mass, together with the counterweight and connecting rod, is 142.8 g, as shown in Figure 3. The test operation steps strictly follow the penetration test specification, T0604, in the test standard [25], and the test temperature is selected as 15, 25 and 30 °C according to T0604. The formula in Appendix A could be used to calculate the shear strength based on the test results and used to evaluate mortar's high-temperature shear resistance [26].

(**a**) (**b**)

Figure 3. *Cont.*



(**c**) (**d**)

Figure 3. Cone penetration instrument: (**a**) Cone needle and weights; (**b**) Photo of the instrument; (**c**) Chart of cone penetration instrument; (**d**) Operating the instruments.

4.2. Bending Beam Rheological Test (BBR)

To evaluate the low-temperature performance of asphalt mortar, the Bending Beam Rheometer test (BBR) is carried out to measure the creep stiffness modulus S and creep rate m of asphalt mortar. Among them, S evaluates the ability to resist deformation, and m evaluates the speed of the stiffness change. The lower the S value and the higher the m value, the better the resistance to low-temperature cracking. The test procedure follows the test specification, T0604, in the test standard [26]. The experimental temperatures are selected as −12, −18, and −24 °C according to T0627 [25]. Figure 4 shows the specimens and test instruments (Cannon Instrument Company, State College, PA, USA).

(**a**) (**b**)

Figure 4. Specimens and BBR instruments: (**a**) BBR test specimens; (**b**) BBR test instruments.

5. Results and Analysis

5.1. Cone Penetration Test

Figure 5 shows the penetration of LPMBAM, LPMRAM, and CGPMRAM at different temperatures and filler-asphalt ratios.

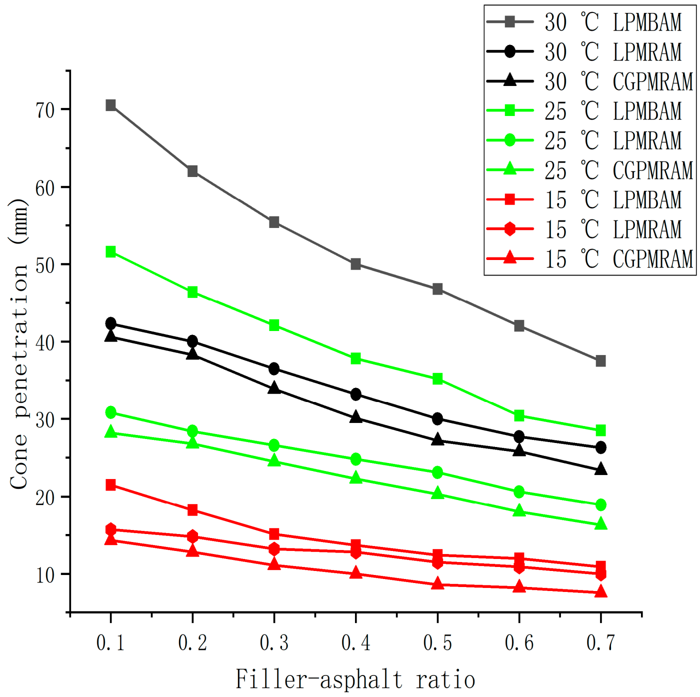


Figure 5. Cone penetration histogram at different temperatures and filler-asphalt ratios.

Figure 5 shows that the cone penetration of asphalt mortar at the same temperature decreases with the increase of the filler-asphalt ratio. The cone penetration value is much lower for rubber asphalt mortar than base asphalt mortar. Taking 0.4 filler-asphalt ratios and 25 °C as an example: the cone penetration of LPMBAM, LPMRAM, and CGPMRAM is 37.8, 24.8, and 22.0 mm, respectively. The cone penetration of LPMRAM and CGPMRAM is 13.0 and 15.8 mm lower than that of LPMBAM, indicating that the shear resistance of the rubber powder-modified mortar is significantly improved by about 34.4%.

As the temperature increases, the cone penetration of the three kinds of mortars increases. The cone penetration trend is still CGPMRAM < LPMRAM < LPMBAM, but the degree of decrease varies among different mortars. Taking 0.4 filler-asphalt ratios as an example: as the temperature increases from 15 °C to 25 °C and 30 °C, the penetration of LPMBAM increases by 24.1 and 12.2 mm; the penetration of LPMRAM increases by 12.3 and 8.4 mm; and the penetration of CGPMRAM increases by 12.0 and 7.8 mm, respectively. The penetration of CGPMRAM changes less than that of LPMBAM and LPMRAM with temperature, indicating that it has the lowest temperature sensitivity and the most stable mechanical properties.

The degree of penetration change also varies among different mortars under different filler-asphalt ratios from 0.1 to 0.7. For example: at 15 °C, LPMBAM decreases by 10.6 mm, LPMRAM decreases by 6.9 mm, and CGPMRAM decreases by 7.3 mm; at 25 °C, LPMBAM decreases by 23.1 mm, LPMRAM decreases by 11.9 mm, and CGPMRAM decreases by 12.9 mm; at 30 °C, LPMBAM decreases by 33 mm, LPMRAM decreases by 16 mm, and CGPMRAM decreases by 17 mm. The change in LPMBAM is the largest at all three temperatures.

The phenomenon may be because the limestone powder can adsorb a large amount of free asphalt in the base asphalt and quickly reduce the penetration. Because rubber powder adsorbs some free asphalt in rubber asphalt, the variation is not apparent; however, the difference in cone penetration of CGPMRAM is more significant than that of LPMRAM, indicating that the adsorption effect of coal gangue powder on rubber asphalt is greater than that of limestone powder.

Referring to the research of Wang et al. [27], the cone penetration degree at 25 °C is selected to calculate the shear strength through the calculation formula in Appendix A to analyze its high-temperature performance. Figure 6 shows the relationship curve between the filler-asphalt ratio and the shear strength. The shear strength of LPMBAM, LPMRAM, and CGPMRAM shows an increasing trend, which can be fitted into an exponential function, and the correlation R^2 coefficients are high, reaching 0.9920, 0.9924, and 0.9949, respectively.

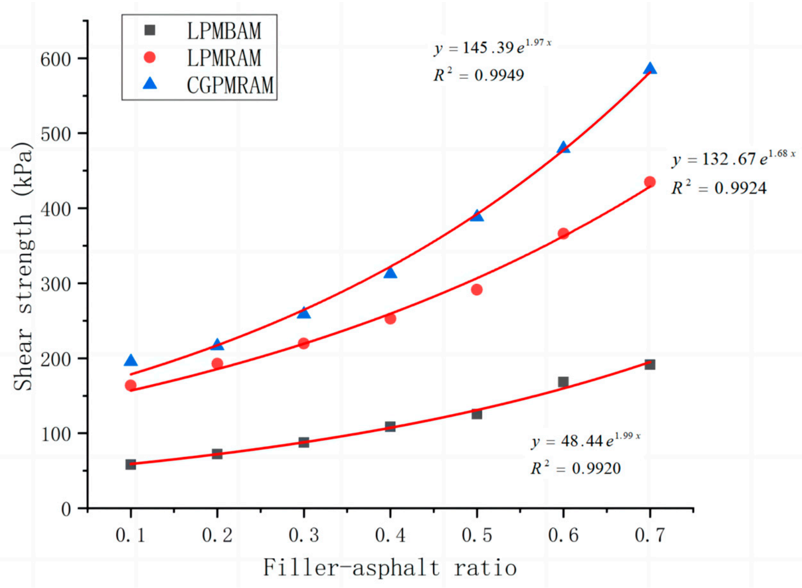


Figure 6. Relationship curves of shear strength and filler-asphalt ratios.

5.2. BBR Test Results and Analysis

Figure 7 shows the stiffness modulus *S* of LPMBAM, LPMRAM, and CGPMRAM at different temperatures and filler-asphalt ratios.

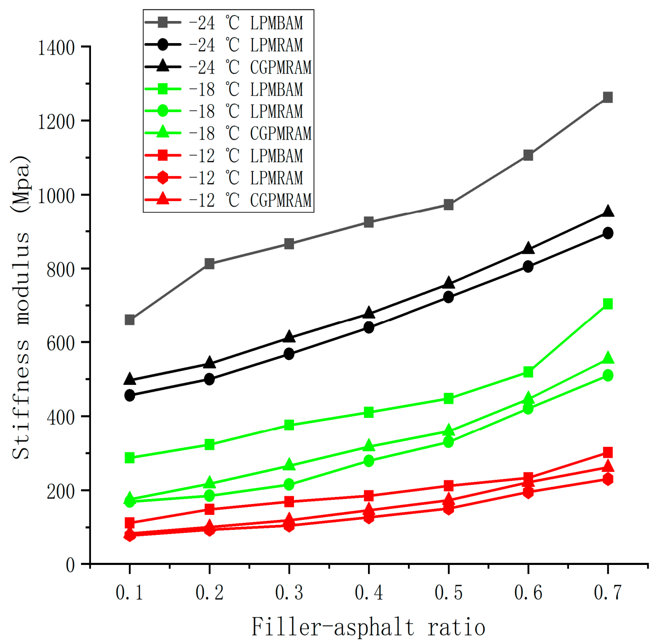


Figure 7. Stiffness modulus *S* of mortar at different temperatures and filler-asphalt ratios.

Figure 7 shows that the stiffness modulus *S* of LPMBAM, LPMRAM, and CGPMRAM increases with increasing filler-asphalt ratio at the same temperature. LPMRAM and CGPMRAM modified by rubber powder have lower stiffness moduli than LPMBAM; for example: at 0.4 filler-asphalt ratios and −12 °C, the stiffness modulus of LPMBAM, CGPMRAM, and LPMRAM are 169, 146, and 127 MPa, respectively. The smaller the *S* value, the stronger the stress relaxation ability of asphalt mortar, and the better the low-temperature crack resistance. The stiffness modulus of LPMRAM is lower than that of LPMBAM by 42 MPa, about 24.9%, which indicates that adding rubber powder improves the low-temperature performance.

As the temperature decreased, the stiffness modulus of the three kinds of mortar increased, and the low- temperature performance decreased. The order of stiffness modulus is LPMRAM < CGPMRAM < LPMBAM. In addition, the degree of change of the stiffness modulus of the three mortars with the decrease in temperature is also different. When the filler-asphalt ratio is 0.4, the temperature decreases from −12 to −18 and −24 °C, the stiffness modulus of LPMBAM increases by 276 and 440 MPa, the stiffness modulus of CGPMRAM increases by 171 and 350 MPa, the stiffness modulus of LPMRAM increases by 152 and 337 MPa. That is due to the addition of rubber powder, which can increase the elasticity of the mortar, reduce the stiffness at low temperatures, and slow down the decrease of the low- temperature performance of the mortar.

According to the research of Liu et al. [28,29], the stiffness modulus at −12 °C is selected to analyze the low-temperature performance of asphalt mortar. Figure 8 shows the relationship curve between the filler-asphalt ratio and the stiffness modulus. The stiffness modulus of LPMBAM, LPMRAM, and CGPMRAM increases with increasing filler-asphalt ratio, which can be fitted into an exponential function. The correlation coefficient R^2 is high for all three types of mortar: 0.9995 for LPMBAM, 0.9945 for LPMRAM, and 0.9978 for CGPMRAM.

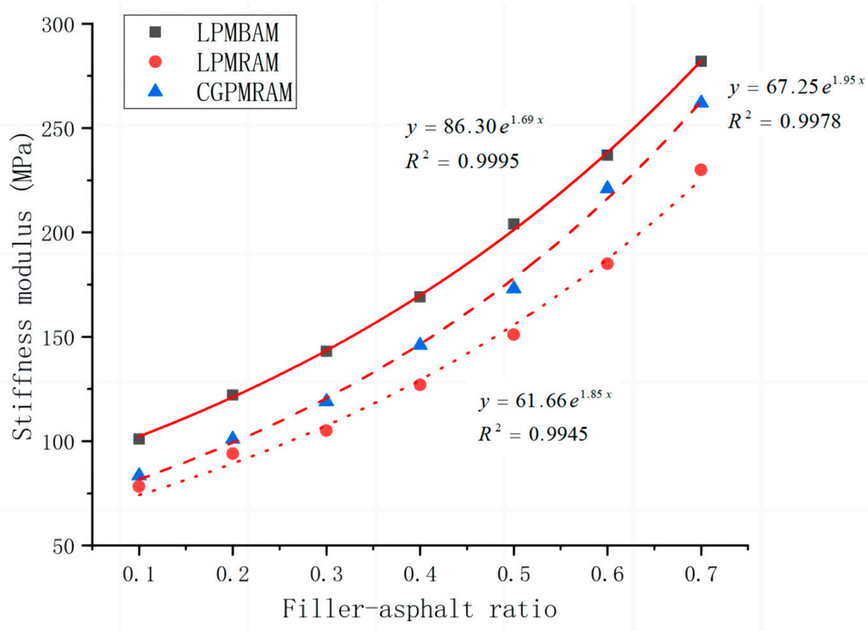


Figure 8. Low-temperature (−12 °C) performance fitting curves of the mortar.

5.3. Analysis of High and Low Temperature Performance Relationship and Optimum Filler-Finder Ratio Range of Rubber Asphalt Mortar

To further explore the effect of mineral powder on the high-temperature and low-temperature performance of rubber asphalt, the high and low-temperature correlation of LPMRAM and CGPMRAM are analyzed. As shown in Figure 9, the shear strength at 25 °C is the X axis, and the stiffness modulus at −12 °C is the Y axis. The scatter plots are drawn and fitted. There is an excellent linear positive correlation between the shear strength and the stiffness modulus for both types of mortar. The correlation coefficient is 0.9973 for LPMRAM and 0.9970 for CGPMRAM., respectively. A higher shear strength indicates better high temperature performance, while a higher stiffness modulus indicates worse low temperature performance. As the shear strength increases, so does the stiffness modulus, which means that the low temperature performance decreases and the high-temperature performance improves.

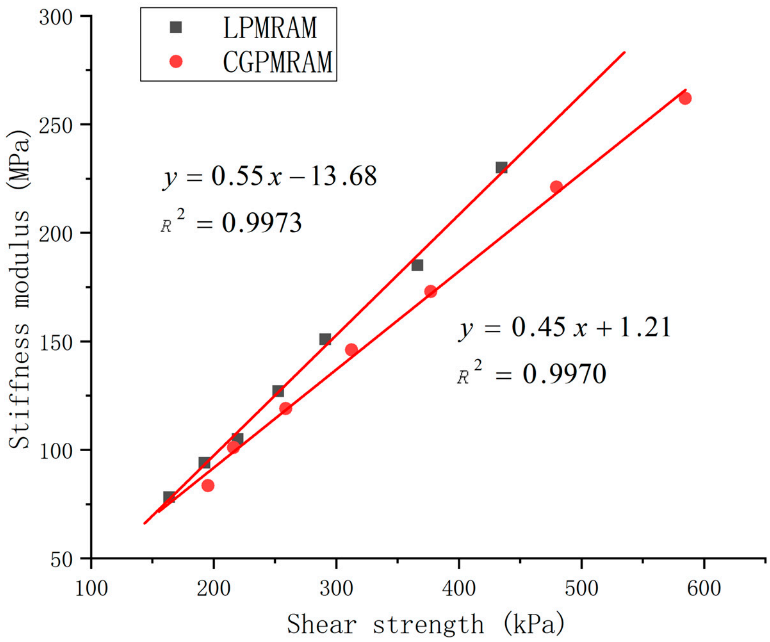


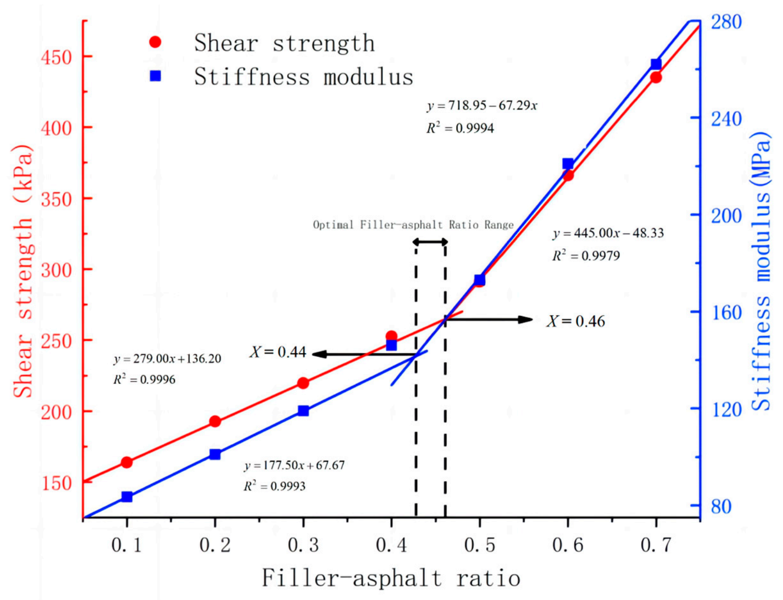
Figure 9. Relationship of high-temperature performance and low-temperature performance of LPMRAM and CGPMRAM.

The above analysis shows that the high temperature and low temperature performance of rubber asphalt mortar is negatively correlated with the increase in the filler-asphalt ratio. To achieve better high and low-temperature performance for rubber asphalt simultaneously, we need to determine the optimal range of filler-asphalt ratio. According to reference [30], using a double linear model and rheological means, the rubber asphalt mortar system can be divided into three stages: slow, migration, and rapid. As shown in Figure 10, taking LPMRAM as an example, the shear strength at 0–0.3 and 0.4–0.7 filler-asphalt ratio representing high-temperature performance is fitted, respectively. The abscissa at the intersection of the two fitted lines is an optimal filler-asphalt ratio determined by the high temperature performance of rubber asphalt mortar.

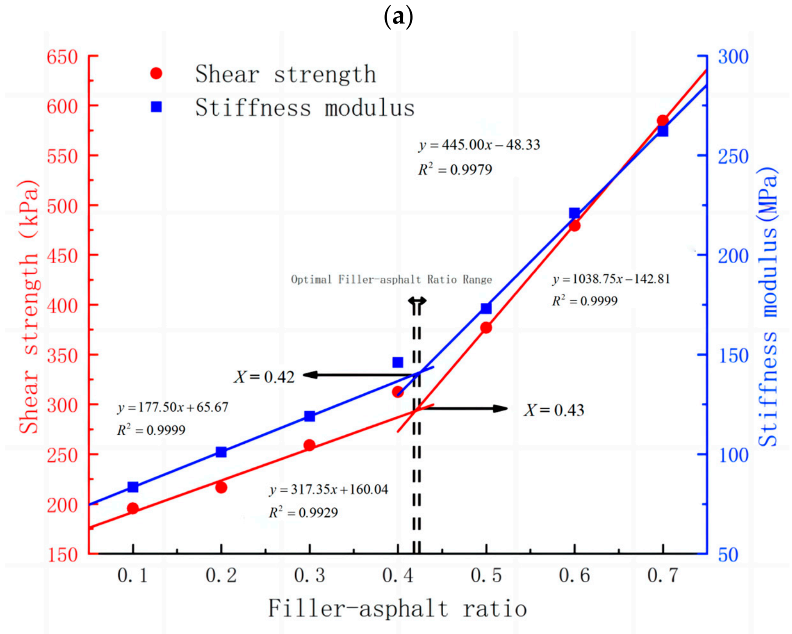
Similarly, the stiffness modulus representing low-temperature performance is fitted to determine another optimal filler-asphalt ratio. The range of the two values is the optimal filler-asphalt ratio range. It can be determined that the optimal filler-asphalt ratio range for LPMRAM is 0.44~0.46, and for CGPMRAM is 0.42~0.43. The optimum filler-asphalt ratio range of mineral powder-modified base asphalt is generally 1.0~1.4 [31], which differs from this paper's optimum filler-asphalt ratio range. The main reason is that adding rubber powder can absorb much free asphalt. When added the mineral powder to rubber asphalt mortar, the amount of free asphalt that the mineral powder can absorb decreases, thus decreasing the optimum filler-asphalt ratio range.

5.4. Mechanism Analysis

Scanning electron microscopy and X-ray fluorescence tests were carried out to analyze the improvement mechanism of coal gangue powder and limestone powder on rubber asphalt. Figure 11 shows the microstructure of limestone powder and coal gangue powder after being magnified 5000 times. Coal gangue powder has a smaller particle size, larger specific surface area, and richer surface structure than limestone powder. Table 3 shows the relative content of compounds in limestone powder and coal gangue powder. Coal gangue powder contains more active oxides like SiO_2 and Al_2O_3 than limestone powder.



(**a**)

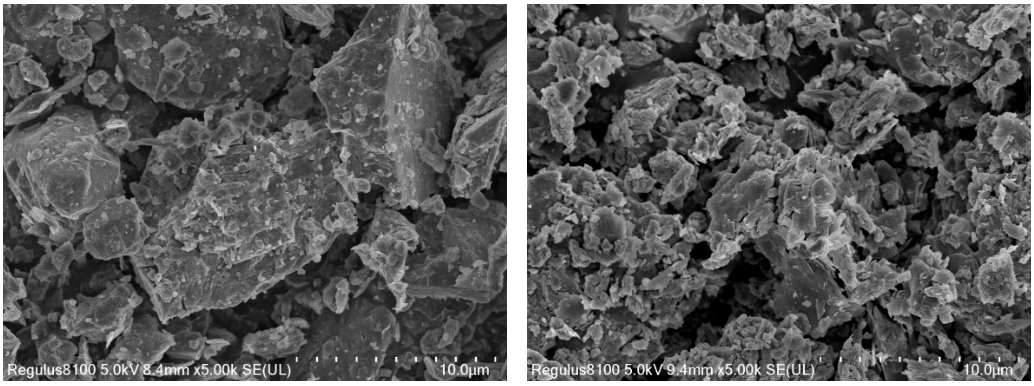


(**b**)

Figure 10. Optimum filler-asphalt ratio range of rubber asphalt mortar: (**a**) LPMRAM; (**b**) CGPMRAM.

Table 3. The relative content of the main chemical components of limestone powder and coal gangue powder.

Technical Performance	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO
Limestone powder	4.64	2.38	0.52	0.65	16.8
Coal gangue powder	30.42	24.08	0.41	0.52	2.2



(**a**) (**b**)

Figure 11. Magnify 5000 times the microscopic morphology photos: (**a**) Limestone powder; (**b**) Coal gangue powder.

These physical and chemical properties make coal gangue powder able to absorb more free asphalt in rubber asphalt so that the relative content of asphaltene near the particles increases, and the consistency of mortar increases, which leads to the increase of shear strength of coal gangue powder modified rubber asphalt at high temperature and the growth of stiffness at low temperature. With the increase of powder content, the mortar becomes thicker. The rise in temperature leads to the thinning of rubber asphalt mortar, which becomes more liquid. However, because the surface of coal gangue powder is rougher than that of limestone powder and more free asphalt could be adsorbed, CGPMRAM's shear strength is higher than LPMRAM, and its high-temperature performance is better than LPMRAM.

6. Conclusions

To explore the high-temperature performance and low-temperature performance modification effect of limestone powder and coal gangue powder on rubber asphalt mortar, the penetration at 15, 25 and 30 °C is measured, and the shear strength at 25 °C is calculated to evaluate its high-temperature shear strength. By the BBR test the stiffness modulus of −12, −18, and −24 °C is measured to evaluate the low-temperature performance. The rheological method and double linear model determine the optimum filler-asphalt ratio range; and the modification mechanism is analyzed. The main conclusions are as follows:

(1) The cone penetration of LPMBAM, LPMRAM, and CGPMRAM decreases with the filler-asphalt ratio increase and the temperature decrease. The shear strength of LPMBAM, LPMRAM, and CGPMRAM increases with the decrease in temperature. Under the same filler-asphalt ratio and temperature, the shear strength of LPMRAM and CGPMRAM is higher than that of LPMBAM. The stiffness modulus of LPMRAM and CGPMRAM is smaller than that of LPMBAM, indicating that the high-temperature performance and low-temperature performance of rubber asphalt mortar are better than that of base asphalt mortar. The shear strength and stiffness modulus of LPMRAM is less than that of CGPMRAM, so the high-temperature performance of CGPMRAM is better than LPMRAM, and the low-temperature performance of LPMBAM is better than that of CGPMRAM.

(2) The shear strength at 25 °C and the stiffness modulus at −12 °C are selected to fit the high-temperature performance and low-temperature performance of LPMRAM and CGPMRAM; according to the rheological means, the double linear model is used to determine that the optimal filler-asphalt ratio range is 0.44~0.46 for LPMRAM, and is 0.42~0.43 for CGPMRAM.

(3) From the 5000 times scanning electron microscope and XRF test, coal gangue powder has smaller particle size, more pore structure, and larger specific surface area than limestone powder. Coal gangue powder contains more active oxides such as SiO_2

and Al_2O_3 than limestone powder. These physical and chemical properties make coal gangue powder able to adsorb rubber asphalt better and improve the high temperature performance of coal gangue powder modified rubber asphalt mortar but slightly worsen the low temperature performance.

(4) Considering the critical influence of asphalt mortar's high and low-temperature performance on the use of asphalt pavement and improving the utilization rate of solid waste coal gangue in line with sustainable development, this paper focused on the high and low-temperature properties of limestone powder-modified and coal gangue powder-modified rubber asphalt; further research should be conducted on mechanical properties and durability to thoroughly evaluate limestone powder-modified and coal gangue powder-modified rubber asphalt and asphalt mixture.

Author Contributions: Conceptualization, W.L.; Data curation, C.Z.; Funding acquisition, G.Y.; Investigation, W.L. and C.Z.; Project administration, W.L.; Supervision, W.L.; Validation, L.L. and L.W. (Lianfang Wang); Writing—original draft, L.L., L.W. (Lipeng Wang) and C.P.; Writing—review & editing, C.P. and G.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the National Key R&D Program of China (No. 2022YFE0104600).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data have been included in the article.

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

Appendix A

$$\tau = \frac{981Q\cos^2(\alpha)}{\pi h^2 \tan(\frac{\alpha}{2})}$$

where τ is the shear strength (kPa); Q is the total weight of the cone needle, connecting rod, and weight; h is cone penetration; α is the cone needle tip angle.

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