Journal of Engineering Science and Technology Review 17 (5) (2024) 145-152

Research Article

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Pavement Performance of Coal Gangue Sand-Asphalt Mixture

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Received 21 June 2024; Accepted 30 September 2024

Abstract

Coal gangue is applicable to roadbed filling and base course of road engineering after breaking up, thus producing a large number of coal gangue sand. The in-situ stacking mode has caused serious damage to the ecological environment because it occupies extensive land resources. Reasonable disposal of coal gangue sand has important significance to the ecological environment. ATB-25 gradation was adopted to discuss the pavement performance of asphalt mixture prepared by replacing machine-made sand completely with coal gangue sand. Five test groups of non-mixture, full-mixture, full-mixture + 0.3% anti-rut agent, full-mixture + 0.4% anti-rut agent, and full-mixture + 0.5% anti-rut agent were designed. The Marshall stability test, Marshall residual stability test, freeze-thaw splitting test, and high-temperature rutting test under 60 ℃ were carried out. The effects of fine aggregate type and anti-rut agent content on the pavement performance of asphalt mixture were studied. The action mechanism of anti-rut agent on the coal gangue sand–asphalt mixture (CGS) was analyzed in combination with pavement performance test results. According to test results, the fine aggregate type can influence the performance of asphalt mixture, and the optimal asphalt content (OAC) of the CGS is increased significantly. The Marshall stability (MS) increases from 7.80 kN to 8.87 kN. After the machine-made sand is completely replaced by gangue sand, the water damage resistance and high-temperature deformation resistance of asphalt mixture decline significantly. With the increase in anti-rut agent content, the high-temperature deformation resistance of asphalt mixture increases gradually, but the water damage resistance of the mixture is not improved effectively. When the anti-rut agent content is 0.3%, the water stability of the asphalt mixture is damaged the least while assuring high-temperature stability. After mixing with the anti-rut agent, fine aggregates in the mixture will form group particles centered at anti-rut agent particles, which increases the interlocking forces among mineral aggregates, thus improving the high-temperature stability of the mixture. The research results will provide theoretical reference to application of CGS in road engineering.

Keywords: Coal gangue sand, Asphalt mixture, Optimum asphalt content, Water stability, High-temperature stability

1. Introduction

Coal gangue is the solid waste produced during coal mining and dressing by washing. It accounts for about 15%–20% of coal output and is one of the solid wastes with the maximum emissions in China [1]. In recent years, the coal gangue stacking volume has been increasing year by year with the extensive exploitation of coal resources in China. At present, the cumulative coal gangue stacking volume in China exceeds 7 billion tons, accounting for about 70 km2. The floor area and environmental pollution problems caused by coal exploitation have attracted wide attention [2]. As a by-product during coal production, coal gangue is hard, similar to rocks. In road construction, coal gangue is usually applied directly to embankment filling and base course projects of pavement or used as coarse aggregates to prepare concrete after multi-stage crushing, thus producing abundant coal gangue sand (particle size: 0–2.36 mm), which is difficult to dispose. Therefore, preparing asphalt mixture by replacing machine-made sand with coal gangue sand completely is practical and reasonable [3]. The mixture pavement performances with different types of fine aggregates are different, and the failure mode under loading also varies. Hence, studying the pavement performances of CGS has obvious practical significance.

When the crushing coal gangue is directly applied to roadbed filling as the base course of pavement and used as coarse aggregate to prepare concrete, it will produce a tremendous amount of gangue sand, which is difficult to dispose, thus influencing the ecological environment. Previous studies on coal gangue as road materials focused on the consumption of coal gangue [4]. However, the use of coal gangue as road materials has to consider not only the consumption problems but also consumption issues of accessory products. When coal gangue is used as roadbed filling, as base course of pavement, and for preparation of concrete, a large number of coal gangue sand is produced, which are difficult to consume. Some mechanical properties of the sand and coal gangue are different. Therefore, in-depth studies on the method of preparing asphalt mixture by replacing machine-made sand completely with coal gangue sand as well as the influences of fine aggregate type on the mixture pavement performance have important significance to expand the comprehensive utilization method of coal gangue. With respect to studies on using coal gangue as road materials, many scholars have studied the performances of coal gangue roadbed filling [5,6], cement stable coal gangue as base course of pavement [7-9], coal gangue concrete, and coal gangue mineral powder [10-12]. These studies mainly

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ISSN: 1791-2377

doi:10.25103/jestr.175.19

focused on coal gangue with a particle size greater than 2.36 mm or lower than 0.075 mm. Nevertheless, a large amount of coal gangue sand with a particle size of 0.075–2.36 mm is produced after coal gangue is crushed in practical engineering. Further studies on how to apply coal gangue sand to asphalt mixture as a pavement material and the mixture pavement performances with different types of fine aggregates are needed.

On this basis, five test groups of non-mixture, full-mixture, full-mixture + 0.3% anti-rut agent, full-mixture + 0.4% anti-rut agent, and full-mixture + 0.5% anti-rut agent were designed. The effects of fine aggregate types on the pavement performances of asphalt mixture were analyzed through the pavement performance tests. Moreover, the action mechanism of anti-rut agent on the CGS was discussed. The results provide an experimental basis to further study the CGS.

2. State of the art

With respect to utilization of coal gangue powder, Ervina Ahyudanari et al. [13] used coal gangue powder as fillers to asphalt mixture and found that using coal gangue powder increased the stability and porosity of asphalt mixture, thus ensuring that the requirements of asphalt concrete standards for heavy-loaded pavement can be met. Li Jiarong et al.[14] prepared asphalt mixture with coal gangue powder and coal gangue ash instead of traditional limestone powder. According to test results, coal gangue powder has prominent application prospects in self-repair of cracked asphalt mixture. Muhammad Murtaza et al. [15] used coal gangue powder as an admixture in cement concrete and studied the influences of coal gangue powder on concrete. Results showed that adding coal gangue powder could increase the compressive strength of concrete. Ziari Hassan et al. [16] explored the application of coal gangue power instead of fillings to micro-surfaces, and test results showed that coal gangue powder had positive influences on deformation caused by decreased traffic loads. Obviously, coal gangue with a particle size lower than 0.075 mm can be applied to asphalt mixture and can improve the performances of asphalt mixture to some extent. However, the particle size requirements can be met only after coal gangue has undergone crushing processing several times. Moreover, the coal gangue consumption is too small to increase the comprehensive utilization of coal gangue.

With regard to research on CGS, Amir Modarres et al. [17-20] from Iran prepared asphalt mixture samples with coal gangue, cement, and mineral powder, and evaluated the mechanical properties of CGS through the Marshall stability test, freeze-thaw splitting test, immersion Marshall, indirect tensile strength, compressive modulus of resilience, and fatigue performance test. Feng X et al. [21] modified coal gangue powder by using the silane coupling agent KH-550 according to the poor low-temperature cracking resistance of CGS. The influences and influencing mechanism of coal gangue powder by silane coupling agent on the pavement performances of mortar and mixture were studied through low-temperature bending beam rheological test, Brookfield viscosity test, adhesive property test, low-temperature bending test, and freeze-thaw splitting test. Results showed that the coal gangue powder by silane coupling agent can significantly improve the high-temperature stability, low temperature crack resistance and water damage resistance of asphalt mixture. Li Ying et al. [22] investigated an asphalt mixture that used coal gangue as coarse aggregates. Results showed that coal gangue aggregates, except sheet-like content, all could meet standard requirements. Zhou Wei et al. [23] investigated the mechanical and physical properties of coal gangue as coarse aggregates of bituminous pavement. They designed the mixing ratio of the CGS by using four different ratios and coal gangue aggregate types of asphalt mixture. On the basis of the optimal asphalt–aggregate ratio, the comprehensive pavement performances of the coal gangue–asphalt mixture were discussed. According to research results, the coal gangue–asphalt mixtures had excellent pavement performances by controlling sheet-like particle contents in the synthesis mixture, and it could be applied to high-class pavement. Therefore, coal gangue might be able to replace mineral powder or coarse aggregates in the asphalt mixture, with a particle size greater than 2.36 mm or lower than 0.075 mm. However, studies on the application of coal gangue sand—that is, coal gangue within the particle size interval of 0.075–2.36 mm—to asphalt mixture are lacking. Therefore, the influences of different fine aggregate types and anti-rut agent contents on the pavement performances of asphalt mixture were analyzed through the pavement performance tests.

To address the low comprehensive utilization of coal gangue, difficult control over heavy metal ions attached to coal gangue, and insufficient applications of coal gangue sand, this study suggested replacing machine-made sand with coal gangue sand completely in asphalt mixture. Five test groups of non-mixture, full-mixture, full-mixture + 0.3% anti-rut agent, full-mixture + 0.4% anti-rut agent, and full-mixture + 0.5% anti-rut agent were designed according to fine aggregate types and anti-rut agent content. The water stability of two types of asphalt mixture was analyzed by Marshall residual stability test and freeze-thaw splitting test. The high-temperature stability of the mixture was analyzed by the rutting test under 60 ℃. The mixtures pavement performances with different fine aggregate types and anti-rut agent contents were analyzed comprehensively. The results provide test references for further studies on CGS.

The remainder of this study is organized as follows. Section 3 elaborates the grading of CGS and the test method of its pavement performances. Section 4 analyzes the test results of the pavement performance of CGS, and investigates the influences of different fine aggregate types on the mixture pavement performances. Moreover, the action mechanism of the anti-rut agent on the CGS was analyzed. Section 5 summarizes the research results and relevant conclusions.

3. Methodology

3.1 Test method

3.1.1 Marshall stability test

1. Standard Marshall stability test

The Marshall stability test was applied to determine the feasibility of the mixing ratio of asphalt mixture. The standard dimensions of the specimens were 101.6 mm in diameter and 63.5 mm in height. The test groups were set according to different asphalt consumption, and each group had 4–6 specimens. The standard Marshall specimens were prepared according to the Marshall compaction method. The two surfaces of specimens were each compacted 75 times. The constant-temperature water bath was adjusted to 60 ℃ ± 0.5 ℃. Each group was kept at constant temperature for 30–

40 min. Later, the MS and flow rate were tested. In combination with the theoretical relative maximum density of asphalt mixture, the OAC was calculated.

2. Immersion Marshall stability test
The peeling resistance of asphalt mixture upon the occurrence of water damage was tested through an immersion Marshall stability test. In other words, the water stability was characterized by Marshall residual stability. On the basis of the OAC, the Marshall specimens were prepared according to the Marshall compaction method, with 75 compaction times on two surfaces, respectively. Test groups A and B were set, with four specimens in each group. The constant-temperature water bath was adjusted to 60 ℃ ± 0.5 ℃. The MS of Group A was tested after maintaining the constant temperature for 30–40 min, while the MS of Group B was tested after maintaining the constant temperature for 48 h. The calculation of immersion Marshall residual stability was based on Eq. (1).

$$MS_0 = \frac{MS_1}{MS} \times 100 \tag{1}$$

where MS_0 is the residual stability of the specimens (%), MS_1 is the stability after heat preservation of the specimens for 48 h (kN), and MS is the standard Marshall stability of the specimens (kN).

3.1.2 Freeze-thaw splitting test

The splitting ratios of asphalt mixture specimens before and after water damage were tested through the freeze-thaw splitting test, thus enabling the water stability of the asphalt mixture to be evaluated. In this test, cylindrical specimens formed by the Marshall compaction method were prepared, and two surfaces of specimens were compacted 50 times. Two test groups A and B were set. Specimens of Group A were kept under room temperature for later use, while specimens of Group B were placed in a constant-temperature water bath for 16 h ± 1 h after water saturation under vacuum conditions. The freezing temperature was 18 ℃ ± 2 ℃. During testing, specimens of Groups A and B were kept in the constant-temperature (25 ℃) water bath for 2 h before the splitting test. The calculation of freeze-thaw splitting-tensile strength ratio was based on Eq (2)-Eq (4).

$$R_{TA} = 0.00628 P_{TA} / h_A \tag{2}$$

$$R_{TB} = 0.00628 P_{TB} / h_B \tag{3}$$

$$TSR = \frac{\overline{R_{TB}}}{\overline{R_{TA}}} \times 100 \tag{4}$$

where R_{TA} and R_{TB} are the splitting strength and the tensile strength of each specimen in Groups A and B (MPa), respectively. P_{TA} and P_{TB} are the test loading values of each specimen in Groups A and B (kN), respectively. h_A and h_B are the heights of each specimen in Groups A and B (mm), respectively. TSR is the freeze-thaw splitting-tensile strength ratio (%). $\overline{R_{TA}}$ and $\overline{R_{TB}}$ are the average splitting strength and the tensile strength of specimens in Groups A and B (MPa), respectively.

3.1.3 Rutting test

The dynamic stability of asphalt mixture was tested through the rutting test. The standard dimensions of the specimens were 300 mm in the length and width, 50mm in height, and shaped by the wheel tracking tester. The specimens were cooled under room temperature and kept at 60 °C in the wheel tracking tester for 6 h. The test was carried out under a 0.7 MPa load at a rate of 42 times/min. The calculation of dynamic stability was based on Eq. (5).

$$ds = \frac{(t_2 - t_1) \times N}{d_2 - d_1} \times C_1 \times C_2 \tag{5}$$

where ds is the dynamic stability of the asphalt mixture (times • mm^{-1}). d_1 and d_2 are the deformation values at the corresponding time t_1 and t_2 (mm), respectively. C_1 and C_2 are the correction coefficients of tester types, with a value of 1.0. N is the back-and-forth rolling speed of the test wheel, with a value of 42 times/mm.

3.1.4 Microscopic test

1. Scanning electron microscopy
As a multi-functional instrument, the scanning electron microscope (SEM) irradiates fine focusing electron beams onto the region that has to be analyzed, thus observing and analyzing coal gangue materials from the micrometer level to the nanometer level. In this study, the Quanta 450 scanning electron microscope (Czech Republic) was applied (Fig. 1) to characterize the microscopic morphology of coal gangue materials, which was used to study the structural characteristics of coal gangue materials.

Fig. 1. Scanning electron microscopy

2. X-ray diffraction
X-ray diffraction (XRD) is an analytical technique that is used to identify the composition and crystal structure of samples. The Rigaku Ultima IV X-ray diffractometer (Japan) was used to test coal gangue samples (Fig. 2). CuKα radiation was used to scan coal gangue samples within the range of 5°–80°.

Fig. 2. X-ray diffractometer

3. Energy-dispersive spectrometer

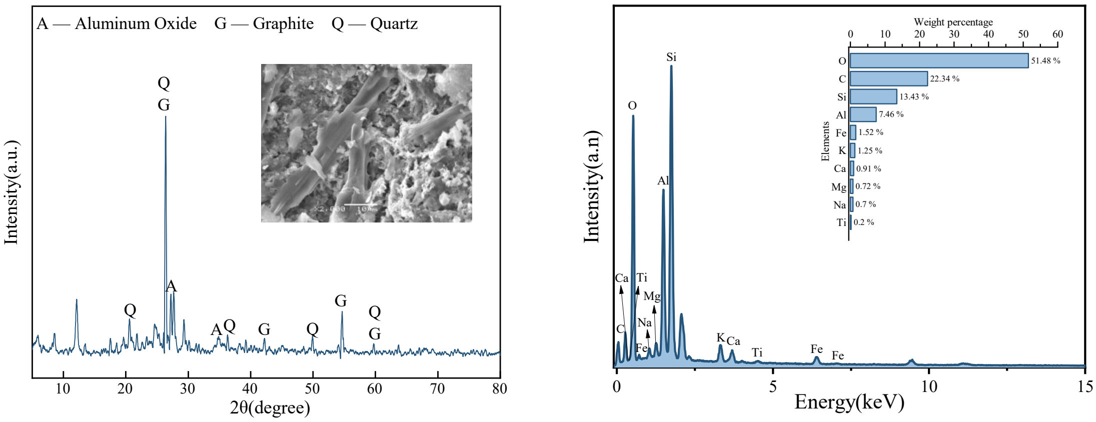
Energy-dispersive spectroscopy (EDS) is conducted to analyze elements on the object surface and is typically used with SEM. In this study, the Max 80 EDS (UK) was applied (Fig. 3) to analyze the element composition of coal gangue samples.

Fig. 3. Energy-dispersive spectrometry

3.2 Testing material

3.2.1 Coal gangue

Coal gangue produced in Dabaodang Mine, Yulin City, Shaanxi Province, China, was applied as the test samples. After being crushed with a hammer crusher, the coal gangue samples with a particle size of 0.075–2.36 mm were chosen. Their performance indexes are shown in Table 1. The composition characteristics of coal gangue were analyzed by an XRD, SEM, and EDS (Fig. 4). Quartz with a high degree of crystallinity was the major mineral of the coal gangue. In addition, some oxides of graphite and aluminum are present. Carbon, oxygen and silicon are major elements, accompanied with some magnesium, sodium, and titanium.



(a) (b)

Fig. 4. Characteristic spectra of coal gangue composition. (a) XRD and SEM. (b) EDS.

Table 1. Performance index of coal gangue sand

Material	Projects	Indicators	Specified value
Coal gangue sand	Density (g/cm^3)	2.583	⩾2.50
	Soundness (%)	10.9	＜12
	Sand equivalent (%)	61.5	⩾60
	Angularity (s)	31.2	⩾30

3.2.2 Limestone

Coarse aggregate, machine-made sand, and mineral powder were all collected from limestone in Liulin, Shanxi Province, China. The performance indexes of coarse aggregates, machine-made sand, and mineral powder are shown in Tables 2, 3, and 4, respectively.

Table 2. Limestone coarse aggregate performance index

Limestone material specification	Projects			
	Density (g/cm^3)	Crush value (%)	Needle sheet content (%)	Adhesion grade with asphalt
3–5 mm	2.685	20.3	/	4
5–10 mm	2.701	19.5	9.6	5
10–20 mm	2.720	18.4	8.5	5
20–30 mm	2.732	19.2	9.1	5
Specified value	⩾2.50	⩽28	⩽15	⩾4

Table 3. Manufactured sand performance index

Material	Projects	Indicators	Specified value
Limestone manufactured sand	Density (g/cm^3)	2.712	⩾2.50
	Soundness (%)	6.0	＜12
	Sand equivalent (%)	84.3	⩾60
	Angularity (s)	40.6	⩾30

Table 4. Limestone powder performance index

Material	Projects	Indicators	Specified value
Limestone powder	Density (g/cm^3)	2.6897	/
	Hydrophilic coefficient	0.66	＜1.0
	Plasticity index	2.5	＜4.0

3.2.3 Asphalt and asphalt modifier

The performance indexes of 90#-A pavement petroleum asphalt produced by China Shandong Jingbo Petrochemical Engineering Company, and the performance index are shown in Table 5. The asphalt modifier adopts high-modulus anti-rut agent, with the specification model being DTPE-M, and is composed of black particles, as shown in Fig. 5.

Fig. 5. High-modulus anti-rut agent

3.3 Gradation composition

Grading used the grading range of ATB-25 coarse-grained asphalt mixture, and the grading mid-value was applied as the target grading. Regrading was conducted level by level. The grading synthesis of CGS and limestone machine-made sand–asphalt mixture (LMS) is shown in Fig. 6 and Table 6.

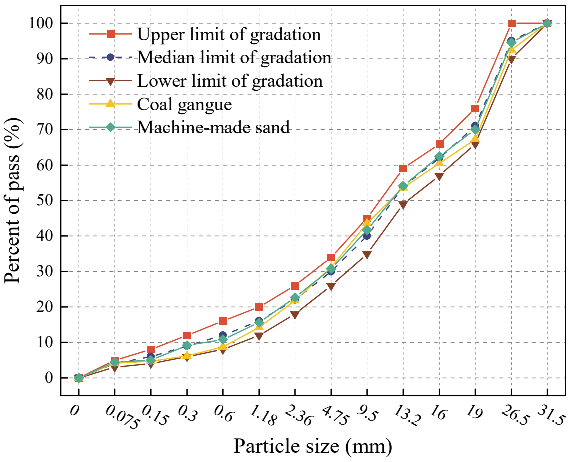


Fig. 6. Gradation composition diagram

3.4 Test groups and test proces

According to the above test methods, four test groups and one control group were set according to fine aggregate types and anti-rut agent content. They were denoted as the control group (L: machine-made sand), test group C1 (coal gangue sand + 0% anti-rut agent), test group C2 (coal gangue sand + 0.3% anti-rut agent), C3 (coal gangue sand + 0.4% anti-rut agent), and C4 (coal gangue sand + 0.5% anti-rut agent). The Fig. 7 shows testing procedures.

Table 5. Asphalt performance index

Projects		Per unit	Indicators	Specified value
Degree of needle into (25 ℃)		0.1mm	93	80~100
Soft point		℃	46.9	⩾45
Degree of postpone (15 ℃)		cm	＞100	⩾100
Density (15 ℃)		g/cm^3	1.0199	/
Wax content		%	2.1	⩽2.2
Mass loss		%	0.002	±0.8
Film-heating test (163 ℃, 5 h)	Penetration ratio	%	65.3	⩾57
	Degree of postpone (10 ℃, 5 cm/min)	cm	＞100	⩾8
	$T_{1,2}$	℃	-18.4	/
	T_{800}	℃	48.6	/

Table 6. ATB-25 synthetic gradation range

Size of screen mesh		Percent of pass (%)												
		31.5	**26.5**	**19.0**	**16.0**	**13.2**	**9.5**	**4.75**	**2.36**	**1.18**	**0.6**	**0.3**	**0.15**	**0.075**
Upper limit of gradation		100	100	76.0	66.0	59.0	45.0	34.0	26.0	20.0	16.0	12.0	8.0	5.0
Lower limit of gradation		100	90.0	66.0	57.0	49.0	35.0	26.0	18.0	12.0	8.0	6.0	4.0	3.0
Median limit of gradation		100	95.0	71.0	62.0	54.0	40.0	30.0	22.0	16.0	12.0	9.0	6.0	4.0
Synthetic gradation	Coal gangue sand	100	92.5	67.3	60.5	53.6	43.6	31.2	21.8	14.2	8.7	6.2	4.7	4.2
	Manufactured sand	100	94.5	70.0	62.5	54.1	41.7	30.8	22.7	15.6	10.8	9.2	5.0	4.5

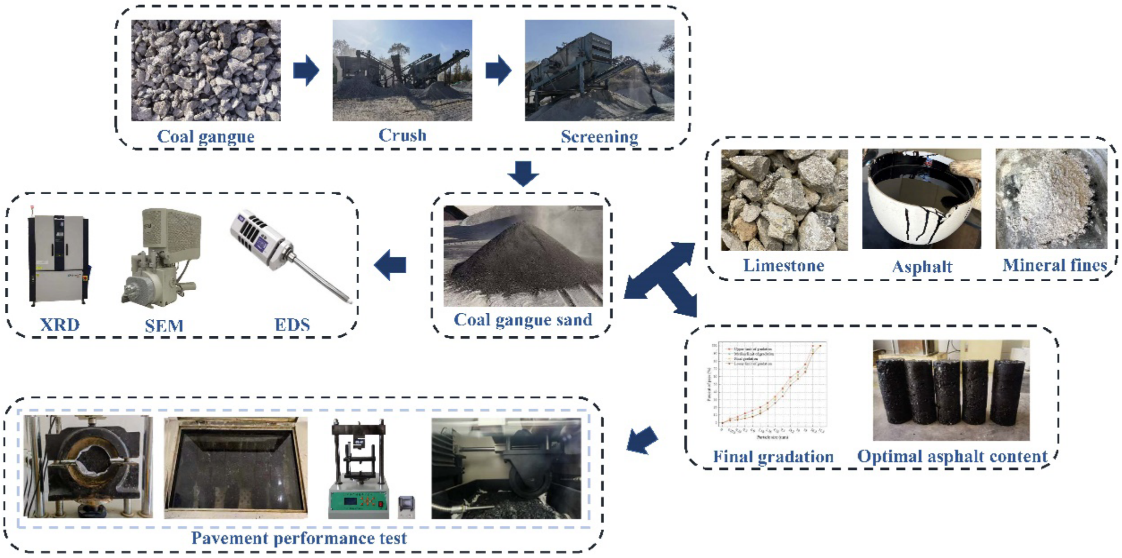


Fig. 7. Test process chart

4. Result Analysis and Discussion

4.1 Optimum asphalt content

The mixing ratio of asphalt mixture was designed according to the grading of ATB-25 minerals. The grading synthesis is shown in Section 3.3. The test showed that anti-rut agent content has a minimal influence on the OAC, which can be ignored. Hence, the OAC of the CGS and LMS was determined only through the Marshall stability test. The test results are shown in Table 7.

Table. 7. Marshall test of asphalt mixtures

Projects	Type	
	CGS	LMS
Optimum asphalt content (%)	4.02	3.83
Bulk density (kg/m^3)	2.334	2.403
Theoretical relative maximum density of asphalt mixture	2.4237	2.5260
Percentage of void (%)	3.42	4.07
Gap rate of mineral (%)	7.86	12.59
Asphalt saturation (%)	56.46	67.96
Marshall stability (kN)	8.87	7.80
Flow value (mm)	2.82	2.28

Table 7 shows that after machine-made sand is replaced by coal gangue sand completely, it can absorb more asphalt because more open pores are present on the surface and sand of coal gangue has a larger specific surface area. As a result, the OAC of mixture has significantly increase. The apparent density of coal gangue sand is lower than that of machine-made sand. Thus, the gross volume density and theoretical relative maximum density of the CGS after replacing machine-made sand with coal gangue sand are lower than those of LMS, but the Marshall stability is increased to some extent.

4.2 Water stability

The residual stability and TSR of CGS, LMS, and CGS with different anti-rut agent contents were tested by the immersion Marshall stability test and freeze-thaw splitting test. Their water stability was evaluated. The test results are shown in Figs. 8 and 9.

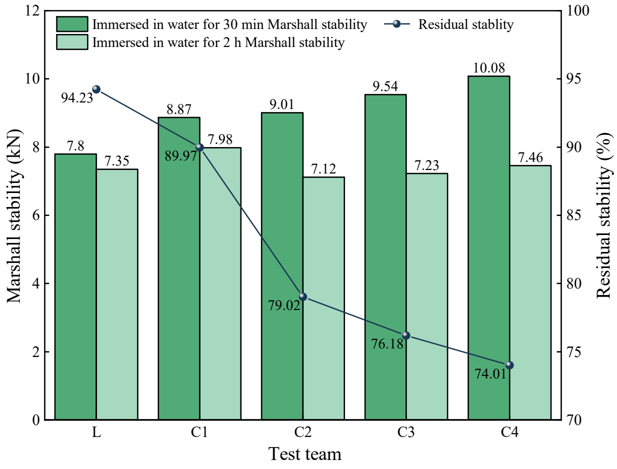


Fig. 8. Results of immersion Marshall stability test

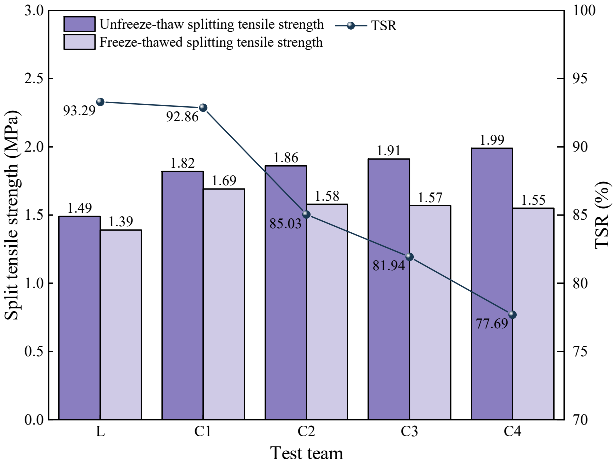


Fig. 9. Results of freeze-thaw splitting test

Figs. 7 and 8 show that after the machine-made sand is replaced completely by coal gangue sand, the residual stability and TSR of mixture decrease significantly. With the increase in anti-rut agent content, the residual stability and TSR of the asphalt mixture both present a decreasing trend. This result reflects that coal gangue sand will decrease the water damage resistance of the mixture. Moreover, the anti-rut agent fails to improve the water damage resistance of the mixture effectively. Compared with machine-made sand, coal gangue sand has higher water absorption and stronger hydrophilicity. In the immersion Marshall test, water molecules strongly adhere to the surfaces of specimens with coal gangue sand after they are immersed in water for a long period, and the asphalt film on the aggregate surface is easy to peel off, thus causing adverse effects on the stability of specimens. In the freeze-thaw splitting test, specimen failure mainly occurs in the freeze-thaw circulation stage of the test. Under a low temperature, asphalt became brittle and bonding force decreased. Some asphalt film that adhered onto the aggregate was broken, and cracks were produced. During thawing in water under 60 °C, the broken asphalt film might be peeled off on the basis of cracks, thus decreasing the bonding force among aggregate particles. After the addition of the anti-rut agent, the asphalt viscosity was increased, thus increasing the bonding force between asphalt and aggregate. This phenomenon was manifested as the increasing splitting and tensile strength of specimens, as well as the decreasing freeze-thaw splitting strength ratio.

4.3 High-temperature stability

According to the rutting test steps under 60 °C and the calculation formula in Section 3.1.3, the deformation values and dynamic stability of CGS, LMS, and CGS with different anti-rut agent contents were calculated. Their high-temperature stability was evaluated, and the results of test are shown in Fig.10.

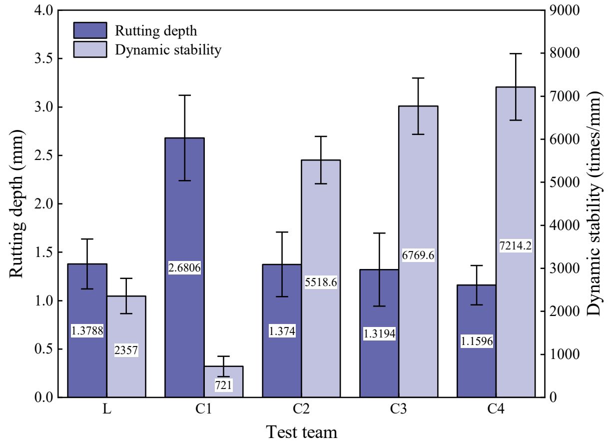


Fig. 10. Rutting test results at 60 °C

Fig. 9 shows that after machine-made sand is replaced completely by coal gangue sand, the rutting depth of the mixture increases obviously and the dynamic stability declines significantly when no anti-rut agent is mixed in. With the increase in the anti-rut agent content, the rutting depth of the mixture decreases obviously, whereas the dynamic stability increases significantly. This result occurred because compared with machine-made sand, coal gangue sand has weaker angularity. After machine-made sand is replaced by coal gangue sand, the adhesion capacity between asphalt and minerals decreases and the internal friction among minerals declines, thus weakening the rutting resistance of the mixture under high temperature. After the anti-rut agent is mixed in, fine aggregates in the mixture enclose and bond into clusters by centering at anti-rut agent particles. Such clusters play a role similar to that of large aggregates in the cooled asphalt mixture. They increase the proportion of aggregates that serve as skeleton support in the mixture and the interlocking force among minerals, thus improving the overall stability of the rutting specimens and increasing the high-temperature rutting resistance of the mixture.

5. Conclusions

The pavement performance tests are performed on asphalt mixture with different fine aggregate types and anti-rut agent contents to study the asphalt mixture pavement performance prepared by replacing machine-made sand with coal gangue sand completely. Moreover, the influencing mechanism of anti-rut agent on CGS is analyzed in combination with pavement performances mainly from the perspective of Marshall stability, residual stability, freeze-thaw splitting strength ratio, and dynamic stability. The following major conclusions could be drawn:

(1) Fine aggregate types can influence the performances of asphalt mixture. After machine-made sand is replaced by coal gangue sand, the coal gangue sand can absorb more asphalt due to the greater number of open pores on its surface and higher specific surface area. Hence, the OAC of the asphalt mixture is increased significantly. However, the gross volume density and theoretical relative maximum density of the mixture both decrease slightly, while the Marshall stability is increased to a small extent.

(2) After machine-made sand is replaced fully with coal gangue sand, the water damage resistance of the asphalt mixture decreases significantly and the anti-rut agent fails to improve the water damage resistance of the mixture effectively. This condition occurred because, as a result of the high water absorption of coal gangue sand, water modules adhere strongly to the surfaces of Marshall specimens that contain coal gangue sand after they are immersed in water for a long period and the asphalt film on the aggregate surface is easy to peel off. This condition has adverse effects on the stability of specimens. In the freeze-thaw splitting test, specimen failure mainly occurs in the freeze-thaw circulation stage. Under a low temperature, asphalt becomes brittle and the bonding force decreases. Some asphalt film adhered onto the aggregate breaks and produced cracks. The damaged asphalt film peels off during thawing, which decreases the bonding force among aggregate particles.

(3) The rutting depth and dynamic stability of CGS are both lower than that of the asphalt mixture with machine-made sand. With the increase in the anti-rut agent content, the rutting depth of the asphalt mixture decreases obviously, whereas the dynamic stability increases significantly. This result occurred because the adhesion capacity between asphalt and minerals decreases due to the poor angularity of coal gangue sand. After the anti-rut agent is mixed in, fine aggregates in the mixture enclose and bond into clusters by centering at the anti-rut agent particles. These clusters serve as skeleton supports in the mixture and increase the interlocking force among minerals, thus improving the high-temperature deformation resistance of the mixture.

Only the water stability and high-temperature stability of coal gangue sand are analyzed with regard to the pavement performance of the CGS. The pavement performance, which is influenced by pavement loading form in practical engineering, has to be further studied. Hence, studying other pavement performances of the CGS further is necessary, which is conducive to understanding the road performances of the CGS more thoroughly.

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