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An Experimental Study of the Road Performance of Cement Stabilized Coal Gangue

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Abstract: The research into the road performance of coal gangue is of great significance for the consumption of coal gangue and reducing pollution. In this paper, the coal gangues were prepared by separation and crushing processes, and their gradations were also optimized. Aiming to identify the possible problems of coal gangue as a pavement base, an unconfined compressive strength test, a splitting test, a freeze–thaw test, and a drying shrinkage test of cement stabilized gangue with varying cement amounts were carried out, and the test results were compared and analyzed. The test results showed that the maximum dry density and optimum moisture content (OMC) of the optimized cement stabilized gangue and cement stabilized macadam increased with cement content. The maximum dry density and OMC of cement stabilized macadam were larger than that of cement stabilized gangue with the same cement content. The optimized 7-day unconfined compressive strength of cement stabilized gangue can meet the requirements for a secondary and lower highway base and subbase. The OMC and cement content are the critical factors affecting the compressive strength loss rate of cement stabilized gangue after freeze–thaw cycles. The smaller the OMC of cement stabilized gangue and the larger the cement content, the lower the compressive strength loss rate. With an increase in cement content, the drying shrinkage strain of cement stabilized gangue increased. The results show that a cement content of 4% is optimal for the cement stabilized coal gangue, which can be used for the light traffic base and heavy traffic subbase of class II and below highways. It provides a basis, guide, and reference for the application of coal gangue materials in a high-grade highway base.

Keywords: coal gangue; gradation; cement content; unconfined compressive strength; freeze–thaw cycle

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1. Introduction

Coal plays an essential role in the energy supply of China and many countries in the world. Coal gangue is produced during coal mining, accounting for almost 10–25% of total coal extraction [1–3]. A large number of coal gangues are piled up around mines. With continuous coal mining, more and more coal gangues are piled up, but the total utilization rate is low [4]. On the one hand, the accumulation of coal gangue occupies many valuable land resources and pollutes the soil, groundwater, and air in the accumulation place. On the other hand, a large amount of coal gangue accumulation may cause spontaneous combustion endangering the safety of the public and property. Therefore, there is an acute need to tackle this underutilization of coal gangue from a sustainability perspective [5–8].

As a suitable filling material, coal gangue was mainly used for filling subsidence areas and land reclamation earlier in many countries. In order to improve the utilization rate of coal gangue, researchers in some European countries started investigating the application of coal gangue in different fields, such as preparation of chemical materials, mining minerals, filling subgrade, and preparation of building materials [9–11]. In recent years, Li, Dong, and others [12–15] have analyzed the mechanical properties, from micro and macro perspectives, of cement mortar with calcined coal gangue replacing the cement content and have analyzed the specific factors affecting its properties. Many experts and scholars [16–20] have carried out a large number of tests to study the mechanical properties of coal gangue concrete and have analyzed the factors affecting its durability. Coal gangue material has been widely used in many civil engineering fields, such as for highway subgrade, a foundation cushion in construction engineering, etc. Many countries have taken the lead in applying coal gangue to engineering examples, such as the road network in northern France, the road network in the Ruhr region of Germany, and the railway stations of Gloucester and Croydon in Britain [21]. The application of coal gangue in highway engineering in China is gradually increasing with the advancement in transport infrastructure [22–24]. Many research findings show that the strength of coal gangue as a subgrade filler can fully meet the requirements of subgrade design [25–28]. At present, coal gangue material is mainly used as a subgrade filler and cushion, and the research into its use as a highway base is relatively scarce.

With the development of traffic infrastructure, the use of coal gangue in road engineering in China is progressively increasing. Relevant research and engineering applications show that the mechanical properties of coal gangue as a subgrade filler can fully meet the requirements of subgrade design [29,30]. He et al. [31] carried out screening tests, compaction tests, consolidation tests, permeability tests, bearing ratio tests, and direct shear tests to study the influence of soil on the engineering mechanical properties of coal gangue. The results indicated that the strength of soil gangue used as subgrade filler can fully meet the subgrade design requirements. Wu et al. [32] studied the strength and deformation characteristics of a coal gangue subgrade filler under different confining pressures, different gradations, and different compactness through large-scale triaxial tests with the method of artificial grading. The test results showed that the compactness of the coal gangue subgrade filler should not be less than 93%. Di et al. [33] conducted a preliminary study on the engineering properties of coal gangue through a compaction test and triaxial strength test. They systematically analyzed the variation model of shear strength parameters, maximum dry density, and optimum moisture content of coal gangue with coarse-grained material content. Geng et al. [34] carried out unidirectional frost heaving tests on common filling materials and coal gangue for high-speed railway subgrade under open system and closed system conditions. The test results showed that it was feasible to use coal gangue as a high-speed railway subgrade filler in permafrost regions. Zhou et al. [35] used lime fly ash stabilized coal gangue as a pavement base material and designed 15 different ratios. The test results confirmed that its strength meets the requirements of the expressway and first-class highway for the base and subbase. However, its freeze-thaw resistance is insufficient, so it is necessary to add cement to improve the durability of stabilized coal gangue. Therefore, the utilization and applicability of coal gangue are limited due to the constraints mentioned above. The utilization rate is not high, which necessitates exploring methods for improvement. The research into the frost resistance and drying shrinkage performance of coal gangue material in the base of high-grade highways is still sparse. The research into the application of coal gangue material in the base of high-grade highways is scarce, which does not allow the full utilization of coal gangue.

Given the existing problems in coal gangue applications as a highway base, this paper takes the coal gangue material produced in the Hebi area of Henan Province as its research subject. The optimum gradation of stabilized coal gangue was determined by using the power function model $y = ax^b$ [36], and cement was used to stabilize the coal gangue. Subsequently, through a compaction test, an unconfined compressive strength test, a freeze–thaw test, a splitting test, and a drying shrinkage test, the mechanical properties and durability of cement stabilized gangue were analyzed. The objective was to provide a basis, guide, and reference for the application of coal gangue materials in a high-grade highway base.

2. Raw Materials

2.1. Coal Gangue

The undisturbed coal gangue used in the test was provided by Hongchang Building Materials Co., Ltd. in Hebi City, Henan Province. The reserves of coal gangue in Hebi City are more than 20 million tons, and these are persistently accumulating. The undisturbed coal gangue was screened in the mining area, and the coal gangue with a particle size less than 30 mm was separated (Figure 1). The coal gangue with a particle size greater than 30 mm was selected for crushing and classification. In order to ensure the particle size of coal gangue, an impact crusher was used for crushing (Figure 2), and the particles greater than 30 mm were crushed and sieved. According to the particle size distribution of coal gangue, it was divided into four grades: machine-made sand, 4.75–9.5 mm, 9.5–19 mm, and 19–31.5 mm, as shown in Figure 3.

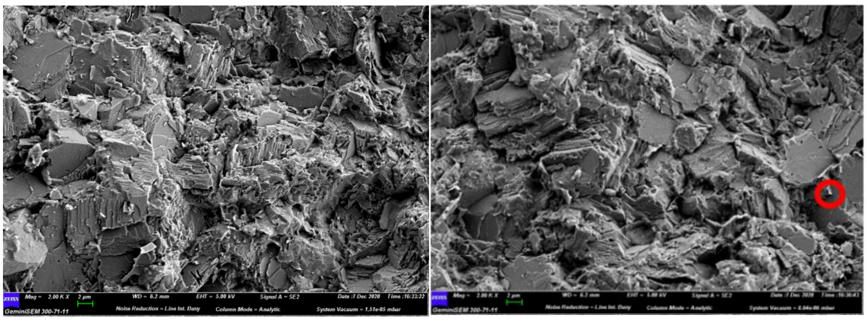
Gemini300 field emission scanning electron microscope (manufacturer: Carl Zeiss, Germany) was used to inspect the surface structure of concrete samples; Bruker D8 Advance X-ray diffractometer (manufacturer: Brooke Company, Germany) was used for X-ray diffraction analysis, and XRD data were analyzed with jade 6 software; The element distribution in the micro region of the material was analyzed qualitatively and quantitatively by SYMMETRYS EBSD energy chromatograph (manufacturer: Oxford Company, UK).The results of the scanning electron microscope (SEM), energy-dispersive X-ray spectroscopy (EDS) analysis, and X-ray diffraction (XRD) analysis are shown in Figure 4. The chemical composition and other physical and mechanical properties are shown in Tables 1–3. It can be seen that the basic physical and mechanical properties met the requirements for the class II highway base and subbase in the Chinese standard JTG/TF20-2015 "Technical guidelines for construction of highway roadbases" [37].

Figure 1. Separation of coal gangue.

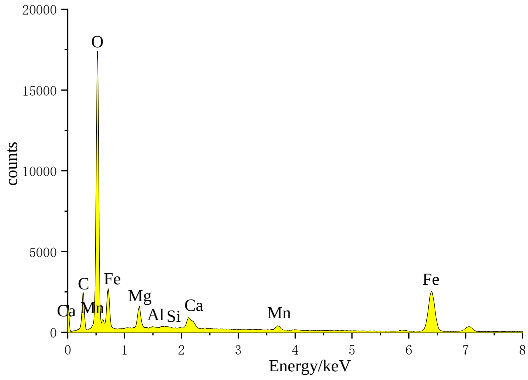
Figure 2. Coal gangue crushing.

(**a**) Machine-made sand (0–4.75 mm) (**b**) 4.75–9.5 (mm) (**c**) 9.5–19 (mm) (**d**) 19–31.5 (mm)

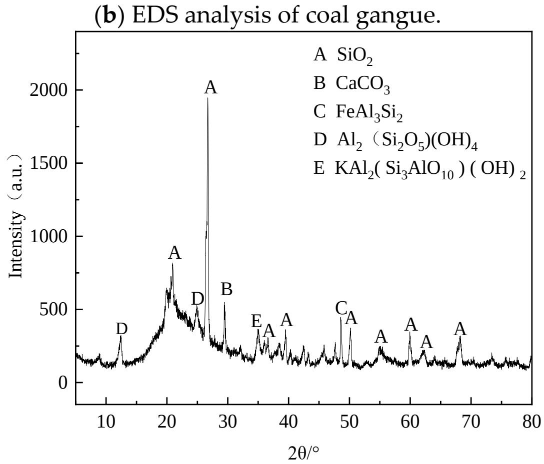
Figure 3. Sampling of coal gangue.



(**a**) SEM microscopy of coal gangue.



(**b**) EDS analysis of coal gangue.



(**c**) XRD spectrums of coal gangue.

Figure 4. Microstructure of coal gangue.

Table 1. Chemical elements of coal gangue (atomic fraction)/wt.%.

O	C	Fe	Mg	Ca	Al	Si	Mn
56.6	24.2	15.2	2.2	0.9	0.4	0.3	0.2

Table 2. Physical and mechanical properties of coal gangue coarse aggregate (wt.%).

Apparent Density/g.cm^{-3}	Bulk Density/g.cm^{-3}	Porosity/%	Crushing Value/%	Dust Content below 0.075 mm/%	Soft Rock Content/%
2.618	1.473	43.8	27.8	0.85	1.2

Table 3. Physical and mechanical properties of coal gangue fine aggregate (wt.%).

Apparent Density/g.cm^{-3}	Bulk Density/g.cm^{-3}	Porosity/%	Fineness Modulus	Water Absorption Rate/%
2.74	1.507	45	3.2	6.9

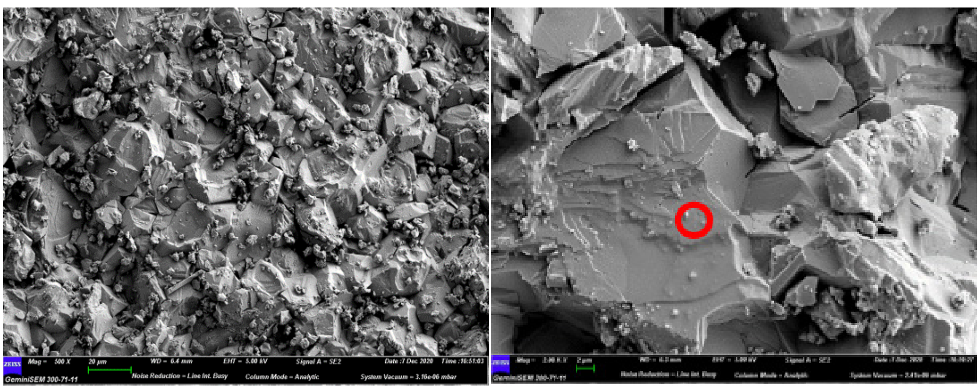
2.2. Crushed Stone

The gravel and machine-made sand used in the test were provided by Hongchang Building Materials Co., Ltd. in Hebi City, Henan Province. Based on the gradation/particle size distribution, the gravel and sand were classified into four grades (machine-made sand, 4.75–9.5 mm gravel, 9.5–19 mm gravel, and 19–1.5 mm gravel), as shown in Figure 5.

(**a**) Machine-made sand (0–4.75 mm) (**b**) 4.75–9.5 (mm) (**c**) 9.5–19 (mm) (**d**) 19–31.5 (mm)

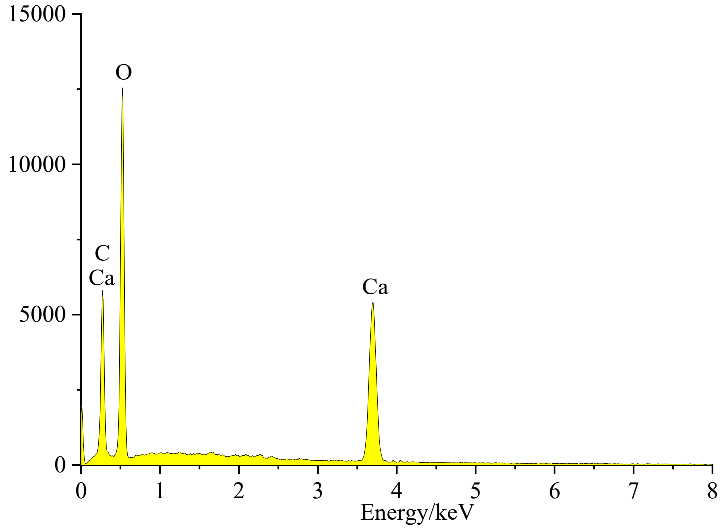
Figure 5. Sampling of crushed stone.

The results of the scanning electron microscope (SEM), energy dispersive X-ray spectroscopy (EDS) analysis, and X-ray diffraction (XRD) analysis are shown in Figure 6. Its chemical composition and physical and mechanical properties are shown in Tables 4–6. It can be seen that its basic physical and mechanical properties can meet the requirements for the class II highway base and subbase in the Chinese standard JTG/TF20-2015 "Technical guidelines for construction of highway roadbases" [37].

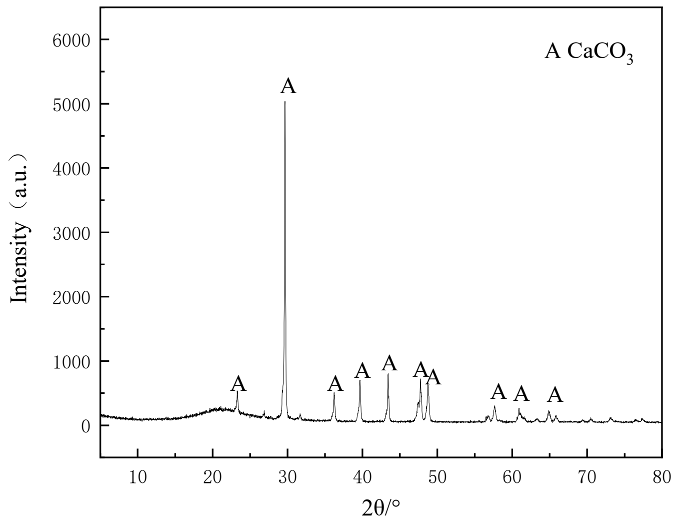


(a) SEM microscopy of crushed stone

Figure 6. *Cont.*



(b) EDS analysis of crushed stone



(c) XRD spectrums of crushed stone

Figure 6. Microstructure of crushed stone.

Table 4. Chemical elements of crushed stone (atomic fraction)/wt.%.

O	C	Ca
63.6	26.3	10.1

Table 5. Physical and mechanical properties of crushed stone coarse aggregate (wt.%).

Apparent Density/g.cm^{-3}	Bulk Density/g.cm^{-3}	Porosity/%	Crushing Value/%	Dust Content Below 0.075 mm/%	Soft Rock Content/%
2.650	1.523	42.5	25.2	0.81	1.2

Table 6. Physical and mechanical properties of crushed stone fine aggregate (wt.%).

Apparent Density/g.cm^{-3}	Bulk Density/g.cm^{-3}	Porosity/%	Fineness Modulus	Water Absorption Rate/%
2.74	1.504	45.1	3.33	3.5

2.3. Cement

Ordinary Portland cement (P·O·42.5) with a density of 3150 kg/m^3 was selected as cement. The properties of cement are shown in Table 7. It can be seen that the cement used in this test met the requirements of TG/TF30 "Technical guidelines for the construction of highway cement concrete pavements". It can be used as the admixture in cement stabilized gangue and cement stabilized macadam.

Table 7. Technical properties of cement.

Fineness/%	Setting Time (h)		Requirement of Normal Consistency/%	Flexural Strength (MPa)		Compressive Strength (MPa)	
	initial	final		3d	28d	3d	28d
3.1	3.6	6.5	28	6.9	9.4	27.6	45.8

3. Test Method

3.1. Gradation Optimization

Firstly, the raw materials of coal gangue and crushed stone with different particle sizes were sieved to determine the gradation curve. Further, the gradation of coal gangue was optimized according to JTG/TF20-2015 "Technical guidelines for construction of highway roadbases" [37] to meet the gradation requirements for a secondary highway base and subbase. The gravel was screened and synthesized to meet the standard gradation based on the original four particle size ranges.

3.2. Compaction Test

According to JTG E51-2009 "Test methods of materials stabilized with inorganic binders for highway engineering" [36], heavy compaction tests were carried out on cement stabilized gangue with a cement content of 3%, 4%, 5%, 6%, and 7% and cement stabilized macadam with a cement content of 4%, 5% and 6% (Figure 7).

(**a**) Material Preparation (**b**) Electric Compaction Instrument

Figure 7. Compaction test.

3.3. Unlateral Limited Compressive Strength Test

According to the compaction test results, the maximum dry density and optimum moisture content of cement stabilized gangue and cement stabilized macadam with different cement contents were determined. The specimens were formed according to the compaction degree of 96%. According to JTG E51-2009 "Test methods of materials stabilized with inorganic binders for highway engineering" [36], the unconfined compressive strength test of cement stabilized coal gangue and cement stabilized macadam was carried out for seven days. The static pressure was applied by the press, and 13 specimens (of size 150 mm × Φ150 mm) for each group were formed. After demolding, the specimens were cured in the standard curing room for seven days. On the last day of the curing period, the specimens were soaked in water for 24 h, and then the surface moisture was removed for subsequent testing of 7-day unconfined compressive strength (Figure 8).

(**a**) Specimen (**b**) Experimental instruments

Figure 8. Unconfined compressive strength test.

3.4. Splitting Tensile Strength Test

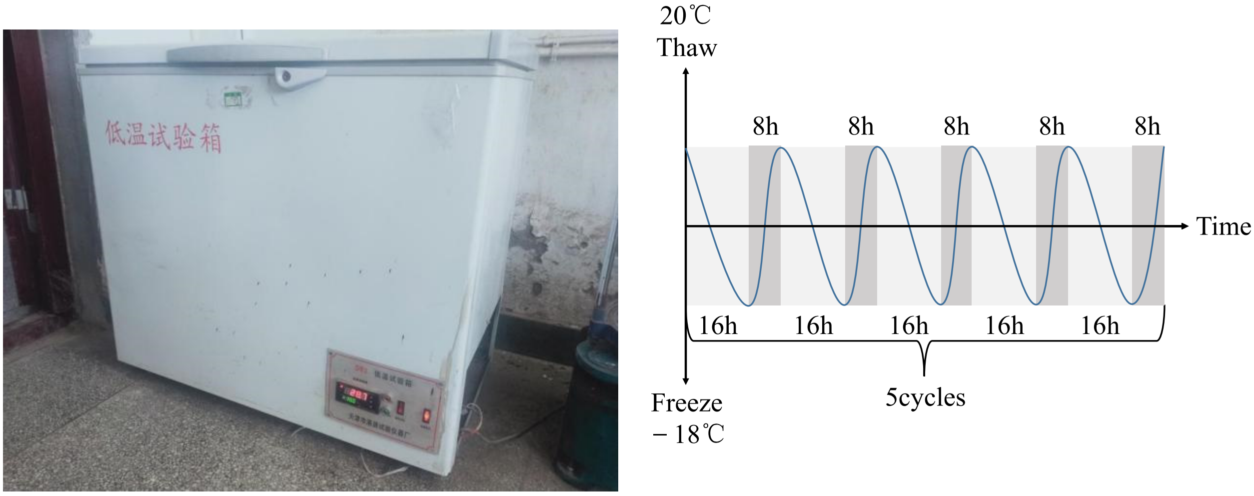
According to JTG E51-2009 "Test methods of materials stabilized with inorganic binders for highway engineering" [36], the splitting tensile test was carried out on cement stabilized gangue with a cement content of 3%, 4%, and 5%. Thirteen specimens (of size 150 mm × Φ150 mm) in total were prepared. After demolding, the standard curing was carried out for 90 days according to the method of T0845-2009 [36]. During the test, the loading rate of the press was controlled at 1 mm/min. The splitting tensile test process is shown in Figure 9.

Figure 9. Splitting tensile test.

3.5. Freeze–Thaw Resistance Test

According to JTG E51-2009 "Test methods of materials stabilized with inorganic binders for highway engineering" [36], the freeze–thaw tests of cement stabilized gangue and cement stabilized macadam with a cement content of 4%, 5%, 6%, and 7% were carried out, respectively. Each group was statically pressed with a press to form 13 specimens (of size 150 mm × Φ150 mm). After demolding and marking, the specimens were put into a low-temperature chamber and frozen at −18 °C for 16 h.

After freezing for one cycle, they were weighed, and each was melted in a 20 °C water tank for 8 h. After melting, the surface of the specimen was dried, and the sample was weighed again. The above freezing and thawing cycles were repeated until five freeze–thaw cycles were completed, and the unconfined compressive strength was measured. The process of the freeze–thaw test and the appearance of specimens before and after freeze–thaw are shown in Figures 10 and 11, respectively.



(**a**) Low temperature test chamber (**b**) Freeze–thaw cycles

Figure 10. Freeze–thaw test process.

(**a**) Before freezing and thawing (**b**) After freezing and thawing

Figure 11. Freeze–thaw test.

3.6. Drying Shrinkage Test

According to JTG E51-2009 "Test methods of materials stabilized with inorganic binders for highway engineering" [36], drying shrinkage tests were carried out on cement stabilized gangue with a cement content of 4%, 5%, and 6% (Figure 12). The mixture was prepared with the best moisture content obtained in the experiment, and the specimen was formed according to the compaction degree of 96%. The static pressure method was used to form the mixture, the speed was 2 kN/s, and the specimen size was 100 mm × 100 mm × 400 mm per beam. Each group had six specimens, out of which three specimens were used to measure the shrinkage deformation while the other three specimens were used to measure the drying shrinkage water loss ratio. The data was recorded every day during the first seven days and after every two days after 7-day age for 31 days.

(**a**) Specimens (**b**) Conservation environment

Figure 12. Dry shrinkage test.

4. Test Results and Data Discussion

4.1. Gradation Optimization Design

First, the raw materials of coal gangue with different particle sizes were sieved. The sieving/screening results are shown in Table 8. According to Appendix A of JTG/TF20-2015 "Technical guidelines for construction of highway roadbases" [37], the gradation design of inorganic binder stabilized material was optimized. Three control points were selected: a nominal maximum particle size of 31.5 mm with a passing rate of 100%, a particle size of 4.75 mm with a passing rate of 40%, and a particle size of 0.075 mm with a passing rate of 2%. The power function model $y = ax^b$ was used to construct the gradation curve of coal gangue. Three control points were brought into the formula of power function model as follows:

$$y = ax^b \tag{1}$$

where: x is particle size (mm), y is the passing rate (%), and 'a' and 'b' are the coefficients (a = 18.807, b = 0.4843).

Therefore, the particle gradation of coal gangue after adjustment is shown in Table 9 and Figure 13 (c-c-2 refers to grade c-c-2 recommended in JTG/TF20-2015 "Technical guidelines for construction of highway roadbases" [37]). Therefore, the particle size distribution of coal gangue designed in this paper was well within the recommended c-c-2 grading range, which meets the gradation requirements for a secondary highway base and subbase [37].The particle gradation of crushed stone is given in Table 10 and plotted in Figure 14.

Table 8. Screening results of coal gangue aggregates with different particle sizes.

Sieve Size/mm	31.5	26.5	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
0–4.75 mm	-	-	-	-	-	-	100	62	45.9	31.7	24.8	15.2	9.2
4.75–9.5 mm	-	-	-	-	100	96.8	0	-	-	-	-	-	-
9.5–19 mm	-	-	100	75.9	40	7.9	0.6	-	-	-	-	-	-
19–31.5 mm	100	71.9	6.1	3.1	2	-	-	-	-	-	-	-	-

Table 9. Coal gangue particle grading.

Sieve Size/mm	31.5	26.5	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Passing (%)	100	92	78.3	72	65.6	56	40	24.1	14.6	9.0	5.4	3.3	2.0
Upper of C-C-2	100	100	87	82	75	66	50	36	26	19	14	10	7
Lower of C-C-2	100	90	73	65	58	47	30	19	12	8	5	3	2

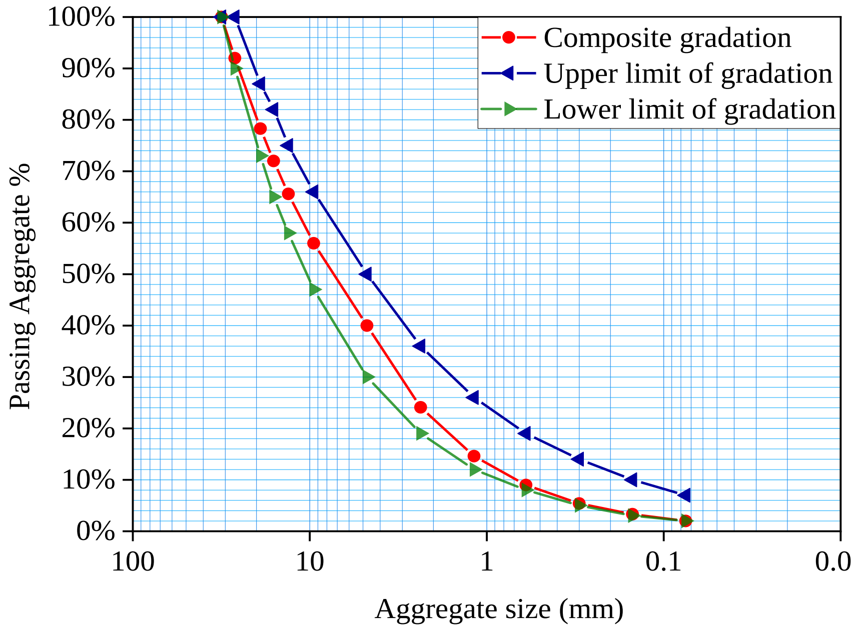


Figure 13. Grading curve of coal gangue.

Table 10. Crushed stone particle grading.

Sieve size/mm	**31.5**	**26.5**	**19**	**16**	**13.2**	**9.5**	**4.75**	**2.36**	**0.6**	**0.075**
Passing (%)	99.8	96.6	86	79.9	70	60.5	38.3	25.6	10.7	1.9
C-C-2	100	100–90	87–73	82–65	75–58	66–47	50–30	36–19	19–8	7–2

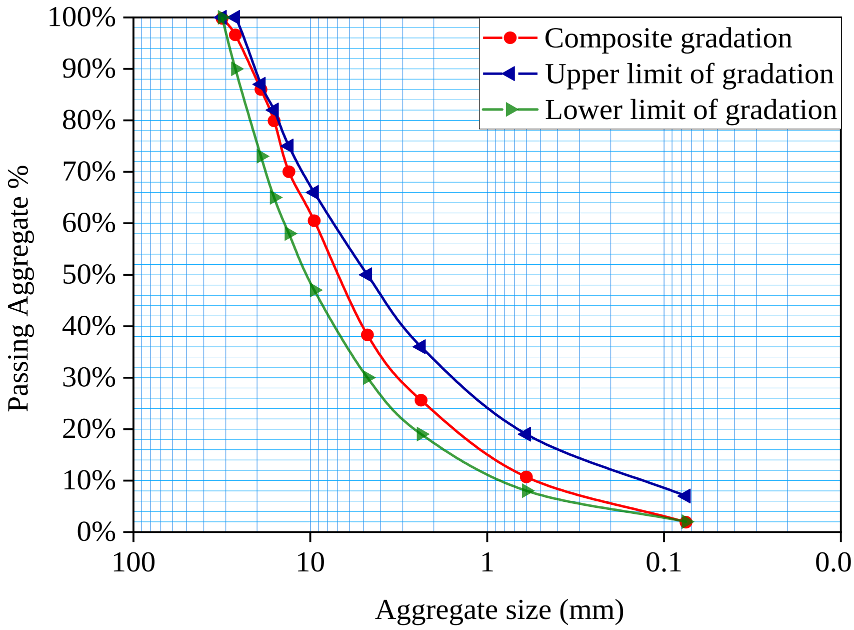
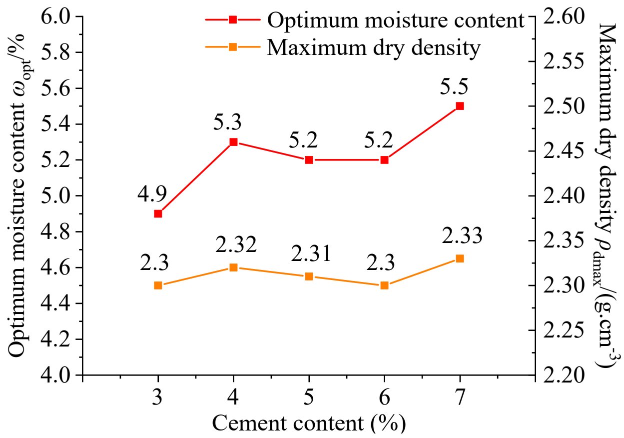


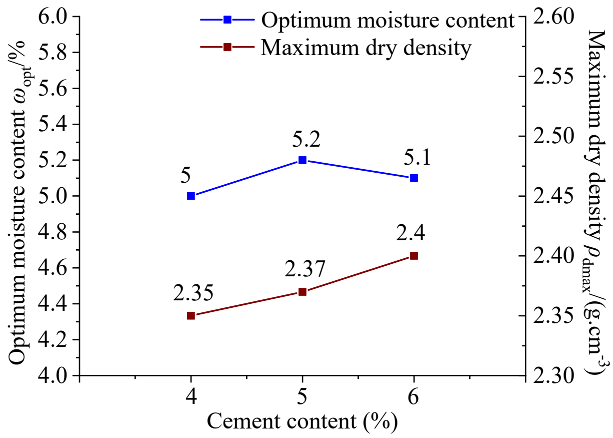
Figure 14. Grading curve of crushed stone.

4.2. Compaction Test

The maximum dry density and optimum moisture content of cement stabilized gangue cement stabilized macadam with different cement contents are shown in Figure 15. It can be seen from Figure 15a that the maximum dry density and optimal moisture content of cement stabilized coal gangue increased with the increase in cement content, and the change range is small. When the cement content was 7%, the maximum dry density and optimum moisture content of cement stabilized gangue were the highest, while with 3% cement content, these were the minimum. Compared with Figure 15a,b, under the condition of the same cement content, the maximum dry density of cement stabilized macadam was higher. The optimum moisture content was smaller than that of cement stabilized gangue.



(**a**) Coal gangue



(**b**) Crushed stone

Figure 15. Test results of compaction test of mixture.

4.3. 7-Day Unconfined Compressive Strength

The representative value of 7-day unconfined compressive strength of cement stabilized macadam with 4% cement content was R_d = 4.0 MPa. The representative values of the 7-day unconfined compressive strength of cement stabilized gangue with different cement contents are shown in Figure 16. It is clear from Figure 16 that the representative value of unconfined compressive strength of cement stabilized gangue with 4% cement content was about 57.5% of the cement stabilized macadam with the same cement content. Compared with the 7-day unconfined compressive strength of 3% cement stabilized gangue, the 7-day unconfined compressive strength of cement stabilized gangue with 4%, 5%, 6%, and 7% cement increased by 0.2 MPa, 1.7 MPa, 1.9 MPa, and 2.1 MPa, respectively. Reasons may be that with the increase in cement content, the pores around the specimen are correspondingly reduced, which can make the structural shape more dense, so as to increase the strength of cement stabilized coal gangue [38]. The 7-day unconfined compressive strength of 7% cement stabilized gangue was higher than that of the 4% cement stabilized macadam. It can be seen from Figure 16 and Table 11 that when the cement content is the same, the 7-day test results of cement stabilized coal gangue in this paper were higher than those of other researchers in Table 11. In this paper, the 7-day unconfined compressive strength of cement stabilized coal gangue with 3% and 4% cement content can meet the requirements for a medium and light traffic base (2.0–4.0 MPa) and a heavy traffic subbase (2.0–4.0 MPa) of class II and below highways, respectively; other researchers needed the cement content of cement stabilized coal gangue to reach 5% or 6%, respectively.

Compared with the 7-day unconfined compressive strength requirements of cement stabilized material base and subbase for different highway grades in JTG/TF20-2015 (“Technical guidelines for construction of highway roadbases” [37]), in this paper, the 7-day unconfined compressive strength of cement stabilized coal gangue with cement content of 5% met the requirements for a heavy traffic base (3.0–5.0 MPa) and an extremely heavy and extra heavy traffic subbase (2.5–4.5 MPa) of class II and below highways. The 7-day unconfined compressive strength of cement stabilized coal gangue with a cement content of 6% and 7% met the requirements of an extremely heavy traffic base (3.0–5.0 MPa) and an extremely heavy traffic subbase of class II and below highways requirements for an extra heavy traffic base (4.0–6.0 MPa) and subbase (2.5–4.5 MPa), respectively.

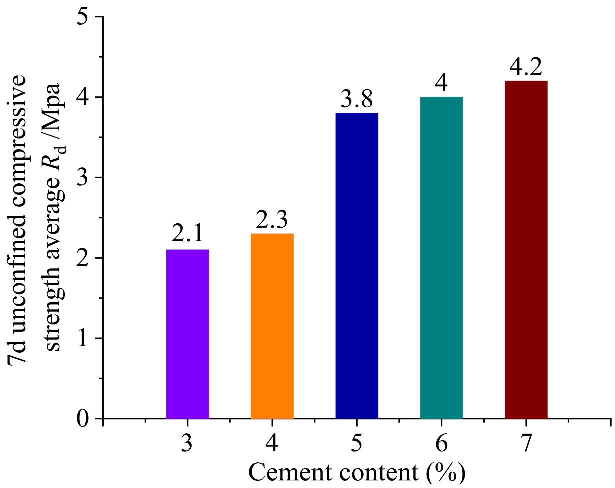


Figure 16. Test results of 7-day unconfined compressive strength.

Table 11. 7-day unconfined compressive strength test results of different researchers.

Researcher	Cao [39]	Yan [40]		Hu [41]	
Cement content/%	4	5	4	5	6
Compressive strength/MPa	1.92	2.69	1.81	2.34	2.92

4.4. Splitting Tensile Strength of Cement Stabilized Coal Gangue

The representative values of the 90-day splitting tensile strength of cement stabilized gangue with different cement contents are shown in Figure 17. It can be seen that the 90-day splitting tensile strength values of cement stabilized coal gangue with 3%, 4%, and 5% content were 0.65 MPa, 0.87 MPa, and 1.06 MPa. Compared with the 90-day splitting tensile strength of 3% cement stabilized gangue, the 7-day unconfined compressive strength of cement stabilized gangue with 4% and 5% cement increased by 0.22 MPa and 0.41 MPa, respectively. The results also indicated that the 90-day splitting tensile strength of cement stabilized coal gangue increased with cement content, and showed the same change law as the unrestricted compressive strength. The splitting tensile strength mainly reflects the cementing ability of cement stabilized aggregate inside aggregate. It mainly depends on the cohesion between aggregates. The C–S–H gel after hydration of cement is the source of this cohesive force [40]. Therefore, an increase in cement content can improve the splitting tensile strength of cement stabilized coal gangue.

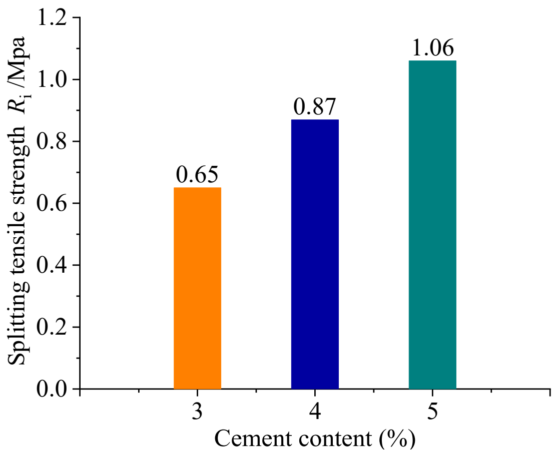


Figure 17. Test results of splitting tensile.

The splitting tensile strength of the cement stabilized macadam gangue mixture with different gradations of 5.5% cement content in [42] was 0.648 MPa and 0.723 MPa, respectively, and the splitting tensile strength of the water cement stabilized macadam gangue mixture with different gradations of 5.5% cement content in [43] were 0.749 MPa, 0.652 MPa, and 0.731 MPa. It was found that the splitting tensile strengths of cement stabilized coal gangue in this paper were higher than those of [42,43]. Reasons may be that the different gradations will lead to different maximum dry density and optimal water content of the sample. In this paper, the power function model $y = ax^b$ [36] was used. The corresponding maximum dry density of the optimized gradation sample was greater than the maximum dry density of [42,43], and the optimal water content was also less than the maximum dry density of [42,43] resulting in a more compact structure of cement stabilized coal gangue optimized in this paper. The recommended range of values for the splitting tensile strength of cement stabilized macadam is 0.4–0.6 MPa in the specifications [36]. Clearly, the 90-day splitting tensile strength of cement stabilized coal gangue with a cement content of 3% and 4% can meet the requirements of the specification.

4.5. Freeze–Thaw Resistance Test of Cement Stabilized Coal Gangue

Table 12 and Figure 18 show the frost resistance index and freeze-thaw compressive strength loss diagram of cement stabilized gangue with 4%, 5%, 6%, and 7% cement content. It can be seen from these results that the compressive strength loss BDR of the cement stabilized coal gangue with cement contents of 4%, 5%, 6% and 7% were greater than 75% after five freeze-thaw cycles, and the mass loss rate was less than 1%. Its compressive strength loss BDR was greater than the frost resistance requirements of lime fly ash stabilized materials in the heavy freezing area of Expressway and class I Highway (70%) [44], and the mass loss rate was less than the specification requirements (5%) [36]. The compressive strength loss of the cement stabilized gangue with 5% and 6% cement was the least, followed by the cement stabilized gangue with 7% cement which had a higher loss in compressive strength after freeze-thaw cycles. The compressive strength loss with 4% cement content was the highest. Reasons may be that the cement stabilized coal gangue with a cement content of 4% has a large number of pores due to the small cement content, and due to its high water content, the volume expansion of the water in the pores during the freezing process is large, which destroys the original pore structure and produces microcracks, resulting in greater strength loss than the other three cement contents [38]. Therefore, the cement content and moisture content are the main factors affecting the compressive strength loss of the cement stabilized coal gangue after freeze-thaw cycles.

Table 12. Frost resistance index.

Cement Content/%	4%	5%	6%	7%
BDR/%	75.16	94.33	92.26	89.29
Mass loss/%	0.07	0.26	0.81	0.24

4.6. Drying Shrinkage Test

It can be seen from Table 13 and Figure 19 that with the increase in cement content, the drying shrinkage strain of the cement stabilized gangue increased. At the same time, the hydration and setting of cement will cause volume shrinkage, which is positively correlated with cement content. Therefore, the larger the cement content, the larger the deformation of cement stabilized gangue, and correspondingly the larger the dry shrinkage strain. The changing trend was drastic at first, and then slowed down with the increase in age [38].

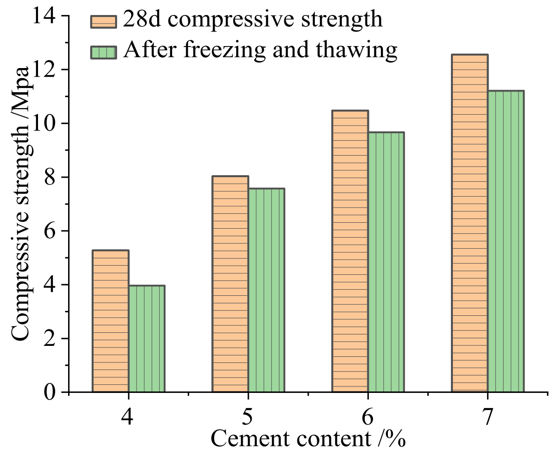


Figure 18. Freeze–thaw compressive strength loss diagram.

Table 13. Dry shrinkage strain value of cement stabilized gangue ($\times 10^{-6}$).

Cement Content/%	Age (d)			
	7	15	23	31
4	112.5	345	512.5	627.5
5	165	382.5	620	850
6	230	480	705	895

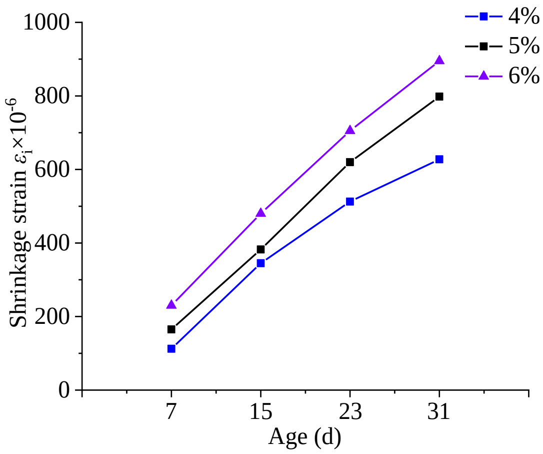


Figure 19. Relationship between dry shrinkage strain and age of cement stabilized gangue.

5. Conclusions

In this paper, according to JTG/TF20-2015, "Technical guidelines for construction of highway roadbases" [37], the gradation design of inorganic binder stabilized materials was optimized, and the power function model $y = ax^b$ was used to optimize the gradation of coal gangue. The optimized coal gangue gradation curve met the gradation requirements for the secondary highway base and subbase. It provides a basis, guide, and reference for the application of coal gangue materials in a high-grade highway base.

(1) Coal gangue was prepared by a sorting and crushing process, and the grading of coal gangue raw materials was optimized by a power function model. The prepared cement stabilized coal gangue pavement base material with 4% cement content had a 7-day unconfined compressive strength of 2.3 MPa, a 90-day splitting tensile strength of 0.87 MPa, a frost resistance index BDR of 75.16%, a mass loss rate of 0.07%, and a 31-day dry shrinkage strain of 627.5×10^{-6}, which can be used for medium and light traffic bases and the heavy traffic subbase of class II and below highways.

(2) The test results show that the cement content and the grading of the coal gangue raw materials are the main factors affecting the 7-day unconfined compressive strength of the cement stabilized coal gangue. An increase in cement content can improve the 90-day splitting tensile strength of cement stabilized coal gangue. Cement content and moisture content are the key factors affecting the frost resistance index of cement stabilized coal gangue. The larger the cement content is, the larger the dry shrinkage strain of cement stabilized coal gangue is, and the shrinkage strain decreases first and then increases with an increase in age.
(3) In view of the possible problems of cement stabilized coal gangue as a pavement base, the comprehensive experimental analyses were carried out to verify the feasibility of cement stabilized coal gangue as a highway base and subbase.

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