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Mechanical and Durable Performance of Lime-Steel Slag-Coal Gangue Mixtures Prepared by a Uniform Design Method for Pavement Base Applications

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To reduce the accumulation of coal gangue and steel slag, a mixture of lime-steel slag-coal gangue for pavement base was prepared. Six groups of lime-steel slag-coal gangue mixtures were designed using a uniform design method. The 7 d unconfined compressive strength, 180 d compressive resilience modulus and 180 d splitting tensile strength tests, the freeze-thaw cycles, and the wet and dry cycles were carried out to study the mechanical properties, frost resistance and water stability. The expansion effect of f-CaO in steel slag on the mixtures was investigated by water immersion. SEM was used to explore microscopic changes in the mixtures. The field application of coal gangue mixture was carried out for two years. The results show that the regression equations obtained by the uniform test have high accuracy. With the increase of lime in the mixture, the mechanical strength, frost resistance, and water stability of the mixtures were first enhanced and then decreased. With the increase of steel slag, the unconfined compressive strength increased, the compressive resilience modulus increased at first and then decreased, the splitting tensile strength decreased, the BDR value decreased, and the strength loss of water stability increased gradually. The internal structure of the mixtures is stable and has good frost resistance. There is no obvious microscopical difference before and after freeze-thaw cycles. The immersion expansion rate of the mixtures was far less than 1.5 %.

Keywords: pavement base, admixture, coal gangue, steel slag, lime, solid waste, uniform design.

1. INTRODUCTION

Coal gangue is a solid waste discharged in the process of coal mining and washing [1]. The existing coal gangue stockpile (the primary treatment method) in China has exceeded 5×10^9 t and is still increasing at the rate of 3.5×10^8 t per year [2]. The accumulated coal gangue mountain not only occupies land resources, but also produces harmful SO_2 and CO gases and CO_2 greenhouse gases from pyrite minerals, which seriously worsen air quality [3]. Moreover, exceeding the rest angle ($38^o - 40^o$) of coal gangue mountain will lead to the collapse or landslide, and even the formation of debris flow, which seriously threatens the life and property safety of people around the mining area. If coal gangue can be used in civil engineering area consuming the largest materials, it can not only realize the resourceful utilization of solid wastes, but also reduce the consumption of natural resources such as sand and gravel, improve the ecological environment, and has high economic value and social significance[4].

In recent years, many scholars have conducted in-depth research on the application of coal gangue mixture in the field of pavement base. Yan et al. [5] studied the effects of cement content and coal cinder substitution rate on the mechanical properties of cement-fly ash-coal cinder-coal gangue mixture. When the cement content increased by 1 %, the 7 d unconfined compressive strength of the mixture increased by 0.9, 0.5 and 0.4 MPa, respectively. When coal cinder replaced 25 %, 50 %, 75 % and 100 % of coal gangue fine aggregate, the 7 d unconfined compressive strength of the mixture decreased by 8.2 %, 12.4 %, 16.8 % and 18.5 %, respectively. It was suggested that the coal cinder replacement rate in actual construction should be about 50 %, and not exceed 75 %. Meng et al. [6] used sodium hydroxide as the active agent to prepare a mixture of mineral powder, steel slag and coal gangue. When the steel slag content was 32.1 % – 72.0 %, mineral powder content was 7.0 % – 13.1 %, and sodium hydroxide content was 3.3 % – 5.7 %. The unconfined compressive strength was 2.11 – 5.40 MPa, the compressive resilience modulus was 613 – 1220 MPa, and the splitting tensile strength was 0.40-1.41 MPa. Li et al. [7] prepared a mixture of cement stabilized crushed stone and coal gangue with the cement content of 5.5 %. When crushed stone was used to replace 26 % – 30 % of coal gangue, the unconfined compressive strength of the mixture was greater than 5.0 MPa, the average compressive rebound modulus of the mixture was greater than 1400 MPa, and the splitting tensile strength of the mixture was greater than 0.4 MPa. Zhang et al. [8] studied the applicability of lime-fly ash-coal gangue mixture in the base and bottom base. When the content of lime, fly ash and coal gangue was 10 %, 15 % and 75 %, respectively, the unconfined compressive strength reached the highest value of 1.95 MPa. Li et al. [9] used coal gangue instead of natural stone to prepare cement stabilized coal gangue subgrade mixture. When the cement content was 4 %, the mixture could not only meet the early strength of 4.16 MPa, but also the shrinkage coefficient of the coal gangue mixture was only 1.12×10^{-2}, indicating the favorable dry shrinkage resistance.

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Steel slag, one of the largest industrial solid wastes, is the oxide generated when the impurity elements in the pig iron (such as Si, Mn, P, etc.) are oxidized in steelmaking. At present, the accumulation of steel slag in China has exceeded 2 × 10^9 t, but its utilization rate is less than 30 % [10]. Therefore, it is urgent to develop new technology to consume steel slag on a large scale and study the feasibility of steel slag used in coal gangue mixture. Although there have a few reports on the mineral powder-steel slag-coal gangue mixture, the price of mineral powder is still higher. Meanwhile, lime is fairly inexpensive and can provide an alkaline environment for the pozzolanic reaction. Therefore, it is meaningful to replace the mineral powder with lime to use in a steel slag-coal gangue mixture. In response to solid waste resourceful utilization, this paper used a uniform design method to use gangue as the aggregate, supplemented with steel slag and a small amount of lime to prepare lime-steel slag-coal gangue mixtures. The mechanical properties were studied through unconfined compressive strength, compressive resilience modulus and split tensile strength tests, and durability (frost resistance and water stability) was determined by freeze-thaw cycle and wet-dry cycle tests. The expansion effect of f-CaO in steel slag on the coal gangue mixture was examined through immersion in water [11]. Finally, the microscopic changes of the mixture after freeze-thaw cycles were investigated with the help of SEM (scanning electron microscope) to reveal the structural damage mechanism.

2. MATERIALS AND METHODS

2.1. Raw materials

1. The spontaneous combustion (firing for 2 – 3 years) gangue from Fengfeng Mining District of Handan City, China is selected, with reddish-brown appearance. Its XRD pattern and particle grading curve are shown in Fig. 1 and Fig. 2 a, respectively. The main chemical composition and technical indexes of the coal gangue are shown in Table 1 and Table 2 respectively.

Table 1. Chemical composition of coal gangue and steel slag

Raw material	Content, %							
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	MnO_2	Others
Coal gangue	61.72	26.85	5.63	2.94	0.97	1.55	0.13	0.21
Steel slag	10.32	7.47	22.56	39.07	6.70	0.68	1.97	11.23

Table 2. Main technical indexes of coal gangue

Apparent density, g·cm^{-3}	Packing density, g·cm^{-3}	Crushing value, %	Firing loss, %	Free inflation rate, %
2.40	1.43	27.86	10.33	10.00

2. Lime is purchased from Wu'an Calcium Lime Powder in Handan City, China, with particle size of 0 – 0.5 mm, with appearance of grayish white, slightly soluble in water and without irritating odor. The effective content of calcium oxide and magnesium oxide is 36.1 %.
3. Steel slag is provided by a steel plant in Handan City, China, with particle size range of 0 – 9.5 mm and black appearance. The grading curve is shown in Fig. 2 b. The main chemical composition is CaO, SiO_2 and Fe_2O_3, as shown in Table 1. Its apparent density is 2.84 g/cm^3 and the water-immersed expansion rate is 1.63 % (< 2 %), meeting the stability requirements of GB/T 25824-2010 [12].
4. Water is tap water from Handan drinking water plant.

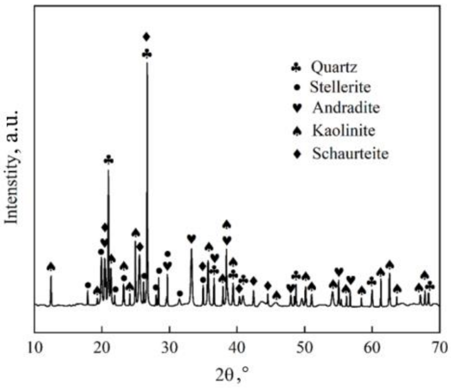
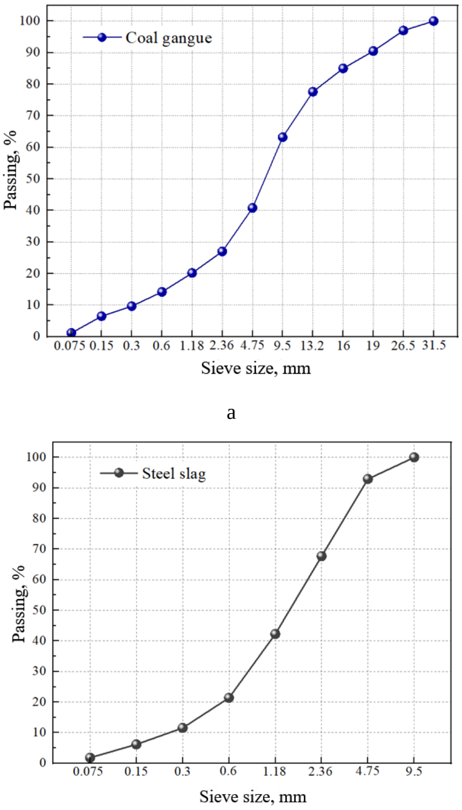


Fig. 1. XRD pattern of spontaneous combustion coal gangue



a

b

Fig. 2. Grading curves of: a – spontaneous combustion coal gangue; b – steel slag

2.2. Mix ratio design

The mix ratio adopts the way of benchmark proportion, that is, the mass of each admixture as the percentage of the coal gangue mass (coal gangue: lime: steel slag = 1: x_1: x_2). Combined with the mass range of each raw material, a 2-factor, 6-level test is designed to adjust the mass range: 65 % to 100 % for coal gangue, 4 % to 16 % for lime, and 10 % to 45 % for steel slag. A uniform test method was used to design the mix ratio [13], as shown in Table 3.

Table 3. Mix ratio of coal gangue mixture

No.	1	2	3	4	5	6
Coal gangue	1.000	1.000	1.000	1.000	1.000	1.000
Lime, x_1	0.088	0.160	0.064	0.136	0.040	0.112
Steel slag, x_2	0.100	0.170	0.240	0.310	0.380	0.450

2.3. Sample preparation

According to the mix ratio in Table 3, the raw materials were fully mixed and cured for 4 h, and then added into the test molds several times. After each addition, the pad was pressed into the molds with the loading rate of 1 mm/min and then pressed under static pressure for 2 min to prevent rebound. The specimens were demolded after 2 h of forming, and then put into a standard chamber (20 °C ± 2 °C, RH ≥ 90 %) for curing to a certain age.

2.4. Test method

The unconfined compressive strength, splitting tensile strength and compressive resilience modulus were tested according to the JTG E51-2009 [14]. The sample was a cylindrical specimen with a diameter of 150 mm and height of 150 mm. Among them, unrestricted compressive strength and splitting tensile strength tests need to prepare 6 groups with 13 specimens in each group, while 180 d compressive resilience modulus tests need to prepare 6 groups with 15 specimens in each group. The results adopted triple mean square error method to eliminate outliers and ensured that the variation coefficient of the same group was less than 15%. The test sample preparation groups are shown in Table 4.

Table 4. Number of test samples

Test	Number of group	Number per group	Total number	remark
Unconfined compressive strength	6	13	78	-
Splitting tensile strength	6	13	78	-
Compressive resilience modulus	6	15	90	The coefficient of variation of test results shall not exceed 15 %
Freeze-thaw test, dry-wet cycle	6	18	108	Each group of 18 specimens consisted of 9 cyclic specimens and 9 contrast specimens
Immersion expansion rate	6	3	18	-

According to Chinese standard JTG E51-2009 [14], the freeze-thaw cycle test needs to prepare 6 groups, and 18 specimens with a diameter of 150 mm × 150 mm are prepared in each group (including 9 freeze-thaw specimens and 9 contrast specimens). The specimens should be cured for 28 days (the test blocks should be put into the water at the last day of curing, and the water surface should be 2.5 cm above the top surface of the specimen). Five freeze-thaw cycles were carried out. For each freeze-thaw cycle, the specimens were frozen at -20 ℃ for 16 h and then thawed at 20 ℃ for 8 h. To evaluate the water stability of the coal gangue mixture, the dry and wet cycle experiment was carried out according to the reference [9]. The dry and wet cycle test requires 6 groups and 18 specimens with a diameter of 150 mm × 150 mm (including 9 dry and wet cycle specimens and 9 contrast specimens) in each group. After standard curing for 28 days (in the last day of curing, the test block should be placed into water for curing, and the water surface should be 2.5 cm higher than the top surface of the specimen), the specimens were subjected to dry and wet cycle tests. During each dry and wet cycle, the specimens were first dried in an oven at 85 ℃ for 12 h, and then soaked in water at (20 ± 2) ℃ for 3 h. The experiment was terminated when the unconfined compressive strength was tested after 15 dry and wet cycles, or when the mass loss exceeded 5 %. The immersion expansion rate with three samples in each group was carried out, according to the requirements of GB/T 24175-2009 [15]. The mixture with a size of 150 mm × 120 mm was placed in a water bath to read the initial height value. The mixture was kept in a 90 °C ± 3 °C water bath for 6 h and then cool naturally. Such an operation was repeated for 10d. The immersion expansion rate was calculated accordin g to Eq. 1:

$$\gamma = \frac{d_n - d_0}{120} \times 100\%, \tag{1}$$

where γ is the immersion expansion rate, %; *dn* is the dial indicator value of *n* days, mm; d_0 was the initial value of the dial, mm; 120 is the initial height of the specimen, mm.

For microscopic characterization, scanning electron microscopy (Zeiss Supra 55, Carl Zeiss, Germany) was used to observe the microscopic morphology of coal gangue mixture at 20 kV voltage and 20 mA current.

3. RESULTS AND DISCUSSION

The uniform test results of 7 d unconfined compressive strength, 180 d compressive resilient modulus, 180 d splitting tensile strength, five freeze-thaw cycles, and fifteen wet-dry cycles of each group after curing to the specified ages are detailed in Table 5.

3.1. Regression equations analysis

The uniform design was used to execute the experiment [16], and the test points were uniformly distributed in the multidimensional space, and the measured data in Table 5 were regressed step by step with the help of Minitab(2021) software to obtain the quadratic polynomial regression equations for the 7 d unconfined compressive strength of the mixture (y_1), compressive resilient modulus (y_2), splitting tensile strength (y_3), change rate of the frost strength (BDR) (y_4) and change rate of the water-stable strength (y_5), as shown in Eq. 2 to Eq. 6.

$$y_1 = 18.15x_1 - 3.10x_2 - 93.01x_1^2 + 11.66x_2^2 + 1.641 \tag{2}$$

$$y_2 = 33805.6x_1 + 3000.9x_2 - 159164x_1^2 - 7682.22x_2^2 - 229.506 \tag{3}$$

$$y_3 = 15.1736x_1 - 0.1752x_2 - 73.1647x_1^2 - 0.031 \tag{4}$$

$$y_4 = 3371x_1 + 307.2x_2 - 12310x_1^2 - 3221x_1x_2 - 109.8 \tag{5}$$

$$y_5 = 253.5x_1 + 27.02x_2 - 912.70x_1^2 - 245.7x_1x_2 - 14.07 \tag{6}$$

The accuracy of the model was evaluated using ANOVA in Minitab software to examine the significance and the coefficients of the model (seen in Table 6).

Table 5. Mechanical properties of lime steel slag coal gangue mixtures

No.	x_1	x_2	Unconfined compressive strength, MPa	Coefficient of variation, %	Compressive resilience modulus, MPa	Coefficient of variation, %	Splitting tensile strength, MPa	Coefficient of variation, %	Frost resistance		Water stability	
									Change rate of mass/%	BDR, %	Change rate of mass, %	Change rate of water-stable strength, %
1	0.088	0.10	2.3	8.2	1742	14.5	0.73	9.2	0.098	94.74	-0.93	1.70
2	0.160	0.17	2.0	8.0	1387	13.9	0.49	10.1	0.160	93.55	-1.30	1.05
3	0.064	0.24	2.4	11.4	1548	13.1	0.58	12.0	-0.250	79.49	-0.89	1.15
4	0.136	0.31	2.5	14.0	1628	7.9	0.63	14.0	-2.310	80.62	-0.95	1.52
5	0.040	0.38	2.7	12.6	905	14.8	0.40	12.5	-0.005	73.90	-0.86	1.13
6	0.112	0.45	3.5	14.6	1349	14.4	0.67	12.9	-0.967	89.02	-0.53	2.66

Note: BDR = (Strength after freeze-thaw cycles/28 d compressive strength) × 100 %.
Change rate of water-stable strength = ((Strength after dry and wet cycles - 28d compressive strength) / 28d compressive strength) × 100 %.

Table 6. Variance analytical results of regression equations

Source	Mean square					F-value					P-value				
	y_1	y_2	y_3	y_4	y_5	y_1	y_2	y_3	y_4	y_5	y_1	y_2	y_3	y_4	y_5
regression	0.33	108503	0.024	71.81	0.458	43.53	258.29	90.64	358.69	281.47	0.113	0.047	0.011	0.04	0.045
x_1	0.07	259191	0.069	88.64	0.502	9.97	617.00	257.34	442.73	306.91	0.195	0.026	0.004	0.03	0.036
x_2	0.02	19488	0.003	46.33	0.359	2.77	46.39	9.41	231.39	219.41	0.345	0.093	0.092	0.04	0.043
$x_1 \times x_1$	0.08	235339	0.066	108.28	0.596	10.71	560.22	246.99	540.84	364.45	0.189	0.027	0.004	0.03	0.033
$x_2 \times x_2$	0.09	39676	-	51.25	0.299	12.19	94.45	–	255.96	182.63	0.178	0.065	–	0.04	0.047
inaccuracies	0.01	420	0.000	0.20	0.002	–	–	–	–	–	–	–	–	–	–

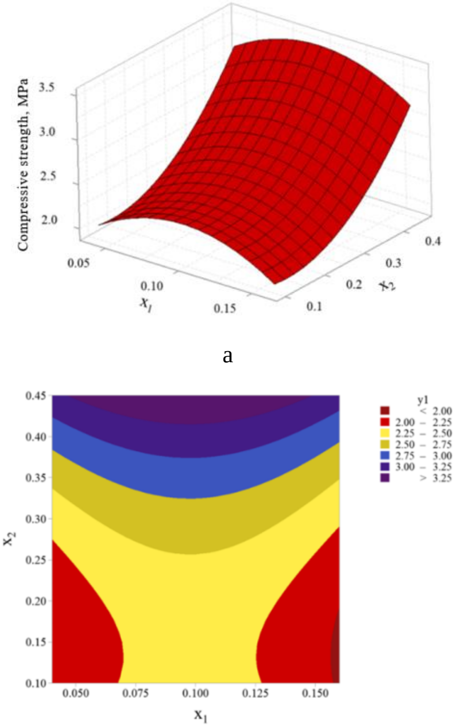
The P-values of the regression equations for the unconfined compressive strength, compressive resilient modulus, splitting tensile strength, BDR and change rate of water-stable strength of the mixtures were 0.113, 0.047, 0.011, 0.04, and 0.045, respectively, which indicated that the model was well fitted, with a high level of confidence degree, and that there was a strong correlation between the simulated values and the actual values.

3.2. Response surface analysis of coal gangue mixture

3.2.1. Response surface analysis of unconfined compressive strength

Fig. 3 shows the response surface diagrams of lime (x_1) and steel slag (x_2) on the 7 d unconfined compressive strength of the mixtures. There was no interaction between lime and steel slag, and the 7 d unconfined compressive strength had a maximum value of 3.5 MPa when the appropriate ratio ($x_1 = 0.112$, $x_2 = 0.45$) was taken. The unconfined compressive strength of the mixtures first increased and then decreased with the increase of lime dosage, and the unconfined compressive strength reached the peak value when the lime (x_1) was 10.5 %. From the coefficients of the factor terms in the regression equation combined with the surface and contour plots, the influence of each component on the compressive strength was steel slag (x_2) > lime (x_1). With the increase of steel slag doping, the 7 d unconfined compressive strength of the mixtures showed a trend of first decreasing and then increasing. When the steel slag (x_2) was in the range of 10.0 % – 20.0 %, it was negatively correlated to the unconfined compressive strength.

When x_2 was in the range of 20.0 % – 45.0 %, it played an enhanced role in the unconfined compressive strength. Spontaneous combustion gangue as the main aggregate of the mixtures had large size particles, and the addition of steel slag filled the voids in the mixtures.



a

b

Fig. 3. Response surface of lime and steel slag to 7 d unconfined compressive strength: a – surface plot of y_1 versus x_1, x_2; b – contour plot of y_1 versus x_1, x_2

Mechanical compaction could make full use of the embedded extrusion between the aggregates [17], so that the structure of the mixtures was denser and improved the early strength of the coal gangue mixtures. The pozzolanic reaction between the lime and the active substances SiO_2 and Al_2O_3 in the spontaneous combustion coal gangue occurred mainly in the later stage. The reaction was relatively slow in the early stage, while excessive dosage of lime would lead to the expansion and destruction of the mixtures.

3.2.2. Response surface analysis of compressive rebound modulus

Fig. 4 shows the response surface diagrams of lime (x_1) and steel slag (x_2) on the compressive resilient modulus of the mixtures. The influencing degree of each component on compressive strength was lime (x_1) > steel slag (x_2). There was no interaction between lime and steel slag, and with the increase of lime (x_1) and steel slag (x_2) dosage, the compressive resilient modulus of all the mixtures showed the trend of first increasing and then decreasing. When the lime (x_1) was 4.0 % to 10.5 %, the compressive resilient modulus of the mixtures increased from 1100 MPa to 1800 MPa, an increase of 63.6 %. The pozzolanic effect of lime was exerted, which played a dominant role in the hydration reaction of the mixtures. With the prolongation of curing ages, the activity of the steel slag was stimulated, which promoted the hydration reaction and produced more gelling material. This resulted in the stiffness of the base layer, which was macroscopically manifested as a rapid increase in the resilience modulus [18]. When the lime (x_1) was 10.5 % – 16.0 %, the compressive resilience modulus decreased from 1800 MPa to 1300 MPa.

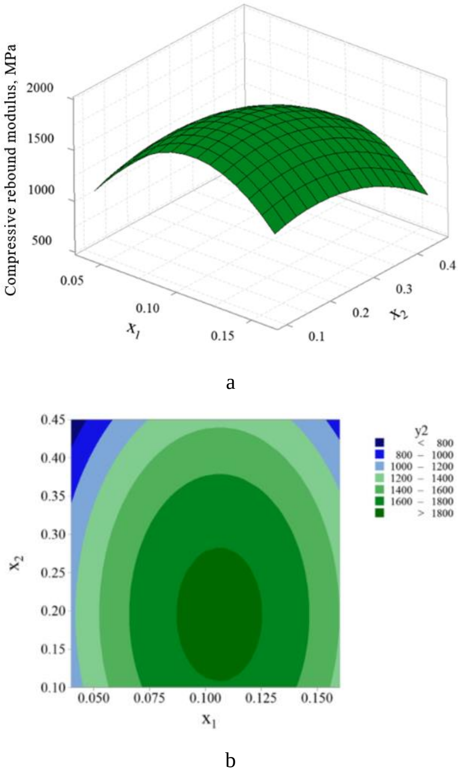


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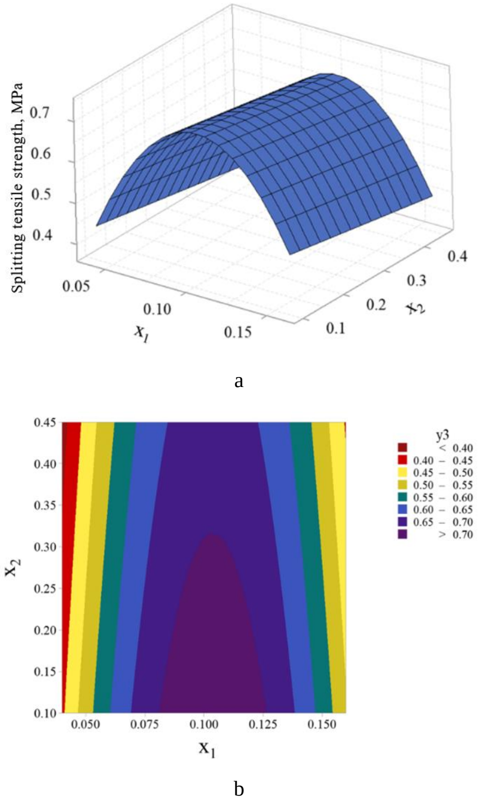
Fig. 4. Response surface of lime and steel slag to compressive rebound modulus: a – surface plot of y_2 versus x_1, x_2; b – contour plot of y_2 versus x_1, x_2

The compressive resilience modulus of the mixture reached a peak of 1800 MPa at 20 % of steel slag (x_2), and then decreased from 1850 MPa to 1350 MPa with an increase of steel slag (x_2) to 45.0 %, which was a decrease of 37.0 %. The decrease in compressive resilient modulus was mainly due to the high calcium oxide dosage from lime, which lead to the destruction of the mixture by micro-expansion. The presence of f-CaO and f-MgO expanded and produced micro-cracks in the mixture at a higher steel slag dosage, resulting in a decrease in the compressive resilient modulus.

3.2.3. Response surface analysis of splitting tensile strength

Fig. 5 shows the response surface diagrams of lime (x_1) and steel slag (x_2) on the splitting tensile strength of the mixtures. The splitting tensile strength of the mix showed a tendency to first increase and then decrease with the increase of x_1, and when x_1 was 10.5 %, the splitting tensile strength had a maximum value of 0.70 MPa. When x_1 is in the range of 10.5 % to 16.0 %, the splitting tensile strength decreases gradually, with the increase of x_1. Steel slag (x_2) showed a linear decrease in the splitting tensile strength of the mixture from 0.73 MPa to 0.67 MPa, a decrease of only 8.95 %, with x_2 in the range of 10.0 % to 45.0 %. The lime dosage had a greater effect on the 180 d splitting tensile strength of the mixtures, and the increase of steel slag dosage had a smaller effect on the splitting strength. This was mainly caused by two aspects of lime. On one hand, the pozzolanic reaction between lime and SiO_2, Al_2O_3 in steel and coal gangue generated many gelling substances and formed a network structure in three-dimensional space to bond coal gangue particles, so that the splitting tensile strength of coal gangue mixtures increased [19].



a

b

Fig. 5. Response surface of lime and steel slag to splitting tensile strength: a – surface plot of y_3 versus x_1, x_2; b – contour plot of y_3 versus x_1, x_2

On the other hand, the excessive use of lime would lead to the internal expansion stress and expansion damage in late period, resulting in a decline in mechanical properties.

3.2.4. Response surface analysis of frost resistance

Fig. 6 is the response surface diagrams of lime (x_1) and steel slag (x_2) on the rate of change of strength of mixtures after 5 freeze-thaw cycles. Combined with Table 5 and Fig. 6, the six groups of mixtures designed by the uniform test have better frost resistance. After five freeze-thaw cycles, the test block has a certain degree of peeling off in the edge of the upper surface and the outer surface, the mass loss rate was less than 5 %, and the BDR values were more than 70 % of the requirements in JTG D50-2017 [20]. There was a certain interaction between lime and steel slag, the change rate of strength after freeze-thaw cycles showed a trend of first increasing and then decreasing with the increase of lime (x_1) and continued to increase with the increase of steel slag (x_2), and there was a maximum value of the change rate of strength when the lime (x_1) was 10.5 %. From the coefficients of the factor terms in Eq. 4 and Fig. 6 b, the influence of each component on the compressive strength was lime (x_1) > steel slag (x_2).

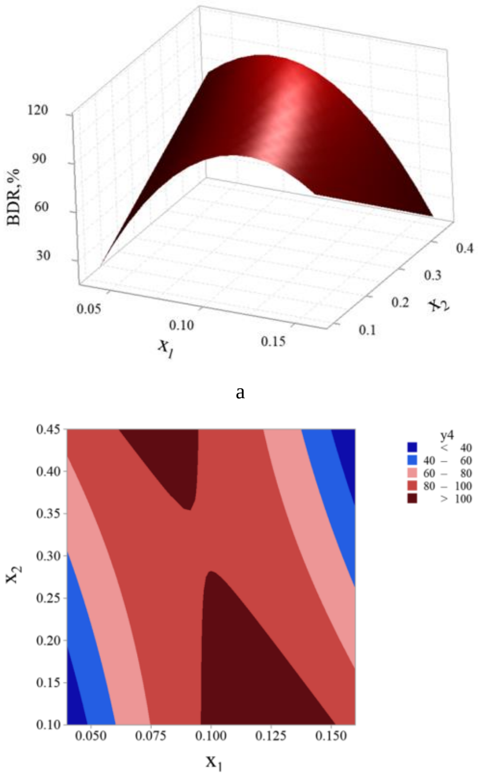


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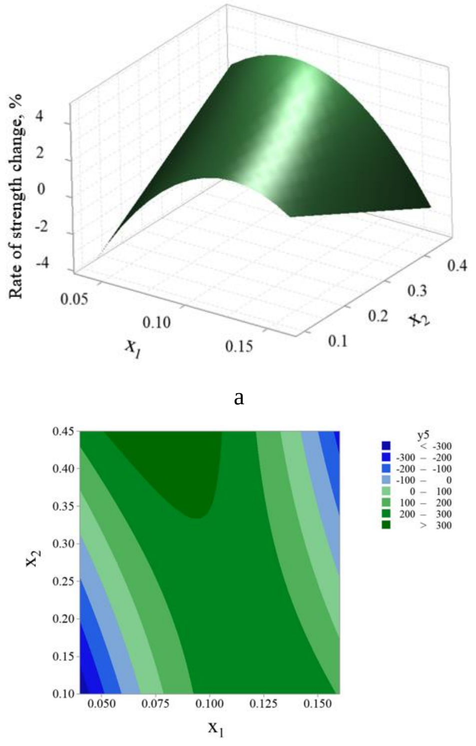
Fig. 6. Response surface of lime and steel slag to the BDR of coal gangue mixtures: a – surface plot of y_4 versus x_1, x_2; b – contour plot of y_4 versus x_1, x_2

In addition to the strength provided by coal gangue as a skeleton structure to resist freeze-thaw damage, the strength generated by lime hydration reaction was a key factor, which was consistent with the results of the 7 d unconfined compressive strength analysis [21]. In addition, the good solidity of steel slag ensured the better frost resistance. A small increase in lime dosage with high dosage of steel slag can prepare a mixture with better frost resistance.

3.2.5. Response surface analysis of water stability

Fig. 7 shows the response surface diagrams of lime (x_1) and steel slag (x_2) on the rate of strength change after fifteen wet and dry cycles. After 15 dry and wet cycles of the mixture, only a small amount of damage occurred at the edge of the specimen, and the damage area was small. Table 5 shows that the maximum change rate in specimen mass was 1.3 % after fifteen wet and dry cycles. The strength of the specimen increased after wet and dry cycles, but the growth was small, with the largest group only 2.66 %. Combined with the 7 d unconfined compressive strength growth, the strength of the mixtures was still in the stage of rapid growth after 28 d of standard curing.



a

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Fig. 7. Response surface of lime and steel slag to the strength change of dry and wet cycles: a – surface plot of y_5 versus x_1, x_2; b – contour plot of y_5 versus x_1, x_2

During the process of wet and dry cycles, the active substances inside the mixtures were still undergoing hydration reaction. Fig. 7 indicated an interaction between lime and steel slag, and the influence of each component on the compressive strength was lime (x_1) > steel slag (x_2). The rate of strength change of the mixtures after dry and wet cycles first increased and then decreased with the increase of lime (x_1), and increased with the increase of steel slag (x_2). Due to the water immersed in the coal gangue mixtures, the active substances in the steel slag hydration reaction generated substances with crystalline structure [22]. This increased the surface area of steel slag, improved the adhesion between steel slag and lime, increased the friction between steel slag and coal gangue, and increased the strength of the coal gangue mixtures. After fifteen dry and wet cycles, the increasing trend of strength indicated that the lime-steel slag-coal gangue mixture applied to the pavement base layer had a better water stability.

3.3. Immersion expansion rate

To investigate the expansion effect of f-CaO in steel slag on lime-steel slag gangue-mixtures, the 6th group ($x_1 = 0.112$, $x_2 = 0.45$) with the highest steel slag dosage in the uniform design was selected to prepare 3 parallel specimens A, B, and C. The results are shown in Fig. 8.

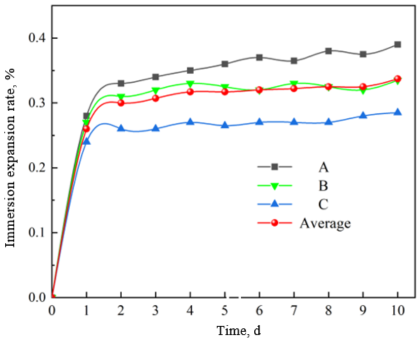

Fig. 8. Expansion rate of the coal gangue mixture after 10 d immersion

The water-immersed expansion of the mixture mainly occurred within the first 2 days and remained stable in the later periods. The average values of the immersion expansion rate in the 1st and 2nd day were 0.26 % and 0.30 %, respectively. After two days, the growth of the expansion rate slowed down. On the 10th day, the average rate of immersion expansion was 0.34 %, far less than the specification requirements of 1.5 %, meeting the stability requirements of steel slag for road use [23].

3.4. Microanalysis

Fig. 9 shows the SEM image of group 6 ($x_1 = 0.112$, $x_2 = 0.45$) after freeze-thaw cycle. As can be seen from Fig. 9, after the freeze-thaw cycle, many small pores appeared, and the length and width of cracks caused by expansion stress gradually expanded, making the mixture more loose and more porous. C-S-H gel was separated from the spatial network structure formed by AFt crystal, and some pores were generated, the overall density was reduced, and the compressive strength was reduced on the macro level.

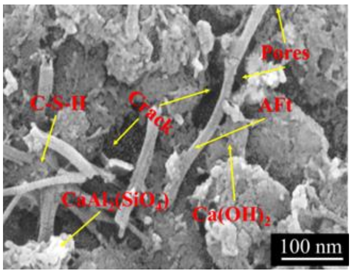

Fig. 9. SEM image of coal gangue mixture after freeze-thaw cycle

SEM analysis showed that a large number of active substances in steel slag and coal gangue reacted with volcanic ash, which promoted the formation of AFt, C-S-H, $CaAl_2(SiO_4)$ and $Ca(OH)_2$, in which $Ca(OH)_2$ was wrapped in a dense network structure formed by the interlacing of C-S-H and $CaAl_2(SiO_4)$. Coal gangue mixture can effectively resist freeze-thaw expansion stress. After freeze-thaw cycle, there are a few small pores in the mixture, which shows little mass loss and strength reduction on the macro level, and has good freeze-resistance.

4. CONCLUSIONS

1. According to the uniform test design, the regression equations of unconfined compressive strength, compressive resilience modulus and splitting tensile strength are derived. After the test of variance and coefficient of variation, the accuracy of each regression equation is high. By reasonably formulating the proportion of lime, steel slag and coal gangue, the prepared mixture can be used to guide the design of pavement base layers and realize the purpose of optimization of engineering application.
2. With the increase of lime content, the mechanical properties, frost resistance and water stability properties of the mixture are shown to first increase and then decrease. With the increase of steel slag content, the unconfined compressive strength increases, the compressive resilience modulus first increases and then decreases, the splitting tensile strength decreases, the loss of freeze-thaw strength continues to decrease, and the loss of water stability strength gradually increases.
3. Immersion expansion mainly occurs in the first 2 days, later remain stable, and immersion expansion rate is much less than the specification requirements of 1.5 %.
4. The addition of steel slag significantly improves the frost resistance of the mixture, and the BDR value exceeds 70 % of the design requirements. The main hydration reaction products of the mixture after 28 d curing are C-S-H, AFt, $CaAl_2(SiO_4)$ and $Ca(OH)_2$. It is less affected by the temperature change, and there is no obvious difference in XRD images before and after freeze-thaw cycles, and it has good frost resistance performance.

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