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Mechanical Properties and Durability of Steel Slag-mineral Powder-coal Gangue Mixture by Uniform Design for Pavement Base

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To realize the utilization of industrial solid waste resources and solve the shortage problem of pavement materials, this paper uses steel slag, mineral powder, and coal gangue to prepare a mixture. A uniform test with 2 factors and 6 levels was designed. Through regression analysis, response surfaces were established to study the mechanical properties of the coal gangue mixture. The hydrated products at different ages were microscopically analyzed by XRD and SEM. The durability including freeze-thaw cycles, dry and wet cycles, and immersion expansion rate were researched. The results show that the 7d unconfined compressive strength of the mixture reaches 2.14 – 6.46 MPa, with a 180d resilience modulus of 954 – 1098 MPa, and a 180d splitting tensile strength of 0.66 – 0.83 MPa. With the increase of steel slag content, the 7d unconfined compressive strength of the mixture first decreases and then increases. The content of mineral powder is positively correlated with the 7d unconfined compressive strength. The 180d compressive resilience modulus decreases first and then increases with the increase of steel slag and mineral powder content. The 180d splitting tensile strength is positively correlated with the content of steel slag and mineral powder. The mixture is less affected by freeze-thaw cycles, with mass loss rates of only 1.77 % – 2.13 %. The mass loss rate of the admixture is 0.87 % – 0.99 % after 10 dry and wet cycles, and the strength is slightly improved. The maximum expansion rate of the mixtures immersed in water for 10d is only 0.28 %. The hydrated reaction between steel slag, mineral powder and coal gangue promotes the formation of more hydration products such as AFt, C-S-H, $CaAl_2(SiO_4)$, and $Ca(OH)_2$. The C-S-H and $CaAl_2(SiO_4)$ are intertwined into a dense network to wrap $Ca(OH)_2$, which improves the compactness of the mixture and effectively resists the freeze-thaw expansion stress. The steel slag-mineral powder-coal gangue mixture meets the requirements of relevant norms and can be well used in pavement bases.

Keywords: coal gangue mixture, steel slag, mineral powder, pavement base.

1. INTRODUCTION

Coal gangue is a solid waste separated from coal mining and washing. The total production of coal gangue in China has reached 7 billion tons and has been one of the largest solid wastes [1]. However, the primary treatment method with coal gangue is stacking, which not only occupies land resources, harms water, soil and air, but also produces potential safety hazards such as landslides [2]. Therefore, it is urgent to carry out harmless treatment with coal gangue.

The utilization of coal gangue for road materials is one of the effective methods to consume coal gangue on a large scale. Many scholars have conducted in-depth research on the performance of coal gangue mixture on roads. Yan et al. [3] studied the mechanical properties of a slag-coal gangue mixture stabilized by cement and fly ash. The results show that the increase in slag replacement will reduce the strength of the mixture. When the slag replacement is about 50 %, the increase of cement content in the mixture will increase the strength of the mixture. When the cement content is 6 %, the 90d unconfined compressive strength can reach 9 MPa, and the 90d splitting strength can reach a maximum of 0.67 MPa. The main hydration products of the mixture are C-S-H (Calcium Silicate Hydrate) and AFt (Ettringite). Yan et al. [4] studied the effect of mix ratios and stabilized material types on the crushing resistance and mechanical properties of coal gangue mixture used as pavement base material. The results show that the crushing value and calorific value of the coal gangue aggregate after the crushing and sorting process are 25.2 % and 23 % lower than those without sorting, respectively. When 10 % fly ash is added, fly ash can play a buffer role in the mixture. The grading change rate of the coal gangue mixture after compaction is reduced by 41.8 %, the 7d unconfined compressive strength is increased by 30.9 %, and the 28d splitting resistance is increased by 64.3 %. Meng et al. [5] used coal gangue, steel slag, and mineral powder as main raw materials and sodium hydroxide as activator to analyze the influence of raw material content on the mechanical properties of coal gangue mixture. The results show that when the content of steel slag is 32.1 % – 72.0 %, the mineral powder is 7.0 % – 13.1 %, and sodium hydroxide is 3.3 % – 5.7 %, The 7d unconfined compressive strength of the mixture is 2.11 – 5.40 MPa, the 180d compressive

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resilience modulus is 613 – 1220 MPa, and the 180d splitting strength is 0.40 – 1.41 MPa. The mixture can be used as the base and bottom base material of expressways and first-class highways. Liu et al. [6] prepared highway pavement base materials with industrial solid wastes such as red mud from the Bayer process, coal gangue, and fly ash as the main raw materials and studied their mechanical properties and durability. The results show that when the total content of red mud and coal gangue is 75 % and the total content of solid waste is 97 %, the 7d unconfined compressive strength can reach more than 6 MPa. After 20 dry and wet cycles, the compressive strength of the mixture with 5 % slag can reach 5.98 MPa. After 5 freeze-thaw cycles, the compressive strength of the pavement base material still reaches 6.89 MPa. In summary, most scholars have applied coal gangue, steel slag, mineral powder, fly ash, and other solid wastes as subgrade and pavement materials, and have achieved good results, confirming that industrial solid waste can be used as road materials.

However, the traditional coal gangue mixture uses lime as an alkaline activator. The unit price of lime is high, and its production process will release greenhouse gases. So, it is urgent to develop a new environmentally friendly mixture without lime. The mineral powder has a potential hydraulic hardness, and the hydration product is the same as cement. Then, this paper chooses mineral powder as an alkali activator instead of lime [7, 8]. It is necessary to add a material with high activity to the coal gangue mixture to supplement the content of calcium and magnesium, and fly ash commonly used in the coal gangue mixture has a high cost. It is urgent to find a solid waste material in large quantities to replace fly ash. As one of the main by-products of the steelmaking process, the local steel slag in Handan has abundant reserves and low price, excellent physical and mechanical properties such as strength, density, wear resistance, firmness, and crushing value. At the same time, the content of calcium and magnesium in steel slag is higher, and it has better activity, which is suitable for road construction materials [9].

2. MATERIALS AND METHOD

2.1. Raw materials

Coal gangue, steel slag, and mineral powder from Handan, China are the raw materials to prepare the mixture. The chemical compositions of the raw material are listed in Table 1. The main chemical components of coal gangue are SiO_2 and Al_2O_3. The steel slag is mainly composed of CaO and Fe_2O_3, while CaO, SiO_2 and Al_2O_3 are the main chemical components of mineral powder.

1. Coal gangue. The coal gangue is reddish-brown, with a packing density of 2.27 g/cm^3, crushing value of 27.5 %, water absorption of 3.16 %, loss of ignition of 10.47 %, free expansion rate of 12.33 % and resistance to the disintegration of 94.23 %. Particle grading and XRD pattern are shown in Fig 1.

Table 1. Chemical composition of raw materials (wt.%)

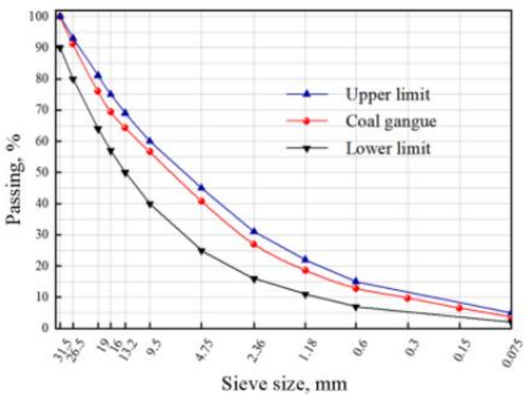
Component	SiO_2	Al_2O_3	Fe_2O_3	K_2O	CaO	MgO
Coal gangue	54.72	26.89	6.33	4.00	2.84	1.08
Steel slag	9.32	7.47	10.56	–	39.07	5.70
Mineral powder	33.98	15.18	0.77	–	39.47	7.77

Particle grading of coal gangue aggregate belongs to the district II. The main mineral phases include quartz, stellerite, andradite, kaolinite, and schaurteite.

2. Steel slag. The fine steel slag with particle size below 4.75 mm is gray black. The packing density is 3.4 g/cm^3, with water absorption of 1.98 %, immersion expansion rate of 1.54 % and crushing value of 24 %.
3. Mineral powder. The activity index of 7d and 28d of Grade S95 mineral powder are 86 % and 100 %, respectively. The density of the mineral powder is 2.9 g/cm^3, with a specific surface area of 428 m^2/kg, mobility ratio of 100 %, setting time ratio of 136 %, firing vector of 0.1 % and vitreous content of 87 %.

2.2. Mix ratio design

The mix ratio was based on the mass of coal gangue, that was, the amount of raw material was the percentage of the relative mass of coal gangue (coal gangue : steel slag : mineral powder = 1 : x_1 : x_2). According to the preliminary experiment, the range of raw materials was 1 of coal gangue, 0.301 – 0.721 of steel slag, and 0.042 – 0.077 of mineral powder. Then a uniform design with 2 factors (x_1 and x_2) and 6 levels (K1 to K6) was used for the mix ratio, as listed in Table 2.



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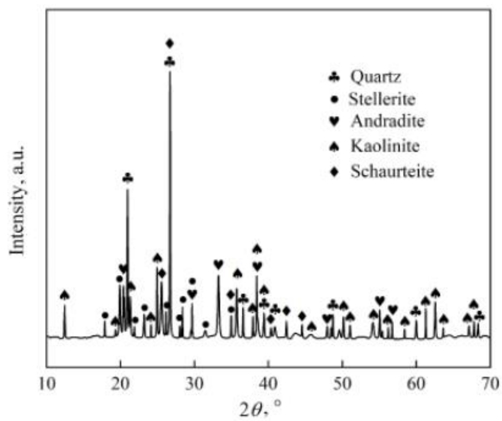


b

Fig. 1. Particle grading and XRD pattern of coal gangue aggregate: a – particle grading; b – XRD pattern

Table 2. Mix ratio design of the coal gangue mixtures

Sample No.	K1	K2	K3	K4	K5	K6
Coal gangue	1	1	1	1	1	1
Steel slag (x_1)	0.301	0.384	0.468	0.551	0.636	0.721
Mineral powder (x_2)	0.042	0.059	0.077	0.032	0.051	0.068

2.3. Sample preparation and test method

2.3.1. Sample preparation

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

2.3.2. Test method

In the mechanical properties test, the 7d unconfined compressive strength, 180d splitting tensile strength and 180d compressive resilience modulus experiments were carried out, according to Chinese standard JTG E51-2009 [10]. The sample dimension was 150 mm in diameter and 150 mm in height. For 7d unrestricted compressive strength and 180d splitting tensile strength, thirteen specimens in each group were used. After 7d of curing in standard conditions (20 ºC ± 2 ºC, RH ≥ 90 %), the specimens were tested on a road material strength tester (TL127-II, Cangzhou Yixuan Test Instrument, China), with a loading rate of 1 mm/min for 7d unrestricted compressive strength test. After 180d of curing, the experiments of 180d splitting tensile strength were conducted on a waterproof coil electronic universal test machine (WDW-50, Jinan Wenteng Test Instrument, China), with a maximum force of 50 kN and loading rate of 1 mm/min. The 180d compressive resilience modulus of fifteen specimens in each group were tested on the WDW-50 test machine, after 180d of curing.

In the durability experiments, nine specimens with dimensions of Φ 150 mm × 150 mm in each group were prepared for the freeze-thaw cycles and dry and wet cycles. After 28d of curing, the coal gangue mixtures were conducted for the freeze-thaw cycle experiment, according to JTG E51-2009 [10]. In each freeze-thaw cycle, the specimens were firstly frozen at -20 ℃ for 16 h and then thawed at 20 ℃ for 8 h. The strength after such 5 freeze-thaw cycles was tested on the TL127-II road material strength tester. To conduct the dry-wet cycle experiment in accordance with the literature [14, 15], the specimens were curried for 28d under standard conditions. During each dry-wet cycle, the samples were firstly dried in an oven at 85 ℃ for 12 h and then soaked in (20 ± 2) ℃ water for 3 h. The experiment was terminated when the unconfined compressive strength was tested after 15 dry and wet cycles, or the mass loss exceeded 5 %. The expansion rate of the mixture was tested according to Chinese standard YB/T 4184-2018 [13]. In each group, three specimens with dimension of Φ 150 mm × 120 mm were used. The mixture was formed in a closed test mold, and then placed in a water bath, and the initial height value was read with a dial indicator. The water bath was then heated to (90 ± 3) ℃ for 6h and cooled naturally. Such an operation was performed for 10 consecutive days. The immersion expansion rate was calculated according to Eq. 1:

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

where γ was the immersion expansion rate, %; d_n was the dial indicator value of the n day, mm; d_0 was the initial value of the dial indicator, mm; 120 was the initial height of the specimens, mm.

For microscopic characterization, the mineral phase composition of the coal gangue mixture was analyzed by an X-ray diffractometer (D/max-3C, Rigaku, Japan). The samples were screened and crushed by 200 mesh. The target anode was Cu K_α (1.5406 Å), with a scanning Angle of 5 – 90°, and a scanning speed of 5°/min. The scanning electron microscope (Zeiss Supra 55, Carl Zeiss, Germany) was used to observe the micromorphology of the coal gangue mixture with a voltage of 20 kV and a current of 20 mA.

3. RESULTS AND DISCUSSION

3.1. Response surface analysis

After curried to the specified age, the mixture specimens are used to test the 7d unconfined compressive strength (y_1), 180d compressive resilience modulus (y_2), and 180d splitting tensile strength (y_3). The results are listed in Table 3. The 7d unconfined compressive strength of the mixture reached 2.14 – 6.46 MPa, with the 180d compressive resilience modulus of 954 – 1098 MPa, and the 180d splitting tensile strength of 0.66 – 0.83 MPa. It meets the 7d unconfined compressive strength requirements (2 – 6 MPa) of pavement base of Grade II and below Grade II road in Chinese standard JTG/T F20-2015 [14].

Table 3. Mechanical properties of the mixture

Sample No.	Steel slag (x_1)	Mineral powder (x_2)	7d Unconfined compressive strength, MPa	Coefficient of variation C_v, %	180d Compressive resilience modulus, MPa	Coefficient of variation C_v, %	180d Splitting tensile strength, MPa	Coefficient of variation, C_v, %
K1	0.301	0.042	2.14	9.0	954	10.7	0.66	13.1
K2	0.384	0.059	2.74	10.0	966	12.1	0.77	12.9
K3	0.468	0.077	4.05	11.0	1000	12.3	0.79	11.1
K4	0.551	0.032	2.24	11.0	1030	13.7	0.74	11.7
K5	0.636	0.051	4.81	7.0	1011	13.0	0.82	13.0
K6	0.721	0.068	6.46	8.0	1098	13.2	0.83	12.2

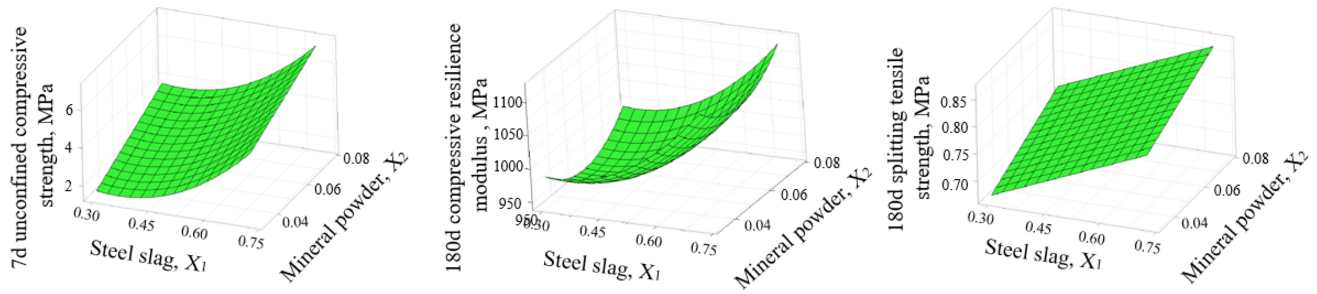
Fig. 2 a shows the response surface diagram of the 7d unconfined compressive strength. When the mass ratios of steel slag (x_1) and mineral powder (x_2) relative to coal gangue were 0.721 and 0.068, the maximum 7d unconfined compressive strength of the coal gangue mixture reached 6.46 MPa. With the increase of steel slag content, the 7d unconfined compressive strength of the mixture first decreased and then increased. The 7d unconfined compressive strength was positively correlated with the mineral powder content. This was due to that the coal gangue had certain grading defects, and there were relatively fewer fine particles. The addition of steel slag and mineral powder could supplement the voids between the mixed materials, play a filling effect, and improve the poor grading of coal gangue. After mechanical compaction, the interlocking effect between aggregates could be fully utilized [15, 16], making the structure of the mixed materials denser. Thus, the strength of coal gangue mixture could be effectively improved.

Fig. 2 b demonstrates the response surface diagram of the 180d compressive resilience modulus. The influence of materials on 180d compressive resilience modulus was as follows: steel slag > mineral powder. With the increase of the relative content of steel slag and mineral powder, the 180d compressive resilience modulus of the mixture decreased first and then increased. This was mainly because many powder particles contained in steel slag provided f-CaO (free CaO) for the mixture, which provided an alkaline environment for the subsequent hydration reaction and generated C-S-H gel, thus increasing the bonding effect [17]. The addition of mineral powder could improve the internal compactness and strengthen the bonding force. Under the action of external pressure, the rebound deformation of the test blocks was smaller, and the compressive rebound modulus was enhanced.

Fig. 2 c illustrates the response surface diagram of the 180d splitting tensile strength. The 180d splitting tensile strength of the mixture was linearly positively correlated with the content of steel slag and mineral powder, and the content of steel slag had a greater influence on the splitting tensile strength. When the mass ratios of steel slag (x_1) and mineral powder (x_2) relative to coal gangue were 0.721 and 0.068, the 180d splitting tensile strength of the mixture reached the maximum value of 0.83 MPa. The 180d splitting strength mostly depended on the bonding force between the inorganic binders and the aggregates [18]. The increase in the content of mineral powder and steel slag promoted the hydration reaction and generated more bonding substance, which was uniformly distributed between the aggregates and the binders, and tightly bound them together, resulting in a significant increase in the splitting strength.

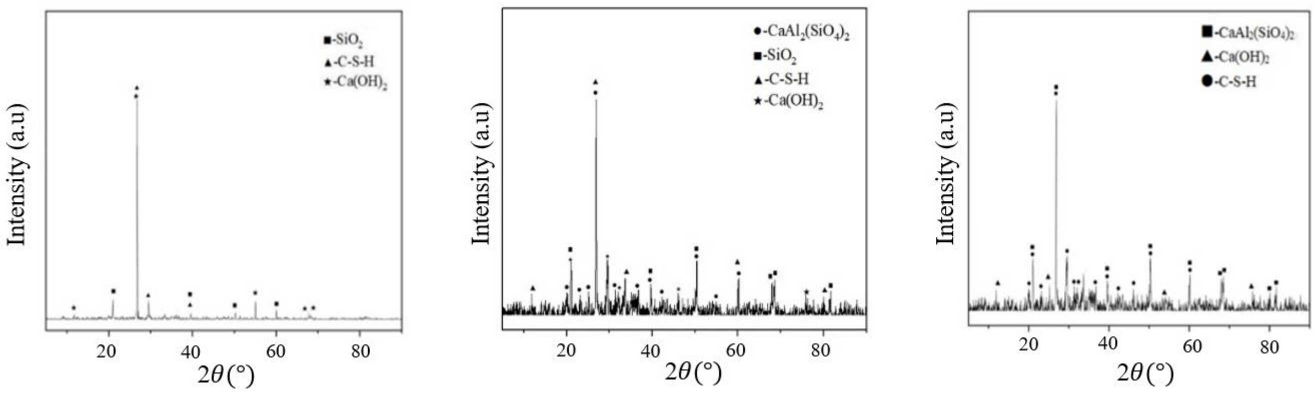
3.2. Microscopic analysis

The phase composition of the K6 mixture after different curing ages is shown in Fig. 3. After curing for 7d in Fig. 3 a, there were a large number of hydration products $Ca(OH)_2$ and C-S-H gel in the mixture, and some SiO_2 that did not participate in the chemical reaction.



a b c

Fig. 2. Response surface diagrams of mechanical properties of coal gangue mixture: a – 7d unconfined compressive strength; b – 180d compressive resilience modulus; c – 180d splitting tensile strength

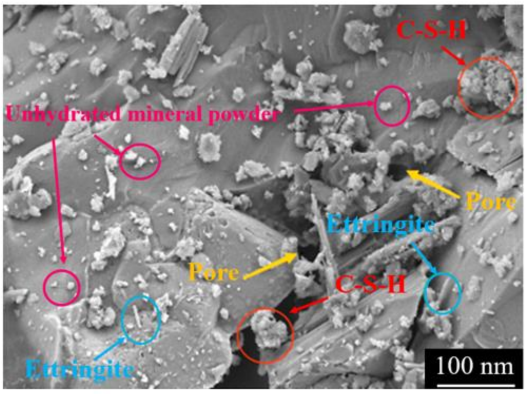


a b c

Fig. 3. XRD patterns of K6 coal gangue mixture at different ages: a – 7d; b – 28d; c – 180d

After curing for 28d in Fig. 3 b, the characteristic peaks of $CaAl_2(SiO_4)_2$ appeared, while the intensity of characteristic peaks of $Ca(OH)_2$ and SiO_2 decreased. After curing for 180d in Fig. 3 c, the SiO_2 diffraction peak was not observed, and the intensity of the $Ca(OH)_2$ diffraction peak was significantly weakened. This was because the active SiO_2 and $Ca(OH)_2$ in the mix performed a secondary hydration reaction, which not only consumed the $Ca(OH)_2$, but also generated hydration products such as $CaAl_2(SiO_4)_2$. Since the secondary hydration reaction continued to the later ages, the diffraction peak intensity of C-S-H gels increased during the age of 28d – 180d.

Fig. 4 is the SEM images of the K6 coal gangue mixture at different ages. In Fig. 4 a, there were a small number of irregular clusters of C-S-H gel, needle-rod AFt and unhydrated mineral powder in the early stage of curing. Due to the incomplete hydration reaction, there were a small number of hydration products, sparse structure and many voids.



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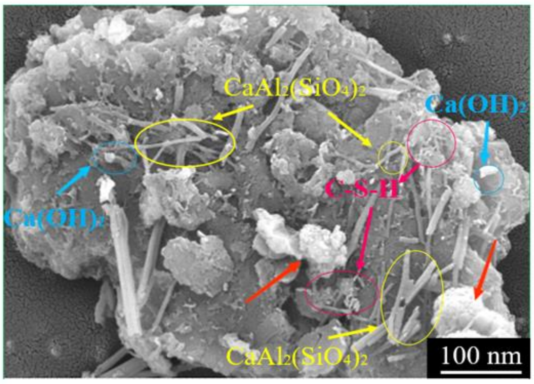


b

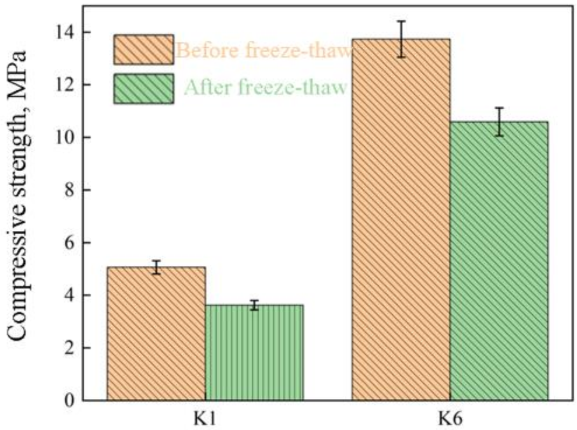
Fig. 4. SEM images of K6 coal gangue mixture at different ages: a – 7d; b – 180d

The internal hydration effect of the whole system was not obvious, resulting in low unconfined compressive strength. After curing for 180d, the bonding materials were fully hydrated, and a large amount of C-S-H gel and $CaAl_2(SiO_4)_2$ were generated, the number of pores was reduced, and unhydrated powder particles were not visible (Fig. 4 b). The bonding substance (C-S-H gel) was interwoven with $CaAl_2(SiO_4)_2$ to form a dense network structure, and the hexagonal plate $Ca(OH)_2$ was wrapped by C-S-H gel. A few SiO_2 played a filling effect in the bonding system, and increased the compactness of the structural system, generating a substantial improvement in mechanical properties.

3.3. Durability

3.3.1. Freeze-thaw cycles

Fig. 5 shows the freeze-thaw cycle test. Before the freeze-thaw cycle test, the compressive strengths of K1 and K6 were 5.06 and 13.73 MPa, respectively. After the freeze-thaw cycle test, the values were 3.62 and 10.59 MPa, respectively. The mass loss rate of the K1 and K6 groups was less than 5 %, and the BDR value ((compressive strength after freezing-thawing cycles/ 28d compressive strength)× 100 %) met the requirements (greater than 70 %) of Chinese standard JTG D50-2006 [19]. Steel slag filled the pores between coal gangue particles, and mineral powder was adsorbed on the surfaces of the steel slag and coal gangue. Bonding substances such as C-S-H gel and $CaAl_2(SiO_4)_2$ were generated after curing, which improved the compactness of the mixture and thus had good freezing-thawing resistance.



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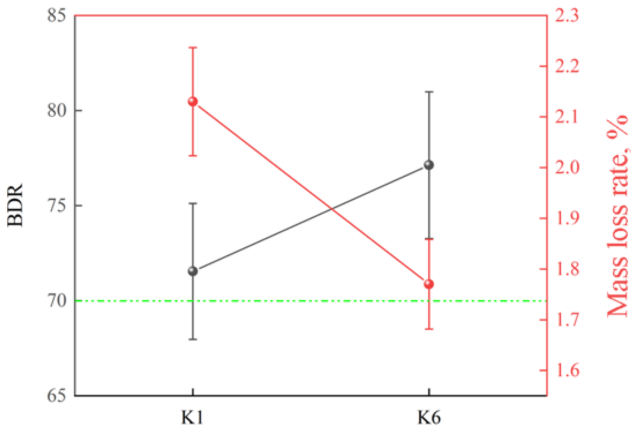

b

Fig. 5. Freeze-thaw cycle test: a – compressive strength; b – BDR value and mass loss rate

Fig. 6 shows the SEM images of the mixture before and after the freeze-thaw cycle. From Fig. 6 a, the hydration products in the mixture before and after freeze-thaw were similar, mainly consisting of a small amount of cluster C-S-H gel, dendritic $CaAl_2(SiO_4)_2$ and hexagonal plate $Ca(OH)_2$. Bonding substances such as C-S-H gel and $CaAl_2(SiO_4)_2$ were interwoven to form a dense structural system. The elongated dendritic $CaAl_2(SiO_4)_2$ filled in the pores could better resist the freeze-thaw expansion stress. With the progress of freeze-thaw cycles, under the action of freeze-thaw expansion stress, some $CaAl_2(SiO_4)_2$ was fractured, and the network structure formed by the interlacing of $CaAl_2(SiO_4)_2$

and C-S-H gel was damaged, which showed a mass loss and a strength decline.

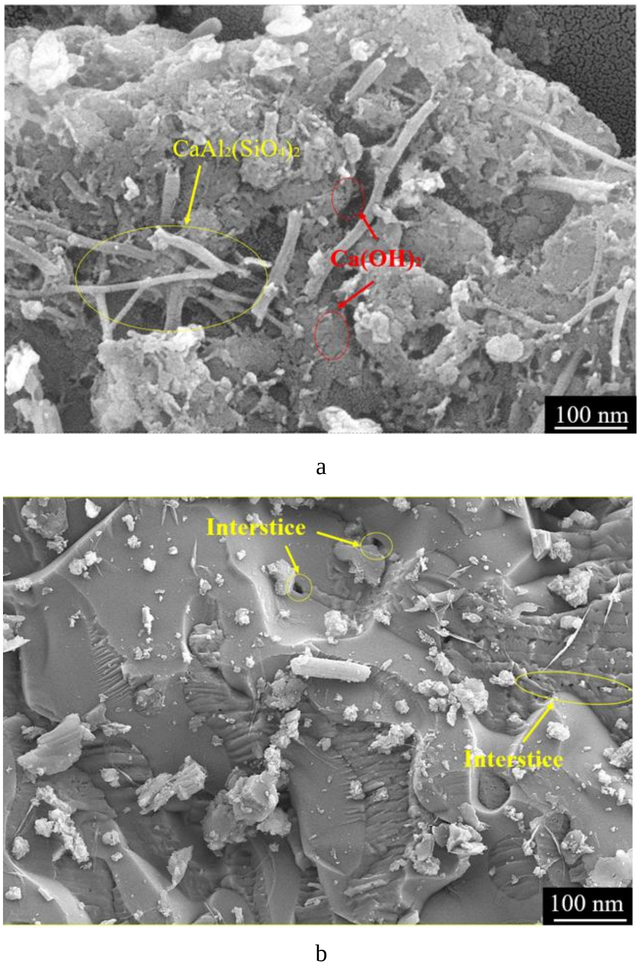

Fig. 6. SEM images of the mixture: a – before freeze-thaw tests; b – after freeze-thaw tests

After freeze-thaw cycles, the physical structure of the mixture surface was damaged, and there were small cracks that were difficult to observe by the naked eye, but the internal structure was dense and not easy to damage, and the mixture had good freezing-thawing resistance.

3.3.2. Dry and wet cycles

Fig. 7 is the dry and wet cycle test of the K1 and K6 mixture. The compressive strength of the K1 group increased from 2.01 MPa before the dry and wet cycle test, to 2.67 MPa after 10 cycles with the strength change rate of 3.28 %. For the K6 group, it was from 5.86 MPa to 6.17 MPa, with a strength change rate of 5.30 %. After 10 dry and wet cycles, the mass loss rates of K1 and K6 groups were 0.99 % and 0.87 %, respectively, indicating that the dry and wet cycles had little influence on the appearance quality of the mixture. After dry and wet cycles, the strength of the two groups increased. This was because in the process of dry and wet cycles, the soaking water entered the interior of the mixture and hydrated with the active substance. With the extension of soaking time, the hydration reaction would also be intensified, thus promoting the improvement of strength. It showed that the steel slag mineral powder coal gangue mixture had good performance of dry and wet cycles when applied to the pavement base.

3.3.3. Immersion expansion rate

Table 4 shows the immersion expansion rate of all six groups. The immersion expansion rate of the mixture first increased and then decreased with the increase of the mineral powder content, and was negatively correlated with the steel slag content. The water expansion of the mixture mainly occurred in the first 5d and remained stable in the later period. This was because the steel slag was a fine aggregate with a particle size < 4.75 mm, which had a high content of active CaO.

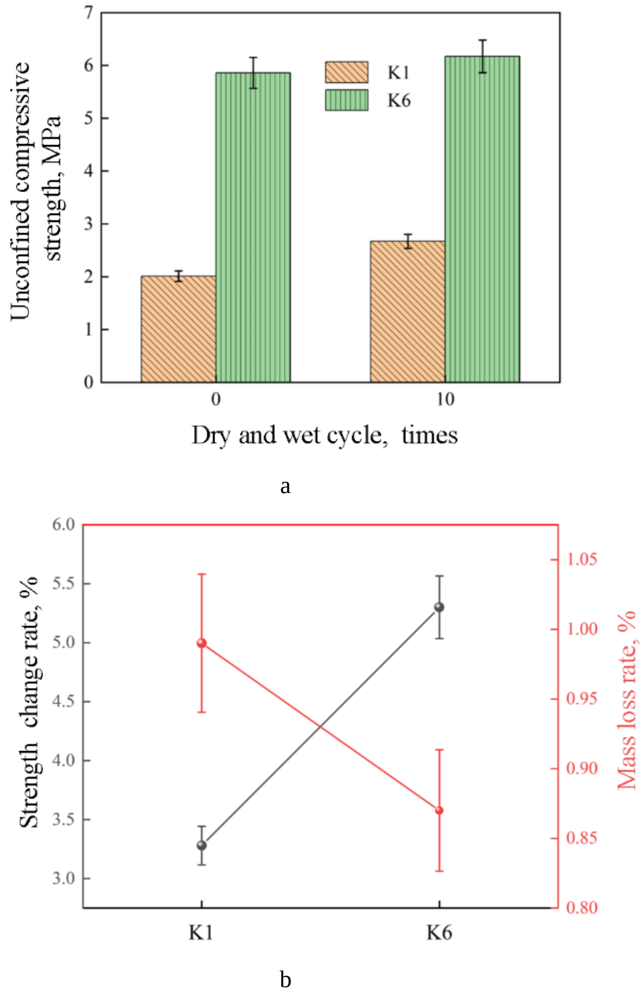

Fig. 7. Dry and wet cycle test: a – unconfined compressive strength; b – strength change rate and mass loss rate

Table 4. Expansion rate of the mixtures after 10d immersion

Soaking time (d)		1	2	3	4	5	6	7	8	9	10
Immersion expansion rate (%)	K1	0.09	0.16	0.23	0.25	0.26	0.26	0.26	0.26	0.26	0.26
	K2	0.13	0.21	0.27	0.28	0.28	0.28	0.28	0.28	0.28	0.28
	K3	0.07	0.12	0.16	0.17	0.18	0.18	0.18	0.18	0.18	0.18
	K4	0.11	0.18	0.20	0.21	0.21	0.21	0.21	0.21	0.21	0.21
	K5	0.12	0.16	0.17	0.18	0.18	0.18	0.18	0.18	0.18	0.18
	K6	0.04	0.10	0.11	0.12	0.13	0.13	0.13	0.13	0.13	0.13

The addition of mineral powder consumed f-CaO in steel slag, promoted the hydration reaction and generated a large amount of $Ca(OH)_2$, thus preventing the volume expansion caused by f-CaO. And the hydrated substance promoted the strength of the mixtures. In addition, the cohesive force between the components and the internal friction resistance between the aggregates also inhibited the expansion development of the mixture. The expansion rate of the mixtures after 10d immersed in water was much less than 1.5%, which was the requirement of YB/T 4184-2018 [13]. It proved again that the steel slag mineral powder coal gangue mixture had good durability and could be used as pavement base material.

4. CONCLUSIONS

1. With the increase of steel slag content, the 7d unconfined compressive strength of the mixture first decreases and then increases. The content of mineral powder is positively correlated with the 7d unconfined compressive strength. The 180d compressive resilience modulus decreases first and then increases with the increase of steel slag and mineral powder content. The 180d splitting tensile strength is positively correlated with the content of steel slag and mineral powder.
2. When the contents of steel slag and mineral powder in the mixture are 40.3 % and 3.8 % (namely the mass ratios of steel slag (x_1) and mineral powder (x_2) relative to coal gangue are 0.721 and 0.068), the mechanical properties reach the best, with 7d unconfined compressive strength of 6.46 MPa, 180d compressive resilience modulus of 1098 MPa and 180d splitting tensile strength of 0.83 MPa.
3. A large number of active substances in steel slag and coal gangue react, promoting the formation of AFt, C-S-H, $CaAl_2(SiO_4)$ and $Ca(OH)_2$, in which $Ca(OH)_2$ is interwoven by C-S-H and $CaAl_2(SiO_4)$ to form a dense network structure, which increases the density of the mixture.
4. The mass loss rate of the mixture after 5 freeze-thaw cycles is less than 5 % and the BDR value is more than 70 %. The mass loss rate of the admixture is 0.87 % – 0.99% after 10 dry and wet cycles, and the strength is slightly improved.
5. The immersion expansion rate of the mixture decreases with the increase of steel slag content and increases firstly and then decreases with the increase of mineral powder. The expansion rate of the mixture mainly occurred in the first 5d and tended to be stable in the later period. The steel slag mineral powder coal gangue mixture has good mechanical properties and durability, and can be used as pavement base material.

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