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Experimental Study Based on Box–Behnken Design and Response Surface Methodology for Optimization Proportioning of Activated Lithium Slag Composite Cement-Based Cementitious Materials

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Abstract: Cement-based cementitious materials occupy a central position in the construction industry, but the problem of high carbon dioxide(CO₂) emissions from cement production has attracted global attention. To meet this challenge, finding low-carbon alternative materials has become a top priority in the research of new building materials. At the same time, the problem of large amounts of lithium slag piling up needs to be solved, and resource utilization has become its potential way out. In this study, the volcanic ash activity of lithium slag was activated by composite activation means of high-temperature calcination and sodium silicate, and it was used as an alternative mix to cement. The Box–Behnken design and response surface method (BBD-RSM) was utilized to optimize the ratio of activated lithium slag composite cement-based cementitious materials, and high-performance new solid waste cementitious materials were prepared. The results show that activated lithium slag composite cementitious materials activated lithium slag exhibit excellent performance when activated lithium slag mass fraction is 7.3%, the sodium silicate dosage is 8.8%, and water–solid ratio is 0.6:1. The composite cementitious material under this ratio shows excellent performance, with fluidity 235.69 mm, gelation time 73.54 s, water evolution rate 1.123%, 3d and 28d compressive strengths, respectively, are 11.54 MPa and 22.9 MPa. Compared with ordinary Portland-cement-based cementing materials, the uniaxial compressive strength, modulus of elasticity, and tensile strength at break of activated lithium slag cementitious material solidified body were increased by 34.33%, 36.43%, and 34.98%, and the compressive deformation and tensile deformation were enhanced by 37.78% and 40%. This study not only provides a theoretical basis and experimental foundation for the preparation of new solid waste cementitious materials, but also provides a new solution for the reinforcement of crushed rock bodies in engineering practice, which is of great significance for promoting the low-carbon development of the construction industry.

Keywords: lithium slag; Box–Behnken design; response surface method; cementitious materials



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1. Introduction

Cement-based cementitious materials have a wide range application in construction structure reinforcement, geological disaster management, dam failure prevention, underground rock reinforcement, efficient solid waste disposal and other engineering fields, which all highlight the important supporting role of cement as a basic material [1,2]. However, the problem that cement production brings about high carbon dioxide emissions is gradually coming to a prominent position, and it has become an important factor that restricts the development of the construction industry [2,3]. According to statistics, carbon dioxide emissions during the production of cement-based materials account for 5–8% of the global total [4]. Therefore, it is of great practical significance to find new materials that can replace or partially replace cement and reduce carbon emissions to realize the high-quality development of the civil engineering industry as well as the goal of carbon neutrality.

The utilization of industrial solid waste materials to manufacture new cementitious materials has a broad prospect [5–7]. The reuse and recycling of industrial solid waste materials offer a sustainable approach to reducing CO₂ emissions. By incorporating these materials into various industrial applications, we can not only mitigate the environmental impact of waste disposal but also contribute to achieving carbon neutrality goals. At present, many scholars have extensively studied industrial solid wastes such as fly ash, coal gangue, and slag as cement substitutes. Wang et al. [6], Liu et al. [7], and Hao et al. [8] significantly improved the properties of cementitious materials by using fly ash as a partial substitute for cement through high-temperature treatment methods. Kim et al. [9] and Fu [10] found that the incorporation of fly ash significantly improved the durability, impermeability, and crack resistance of cementitious materials.

Su et al. [11], Ma et al. [12], Sun et al. [13] successfully applied coal gangue in cementitious materials to improve the strength and durability of the materials while significantly reducing the cost.

Liu et al. [14] concluded that green cement mortar with better compressive strength and resistance to chloride ion permeability can be developed by incorporating activated slag in cement mortar. The studies of Gorospe et al. [15], Xiang et al. [16] also showed that the incorporation of slag could improve the sulphate erosion resistance and durability of cementitious materials. These studies not only verified the potential value of industrial solid wastes in resource utilization, but also provided innovative ideas for other industrial solid wastes.

With the rapid development of the new energy vehicle market and the continuous progress of lithium battery technology, lithium dross production has also increased dramatically. Just China's lithium dross has totaled more than 15 million tons. Currently, the global lithium dross resource utilization rate is only 6%. Most of lithium slag is disposed via conventional methods such as piling and landfill, resulting in serious waste of resources and environmental pollution. Therefore, how to effectively deal with lithium slag has become an urgent problem in China, and even the world.

Lithium slag, as a by-product of lithium carbonate extraction, is mainly composed of oxides, carbonates, and hydroxides, etc., and contains a large amount of silicon, aluminum, iron, calcium, and other oxides. It has similar chemical composition with cement clinker, and its volcanic ash activity is higher than that of gangue, fly ash and other industrial solid wastes, which is expected to be a powerful supplement to cement-based materials [1,17]. Wu et al. [18] pointed out that the incorporation of lithium slag powder in concrete can significantly improve its densification and impermeability, while showing excellent resistance to freeze–thaw cycles, sulfate attack, and carbonation. It has also been pointed out that the incorporation of lithium slag can significantly affect the gelation time and compressive strength of concrete [19,20]. Therefore, it is important to focus on the important influencing factor of lithium slag dosage (mass fraction) in the related research. These research results provide a theoretical basis for the application of lithium slag in cement-based cementitious materials.

Nevertheless, the volcanic ash activity of lithium slag in its original state is still low, which limits its wide application in cementitious materials [21]. To improve the activity of lithium slag, researchers have explored various methods, such as the use of alkali excitors, high-temperature calcination, and high-temperature complex alkali excitation to activate lithium slag [22,23]. Dong et al. [24], Liu et al. [25] found that alkali excitors could effectively promote the dissolution and hydration reactions of silicates and aluminates in lithium slag, which in turn improved the volcanic ash activity of lithium slag and help to improve the compressive strength of lithium-slag-cement-based cementitious materials and their durability performance. In addition, Shen et al. [26] found that alkaline exciter dosing significantly affected the lithium slag activity. Wu [18] and Wang et al. [27] found that high-temperature complex alkali excitation was more effective in improving the activity of lithium slag. In their study, it was pointed out that high-temperature calcination transforms the silicate and aluminate structures in lithium slag, making them more susceptible to

react with calcium hydroxide in cement-based cementitious materials. Meanwhile, alkali excitation further promotes the dissolution and hydration reactions of lithium slag by introducing specific alkaline substances. These methods improve the utilization and performance of lithium slag in cementitious materials by altering the physical and chemical properties of lithium slag, making it easier to react with other components in cementitious materials [28,29].

Despite the positive trend of research related to the use of lithium slag as a cement substitute, the research on the use of high-temperature alkali excitation compounding to activate the volcanic ash activity of lithium slag and then prepare high-performance activated lithium slag cement-based cementitious materials is still at an early stage and lacks systematic proportioning and application studies. This study aims to optimize the ratio of hot-activated lithium-slag-sodium silicate composite cement-based cementitious materials using the Box–Behnken design and response surface method, to provide strong theoretical support and practical guidance for the rational resource utilization of lithium slag and the sustainable development of the construction industry.

Box–Behnken design is an efficient experimental design method which can reduce the number of experiments, lower the experimental cost, shorten the experimental time and significantly improve the experimental efficiency under the premise of guaranteeing the amount of information, and the experimental method has been widely used in traditional fields such as chemistry [28,29], biology [30,31], medicine [32,33] and engineering [23,24]. With the continuous development of new materials in recent years, the method also has a promising application in emerging fields such as recycled concrete [34,35] and high-performance composites [3,15,18]. The development of cementitious materials involves the interaction of multiple factors, and the complexity of these factors makes it difficult to meet the needs of traditional single-factor analysis methods, which can be solved by the box-type Behnken design and response surface methodology.

On this basis, the study activated the volcanic ash activity of lithium slag by high-temperature calcination and sodium silicate complex. The activated lithium slag was used as a partial cement replacement admixture. Box–Behnken design and the response surface method was used to optimize the ratio of activated lithium slag-sodium silicate composite cement-based cementitious materials (hereinafter referred to as composite cementitious materials), to prepare a new type of cement-based cementitious materials. The effect of the composite cementitious material in reinforcing crushed rock is compared with that of ordinary silicate cementitious material, which verifies the scientific rationality of the ratio determined in this study. This study is conducive to promoting the wider application of lithium slag in cement-based cementitious materials and provides strong support for the research and development of new materials and technological innovation.

2. Materials and Methods

2.1. Material Characterization

The active lithium slag and water glass composite cement-based cementitious material prepared in this study is composed of active lithium slag powder, cement, water glass, water-reducing agent and water mixed in a certain proportion.

2.1.1. Lithium Slag

The lithium slag selected for the test is yellow lithium mica slag, taken from the city of Yichun, Jiangxi Province, China, known as “Asia’s lithium capital”. The specific surface area is $322 \text{ m}^2/\text{kg}$, density is $2.6 \text{ kg}/\text{m}^3$, the median diameter is $19.34 \mu\text{m}$, and the amount of water required is less than 115%. The mineral composition measured by XRD diffraction analysis is shown in Table 1. The chemical composition of lithium slag is mainly SiO_2 and Al_2O_3 (active silica-aluminum composition), accounting for 80.92%, indicating that it has high volcanic ash activity. The XRD physical analysis spectrum of this lithium slag is shown in Figure 1, and its mineral composition mainly contains gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), quartz, square zeolite, muscovite, and kaolinite, etc. These components can have a secondary

hydration reaction with cement hydration product $Ca(OH)_2$ in an alkaline environment to generate cement gel, which is conducive to the improvement of the mechanical properties of cement stone.

Table 1. Chemical composition of lithium slag.

Chemical Composition/%	SiO ₂	Al ₂ O ₃	CaO	K ₂ O	Na ₂ O	Fe ₂ O ₃	MgO	LOI
Lithium slag	54.21	26.71	1.30	2.93	0.93	9.26	3.37	17.39

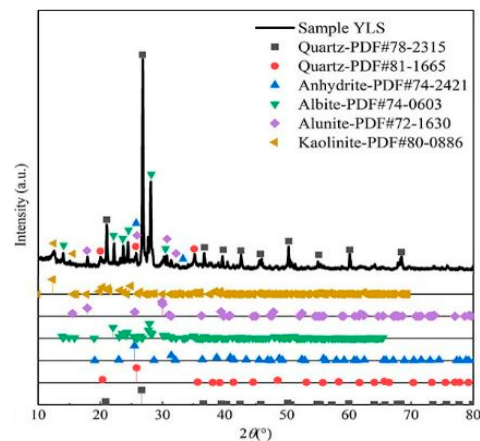


Figure 1. XRD pattern of lithium slag.

In this paper, a simple and easy sieving method was used to sieve lithium slag powder using sieves with different apertures, and the particle content of different particle size ranges was determined by weighing the mass of the residue on different sieves, as shown in Table 2, in which particles smaller than 75 μm accounted for 13.64% of the total, indicating that its specific surface area is larger, which is also the reasons that the volcanic ash activity of lithium residue is higher than that of industrial solid waste such as coal gangue and fly ash.

Table 2. Basic physical properties of lithium slag.

Original Particle Size/%	<2	<1.25	<1	<0.5	<0.3	<0.25	<0.1	<0.075
Lithium slag	100	63.84	62.21	47.99	32.30	30.99	24.49	13.64

In this test, lithium slag with a particle size of less than 75 μm was selected as an admixture to replace cement, and these key physical indicators of lithium slag are in line with the industry standard of YBT 4230-2010, “Ground lithium slag used for cement and concrete” [36].

2.1.2. Sodium Silicate

Sodium silicate, as a commonly used alkali exciter, plays a crucial role in the preparation of gelling materials [13]. The SP liquid type sodium silicate was chosen for this experiment.

The modulus and Baumé degrees of sodium silicate are important factors in determining the basic properties of cementitious materials [15,16]. In this experiment, eight types of sodium silicate were selected: modulus was taken as 3.3, and Baume degrees were taken as 30° Bé, 38° Bé, 45° Bé, and 50° Bé; Baume degrees were taken as 38° Bé, and modulus was taken as 2.6, 2.8, 3.0, and 3.3, respectively.

This study systematically investigated the effects of different types of sodium silicate on the basic properties of composite cementitious materials, such as fluidity, gelation

time, water evolution rate and 3d, 28d compressive strength, and the results are shown in Figure 2.

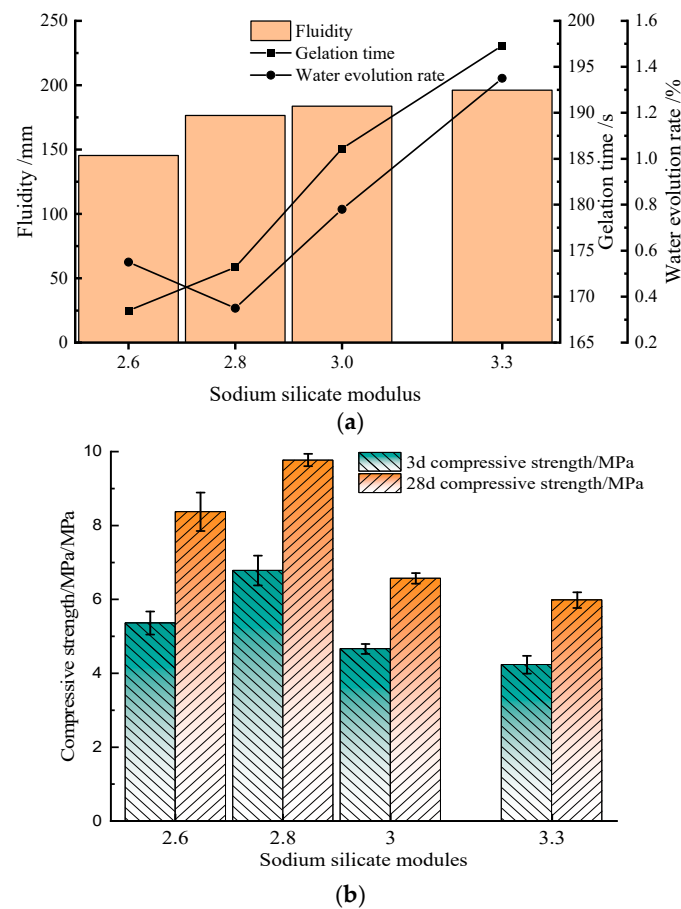


Figure 2. Influence of sodium silicate modulus on the basic properties of composite cementitious. (a) Influence of sodium silicate modulus on the fluidity, gelation time and water evolution rate of composite cementitious materials; (b) The effect of sodium silicate modulus on 3d and 28d compressive strength of composite cementitious materials.

Figure 2a shows as sodium silicate modulus increases from 2.6 to 3.3, fluidity and gelation time of the cementitious material increase, and water evolution rate decreases first and then increases; when the sodium silicate modulus is 2.8, it reaches the minimum value of 0.35% (Meeting engineering requirements). Figure 2b shows 3d and 28d compressive strengths are maximum when sodium silicate modulus is 2.8. Therefore, it is reasonable to choose the water glass modulus of 2.8.

Figure 3 shows with sodium silicate Baumé degrees increasing from 30°Bé to 50°Bé, fluidity is almost unaffected, gelation time and compressive strength are gradually increased, and water evolution rate is gradually reduced. When sodium silicate Baumé degrees is 50°Bé, gelation time is about 225 s, and water evolution rate is about 0.35%, which are in line with the requirements of the project [23,25]. Therefore, sodium silicate Baumé degrees is more reasonable at 50°Bé.

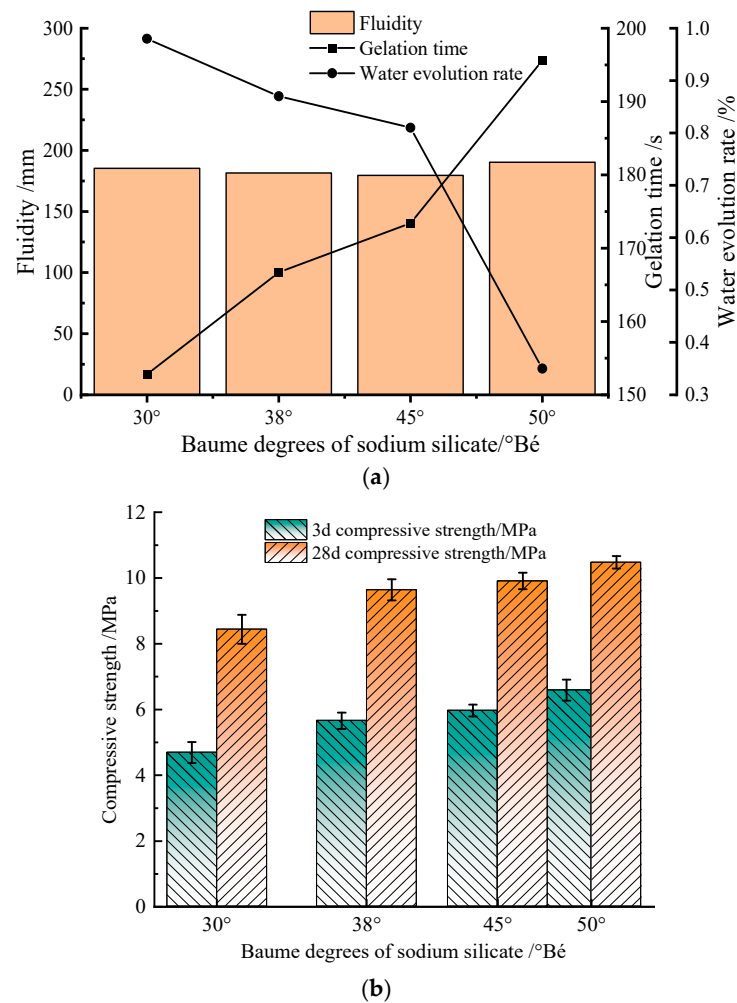


Figure 3. Influence of sodium silicate Baumé degrees on the basic properties of composite cementitious materials. (a) Influence of sodium silicate Baumé degrees on fluidity, gelation time and water evolution rate of composite cementitious materials; (b) Influence of sodium silicate Baumé degrees on 3d and 28d compressive strength of composite cementitious materials.

2.1.3. Cement

Model P·O 42.5 cement was selected for the test, which is widely used in engineering and has high strength and stability.

2.1.4. Water-Reducing Agent and Water

This test uses polycarboxylic acid water-reducing agent, which is a commonly used cement concrete admixture [19], and the test results of its related indexes are shown in Table 3, and all indicators are in line with the requirements of Test Method for Homogeneity of Concrete Admixtures (GB/T8077-2012) [37] and Concrete Admixtures (GB/T8076-2009) [38]. Water for test is tap water, which has stable water quality and meets the basic requirements for the preparation of cementitious materials.

Table 3. Performance indexes of naphthalene series water-reducing agent.

20% Liquor PH	Air Dosage/%	Water-Reducing Rate/%	CI- /%	Fineness
7~9	≤6	≥45	≤0.3	0.315 mm screen residue <1%

2.2. Experimental Methodology

2.2.1. Lithium Slag Hot Activation Test

To explore the excitation degree of the calcination temperature on lithium slag activity, activation tests at different calcination temperatures were carried out. Firstly, the large lithium slag was crushed and sieved, and the lithium slag powder with a particle size of less than 75 μm was selected, which was evenly spread in the tray and put into the horse-boiling furnace for high-temperature calcination activation.

The experiment was set up with 1 control group and 4 test groups. The control group (YLS0) indicates that the doped lithium slag powder was not activated. In test group, lithium slag powder was activated by high-temperature calcination at 600 °C, 700 °C, 800 °C and 900 °C, which were labeled as YLS600, YLS700, YLS800 and YLS900, respectively. After reaching the set calcination temperature, the constant temperature was maintained for 2 h, and then the switch of the horse-boiling furnace was turned off, and the slag powder was taken out after it was naturally cooled down. After reaching the set calcination temperature, the constant temperature was kept for 2 h, then the switch of the horse-boiling furnace was turned off, and it was taken out after cooling naturally, and then it was analyzed by XRD diffraction to determine the influence of calcination temperature on the activity of lithium slag.

2.2.2. Box–Behnken Design and Response Surface Method (BBD-RSM) Test

In this paper, BBD-RSM is used to systematically study activated lithium slag mass fraction, the sodium silicate dosage and the water–solid ratio of three key factors and the interaction between the two factors on the composite cementitious materials, such as fluidity, water evolution rate, gelation time and compressive strength, and finally to obtain the optimal ratio between the influencing factors. The specific steps are as follows:

(1) Set activated lithium slag mass fraction, sodium silicate dosage and water–solid ratio as independent variables, which are, respectively, denoted as x_1 , x_2 and x_3 . According to engineering practical experience and related research results [35], this paper sets the levels of x_1 as 5%, 10% and 15%, x_2 as 6%, 8% and 10%, and x_3 as 0.6:1, 0.8:1 and 1:1. These indexes directly reflect cementitious material's engineering performance. Therefore, it is important to optimize them [34,35]. The water–solid ratio is defined as the ratio of the weight of the free water contained in the cementing material to the total weight of cement and lithium slag powder.

(2) To comprehensively reflect the performance characteristics and grouting effect of cementitious materials and optimize the ratio of cementitious materials, fluidity Y_1 , gelation time Y_2 , water evolution rate Y_3 , 3d compressive strength Y_4 , and 28d compressive strength Y_5 of composite cementitious materials were selected as the response values, and these indexes have a significant influence in the practice of grouting engineering [34,39].

(3) According to the selected factors and levels, BBD-RSM was used to design the experimental configurations of three factors, five levels, and three center points, and the coding of independent variables and the level design are shown in Table 4.

Table 4. Box–Behnken design and response surface method (BBD-RSM) factor coding and level.

Independent Variable Factor	Code Level		
	−1 (Low Level)	0 (Center Level)	1 (High Level)
$x_1/\%$	5	10	15
$x_2/\%$	6	8	10
x_3	0.6:1	0.8:1	1.0:1

Taking the center level in Table 4 as the base group, the level coded values are calculated according to Equation (1):

$$X_i = (x_i - x_0)/\Delta x \quad (1)$$

In the formula: X_i is the coded value of the independent variable x_i . x_0 is the value of the independent variable x_i at the center level. Δx is the step difference between the independent variables.

According to Table 4, 17 groups of experimental schemes were designed as shown in Table 5, and the experimental errors were reduced by setting up multiple repetitive experimental groups (Numbered from 9 to 13).

Table 5. Box–Behnken design and response surface method (BBD-RSM) proportioning design scheme.

Group	1	2	3	4	5	6	7	8	9
$x_1/\%$	−1 (5%)	−1 (5%)	−1 (5%)	−1 (5%)	0 (10%)	0 (10%)	0 (10%)	0 (10%)	0 (10%)
$x_2/\%$	−1 (6%)	1 (10%)	0 (8%)	0 (10%)	−1 (6%)	1 (10%)	−1 (6%)	1 (10%)	0 (8%)
x_3	0 (0.8:1)	0 (0.8:1)	−1 (0.6:1)	1 (1:1)	−1 (0.6:1)	−1 (0.6:1)	1 (1:1)	1 (1:1)	0 (0.8:1)
Group	10	11	12	13	14	15	16	17	
$x_1/\%$	0 (10%)	0 (10%)	0 (10%)	0 (10%)	1 (15%)	1 (15%)	1 (15%)	1 (15%)	
$x_2/\%$	0 (8%)	0 (8%)	0 (8%)	0 (8%)	−1 (6%)	1 (10%)	0 (8%)	0 (8%)	
x_3	0 (0.8:1)	0 (0.8:1)	0 (0.8:1)	0 (0.8:1)	0 (0.8:1)	0 (0.8:1)	−1 (0.6:1)	1 (1:1)	

(4) Prepare composite cement-based grouting materials according to the test program in Table 5, and determine the flow rate by “inverted cone method” and the setting time by “inverted cup method” in accordance with the conventional experimental methods. The water evolution rate was determined by measuring cylinder method, and the uniaxial compressive strength test was carried out for 3d and 28d according to “Test Method for Basic Properties of Ordinary Portland Cement Mortar” JGJ/T70-2009” [40].

2.2.3. Optimal Proportion Verification Test

To verify the reasonableness of optimal proportioning, in this test, grouted consolidated bodies of activation lithium-slag-cement-based cementitious materials (Abbreviations, *ALS*) under optimal proportioning is used as test group, and grouted consolidated bodies of ordinary Portland cement cementitious materials (Abbreviations, *OPC*) is used as control group, and tests of uniaxial compressive strength, modulus of elasticity, and split tensile strength are carried out on their consolidated bodies, respectively. All tests involved are carried out with reference to the Standard for Test Methods of Physical and Mechanical Properties of Concrete (GB/T50081-2019) [41]. The object of grouting reinforcement is selected as coal gangue, a common associated solid waste in coal mining process.

To reduce the error of indoor test, and to realize the aggregate particle size used in indoor test matched with the particle size of crushed gangue in engineering field, this test configured the crushed gangue pile with the particle size fractal dimension D of 2.5 [35,39]. The crushed aggregate mass in each particle size interval, as shown in Figure 4a. The fractal curves of aggregate particles are shown in Figure 4b. Eq. M_i is aggregate particles mass in $R_i \sim R_{\min}$ particle size interval; M_0 is the total mass of aggregate particles in the $R_{\min} \sim R_{\max}$ particle size interval; R_i is aggregate particles mass with particle sizes not larger than i ; $R_{\max}$ is aggregate mass with the largest particle size.

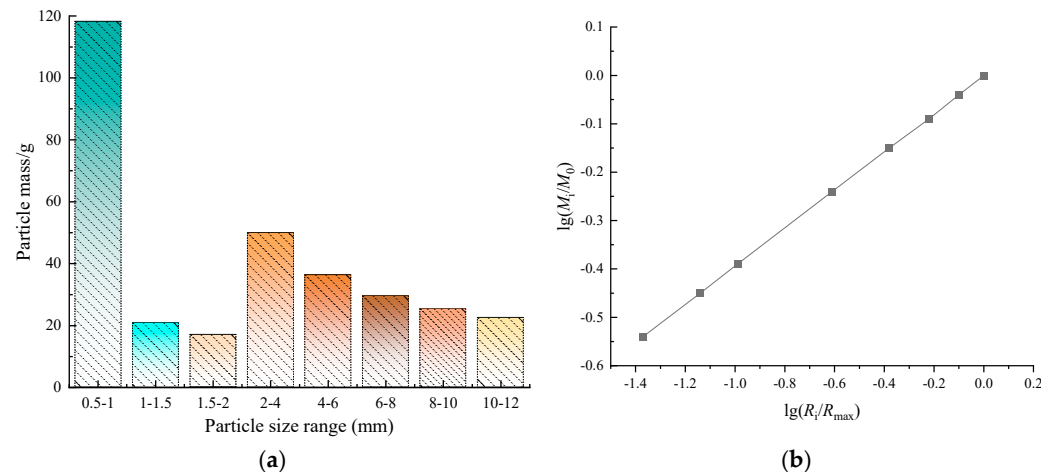


Figure 4. Particle size distribution of coal gangue aggregate. (a) Aggregate particle–mass ratio of each particle size range; (b) Coal gangue aggregate particle fractal curve.

It can be seen in Figure 4b that the particle–mass ratio within each particle size interval obeys the fractal dimension gradation curve, which meets the uniform description of aggregate particle size distribution [39].

The performance of grouting consolidated body is closely related to its internal structure [23,24]. Therefore, in this study, scanning electron microscope (SEM) test was used to observe the microstructural changes and further explore the mechanism of its performance changes. The instrument used in this test is NovaNanoSEM450 field emission scanning electron microscope (FEI company, Hillsboro, OR, USA), as shown in Figure 5.



Figure 5. NovaNanoSEM450 field emission scanning electron microscope.

2.3. Summary

Figure 6 shows the test flowchart of this chapter. This chapter identifies the raw materials required for the preparation of the composite cementitious materials and describes the tests to be carried out: the lithium slag thermal activation test, which aims to improve the lithium slag volcanic ash activity, the *BBD-RSM* test, which determines the optimal proportioning of the composite cementitious materials, and the validation test under the optimal proportioning. In addition, this chapter presents the correlation between the Box–Behnken Design and response surface methodology (*BBD-RSM*) tests, and the proportion optimization and its mechanism. It is the basic work for the subsequent tests.

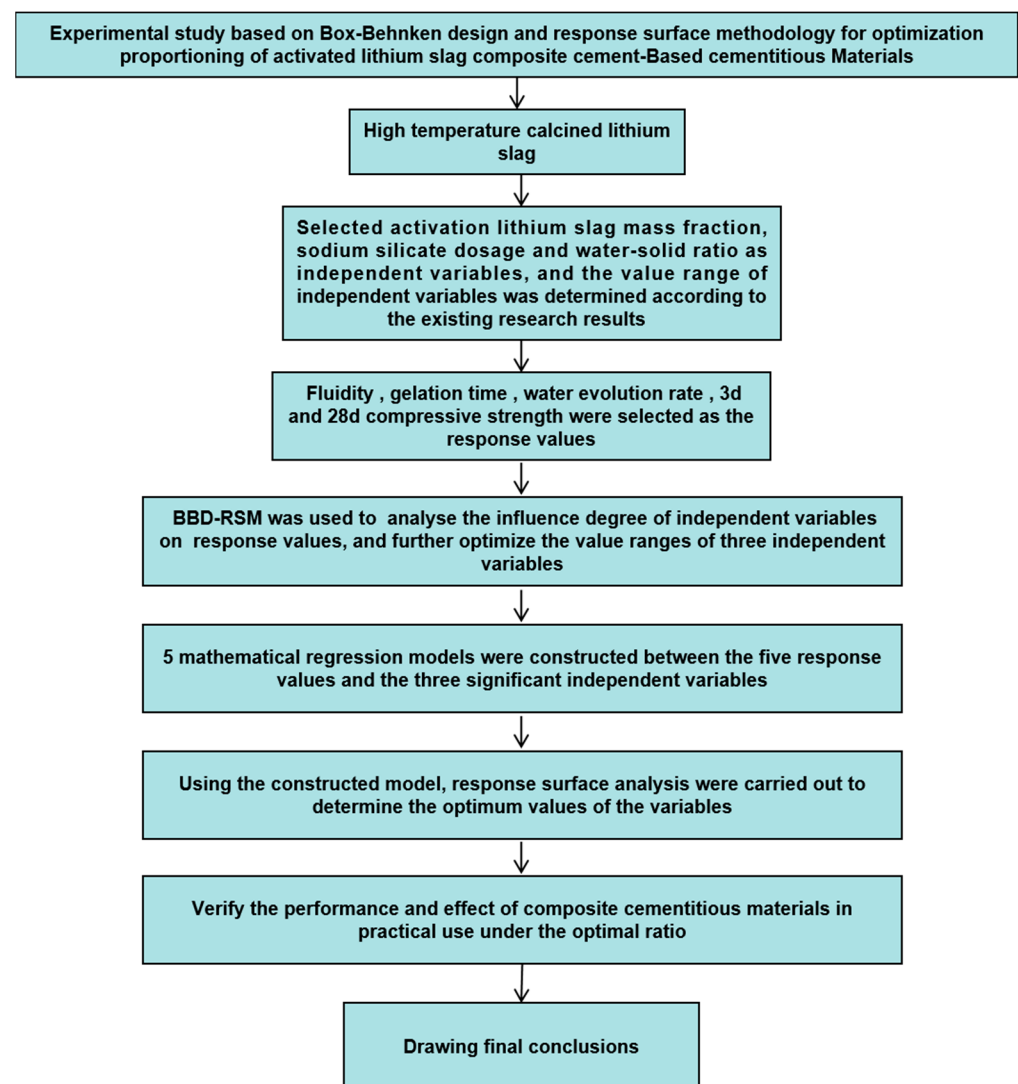


Figure 6. The test flowchart of this chapter.

3. Results and Discussion

3.1. Effect of High-Temperature Calcination on the Activity of Lithium Slag

Figure 7 shows XRD patterns of lithium slag at different calcination temperatures. Figure 7a shows that the diffraction peak intensities of kaolinite, sodalite, quartz and alunite in the lithium slag reach the highest at the calcination temperature of 700 °C, and the active components Al_2O_3 and SiO_2 are the most abundant. After the calcination temperature is higher than 700 °C, amorphous biotite kaolinite generates mullite, which leads to the increase in crystallinity, the dissolution of alunite, and the decrease in active components. Figure 7b also shows that the activity index of lithium slag calcined at 700 °C is the largest. It indicates that the optimal calcination temperature of lithium slag is 700 °C. Therefore, in this study, the lithium slag calcined at 700 °C was selected as an incorporated to replace part of the cement.

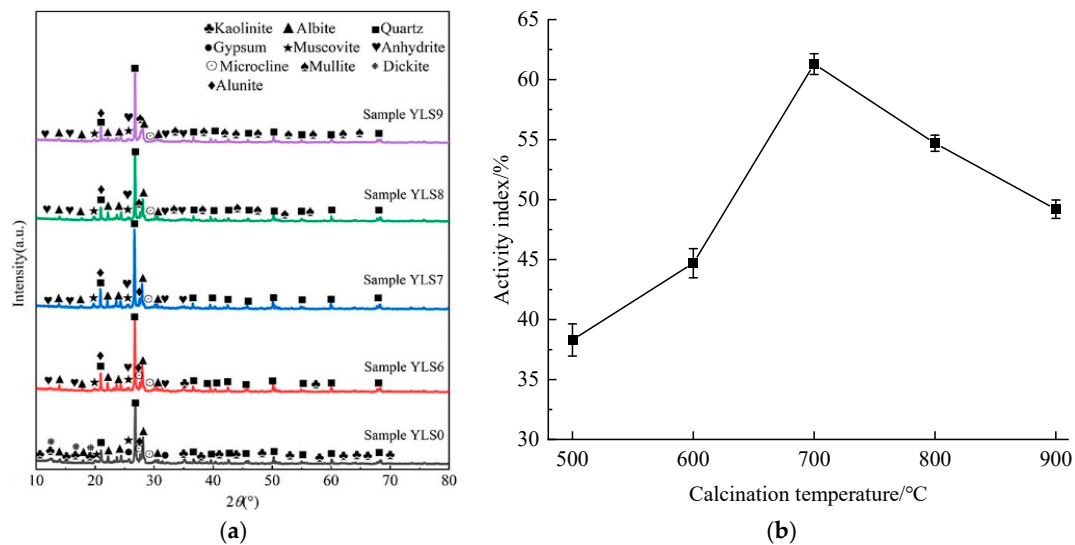


Figure 7. XRD patterns and activity index of lithium slag at different calcination temperatures. (a) XRD patterns; (b) activity index.

3.2. Effect of Independent Variables and Their Interaction Terms on Each Response Value

3.2.1. Effects of the Respective Variables on Each Response Value

Test results of 5 response values of lithium slag composite cementitious materials at 17 groups different ratios designed in Table 5 are shown in Table 6.

Table 6. Design and results of response surface test.

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Y_1/mm	237.6	256.5	236	276.5	223	230	234.5	235	235	234	235	236	234.5	179	186	194.5	220.5
Y_2/s	76.8	76.9	61.3	63.7	83.1	89.8	85.3	99.5	90.8	91.2	89.8	90.3	91.7	130.9	140.6	127.6	136.4
$Y_3/\%$	1.7	1.5	1.4	1.8	1	0.9	1.3	1.2	1.1	1.1	1.1	1.1	1.1	0.6	0.6	0.8	0.3
Y_4/MPa	6.6	6	11.6	3.3	10.9	12.2	3.3	2.6	5.7	6	6	5.8	6.1	4.7	4.5	12.1	2.4
Y_5/MPa	16.3	13.7	21.4	12	22.1	20.1	8.3	6.4	17.4	17.1	17.4	17.4	17.5	11.3	9.9	20.9	4.6

The 17 groups test results in Table 4 were analyzed and processed using *RDM-BBD*, and the least squares fitted mathematical regression models between 5 response values and the independent variables activated lithium slag mass fraction x_1 , sodium silicate dosage x_2 , and water–solid ratio x_3 were respectively, constructed using the quadratic model as shown in Equations (2)–(6).

$$Y_1 = 234.90 - 28.33x_1 + 4.18x_2 + 10.38x_3 - 2.97x_1x_2 - 3.63x_1x_3 - 1.63x_2x_3 - 9.44x_1^2 - 10.69x_2^2 + 6.41x_3^2 \quad (2)$$

$$Y_2 = 90.77 + 32.12x_1 + 3.85x_2 + 2.87x_3 + 2.41x_1x_2 + 1.59x_1x_3 + 1.88x_2x_3 + 11.71x_1^2 + 3.84x_2^2 - 5.20x_3^2 \quad (3)$$

$$Y_3 = 1.10 - 0.51x_1 - 0.05x_2 + 0.063x_3 + 0.023x_1x_2 - 0.21x_1x_3 + 0.003x_2x_3 - 5.39x_1^2 - 6.54x_2^2 + 4.56x_3^2 \quad (4)$$

$$Y_4 = 5.92 - 0.48x_1 - 0.014x_2 - 4.39x_3 + 0.10x_1x_2 - 0.37x_1x_3 - 0.49x_2x_3 - 0.19x_1^2 - 0.30x_2^2 + 1.62x_3^2 \quad (5)$$

$$Y_5 = 17.35 - 2.07x_1 - x_2 - 6.65x_3 + 0.32x_1x_2 - 1.72x_1x_3 + 0.028x_2x_3 - 1.03x_1^2 - 2.52x_2^2 - 0.602x_3^2 \quad (6)$$

To ensure the reliability of the above five mathematical models, their reliability indexes were verified separately and the results are shown in Table 7.

Table 7. Validation results of the mathematical regression model.

Reliability Index	Fluidity	Gelation Time	Water Evolution Rate	3d Compressive Strength	28d Compressive Strength
R^2	0.9566	0.9921	0.9674	0.9904	0.9988
R^2_{adj}	0.9779	0.9819	0.9478	0.9781	0.9974
R^2_{pre}	0.9489	0.9766	0.9376	0.9561	0.9843
SNR	13.97	32.45	25.35	27.10	83.42
CV	3.63	3.39	7.01	7.48	1.85

The coefficient of determination R^2 indicates the influence degree of independent variables taken on the response values. The larger R^2 , the higher influence is indicated. R^2 in Table 7 are all greater than 0.95, indicating that the three independent variables have a high influence degree on each response value.

The correction correlation coefficient R^2_{adj} , indicates the degree to which response value changes can be analyzed by the model. In Table 7, R^2_{adj} are all greater than 0.95, indicating that the effect of the independent variables on each response value can be analyzed by this numerical model.

The prediction correlation coefficient, R^2_{pre} , indicates the prediction reliability of the model. The R^2_{pre} in Table 7 are all greater than 0.90, and are closer to 1, which shows that the predictive reliability of the 5 constructed response value models is high [34,35].

The signal-to-noise ratio (SNR) indicates the reasonableness of the established model. The signal-to-noise ratios in Table 7 are all much greater than 4, indicating that the model constructed for the response values can predict the changes in the response values well [39].

The coefficient of variation (CV) indicates how well the regression model fits the sample data points. When it is under 10%, it indicates that the model's predictions are highly aligned with the observed test data [34,35,39]. The CVs in Table 7 are all less than 10%, indicating that the regression model equations fit the test data points well, the error is small, and stability is high [39,42].

To investigate the significance of independent variables and the effect of the interaction terms of independent variables on each response value, this section performs significance tests and ANOVA on Equations (2)–(6). F values are usually used to compare the significance or not of the differences between groups of factors, and the larger the value, the stronger the significance of the model, which indicates the higher simulation accuracy [43]. p values can test the significance of experimental data that are not related to the model [33,44], and in general, the larger F value is larger, p value is smaller, and when p value is <0.05 , it means that the effect of the independent variable on the response value is significant. Conversely, it is not significant.

According to the p value in Table 7, the significant independent variables of Y_1 are x_1 and x_3 , and the significant interaction terms are x_1x_2 and x_1x_3 . The significant independent variables of Y_2 are x_1 , x_2 , x_3 and the significant interaction terms are x_1x_2 , x_1x_3 . The significant independent variables of Y_3 are x_1 and the significant interaction terms are x_1x_2 , x_1x_3 . The significant independent variables of Y_4 are x_1 , x_3 and the significant interaction terms are x_1x_3 , x_2x_3 . The significant independent variables of Y_5 are x_1 , x_2 , x_3 and the significant interaction terms are x_1x_2 , x_1x_3 , x_2x_3 .

Based on the above analyzed results, the effects of three independent variables on five performance indexes of the composite cementitious materials were further predicted according to Equations (2)–(6), and the results are shown in Figure 8.

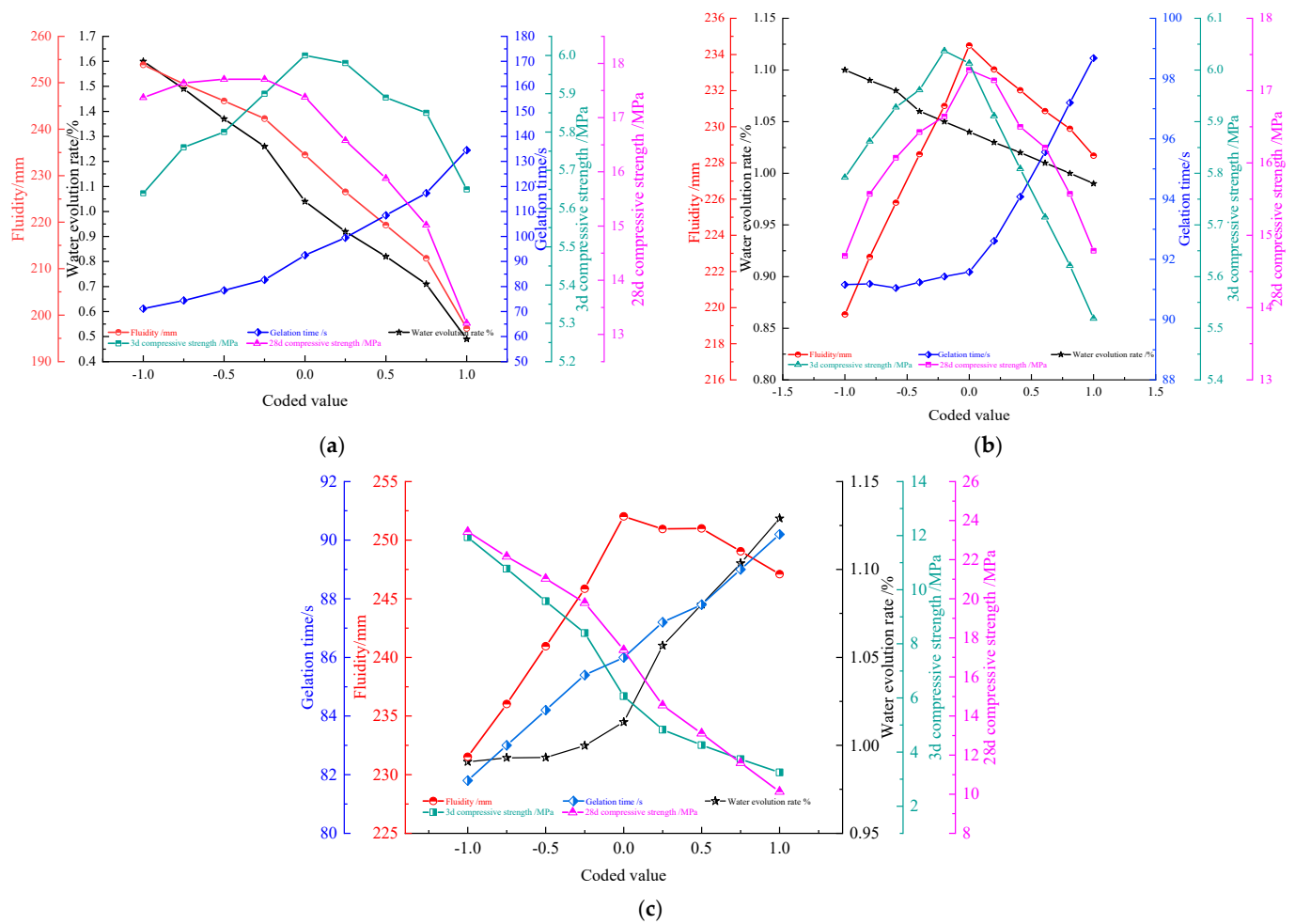


Figure 8. Influence of 3 independent variables on 5 response values. (a) The influence of independent variable lithium slag dosage on 5 response values; (b) The influence of independent variable sodium silicate dosage on 5 response values; (c) The influence of water–solid ratio of independent variable on 5 response values.

Figure 8a–c, respectively, shows the effect of activated lithium slag mass fraction x_1 , sodium silicate dosage x_2 , and water–solid ratio x_3 on fluidity Y_1 , gelation time Y_2 , water evolution rate Y_3 , 3d compressive strength Y_4 and 28d compressive strength Y_5 .

From Figure 8a, the increase in activated lithium slag mass fraction x_1 will cause the fluidity Y_1 and water evolution rate Y_3 to be greatly reduced, while causing the gelation time Y_2 to be greatly increased. As activated lithium slag mass fraction x_1 increases to about 8%, 3d compressive strength, Y_4 , and 28d compressive strength, Y_5 , show a significant increase; as x_1 continues to increase, Y_4 and Y_5 begin to decrease significantly. It was verified that the activated lithium slag mass fraction x_1 had a significant effect on all five response values, which is consistent with the analytical results in Table 8.

The reason is that the increase in activated lithium slag mass fraction causes the increase in internal surface area of the particles in cementitious materials, and free water is largely adsorbed, resulting in a decrease in fluidity and water evolution rate. At the same time, a smaller mass fraction of activated lithium slag will make lithium slag's hydration reaction untimely, and internal active ingredient molecules $Al-O$ and $Si-O$ require higher fracture energy, which leads to prolonged chemical reaction time of SiO_3^{2-} or SiO_4^{4-} and AlO_2^- with hydration product $C-H$. The compressive strength of the cementitious material is the greatest at the middle-coded value because the incorporation of activated lithium slag in the early stage accelerated the production of $C-H$ gel. With the continued incorporation of activated lithium slag, the OH^- content provided by sodium silicate is relatively reduced,

resulting in an inadequate hydration reaction of the lithium slag and a relative reduction in content of the flocculated gel, which ultimately leads to reduced compressive strength.

Table 8. Analysis of variance results of regression model.

Response Value	Value	$x_1/\%$	$x_2/\%$	x_3	x_1x_2	x_1x_3	x_2x_3	x_1^2	x_2^2	x_3^2
Y_1	F	93.2400	2.0300	12.5100	0.5143	0.7636	0.1534	5.45	6.99	2.52
	P	<0.0001	0.1977	0.0095	0.0465	0.7069	0.0112	0.0523	0.0333	0.1568
Y_2	F	782.930	11.2200	6.2700	2.2000	0.9535	1.3400	54.74	5.90	10.80
	P	<0.0001	0.0923	0.0508	0.0116	0.0614	0.045	0.0001	0.0455	0.0134
Y_3	F	267.560	2.5700	4.0200	0.2604	22.150	0.0032	6.7341	5.4341	3.514
	P	<0.0001	0.1399	0.0728	0.0209	0.9559	0.0008	0.0002	0.0437	0.1143
Y_4	F	8.0000	0.0065	661.70	0.1718	2.2900	4.1700	0.6442	1.59	47.38
	P	0.0255	0.9380	<0.0001	0.0509	0.0471	0.0056	0.4486	0.2481	0.0002
Y_5	F	452.18	104.61	4664.600	5.4000	156.36	0.0399	228.38	353.40	20.07
	P	<0.0001	<0.0001	<0.0001	0.0532	<0.0001	0.0474	<0.0001	<0.0001	0.0029

From Figure 8b, with x_2 increasing, Y_2 of the composite cementitious material shows a significant increasing trend, and Y_1 , Y_4 , and Y_5 all increase first and then decrease. Among them, Y_1 and Y_4 have an overall insignificant magnitude change, while Y_5 increases or decreases very significantly. Y_3 decreases slowly with x_2 increase. This is consistent with the analysis in Table 8.

The reason is, x_2 increase caused the water content to increase, diluting the grout slurry and leading to Y_1 of cementitious material to increase. When x_2 was not in excess, the free water required for the hydration reaction of cement and lithium slag was sufficient, so Y_1 , Y_4 , and Y_5 also increased. With x_2 increasing continuously to the middle-coded value, the pores are filled by a large amount of free water, and the excessive OH^- ions may interfere the orderly arrangement and polymerization of the molecules of the cementitious constituents, which makes difficult to form the cementation structure, which prolongs the cementation time and leads to a decrease in the compressive strength and water evolution rate.

From Figure 8c, the change rates of Y_1 , Y_2 , Y_3 , Y_4 , and Y_5 are all approximately linear, indicating that x_3 increase has a significant effect on each response value. The reason is, x_3 increase improves the free water content, diluting the slurry, and water evolution rate naturally increases. At the same time, free water fills the voids and the cementation production slows down, making Y_2 prolonged, Y_1 larger, and the formation of gel components difficult, leading to a decrease in Y_4 and Y_5 . Therefore, the water–solid ratio is a key independent variable and must be scientifically and reasonably optimized to obtain the ideal material properties.

3.2.2. Effect of Interaction Term of Independent Variables on Each Response Value

According to Equations (2)–(6), Design-Expert Software (DX13) is used to construct 3D response surfaces, showing the influence of independent variables interaction terms on each response value.

According to p -values in Table 8, it can be seen that the interaction terms x_1x_2 and x_1x_3 are significant influences on the fluidity Y_1 , and according to p -values in Table 8, it can be seen that the interaction terms x_1x_2 and x_1x_3 are significant influences on the fluidity Y_1 , and 3D response surfaces are shown in Figure 9, which are parabolic surfaces with openings sloping downward to the ridges.

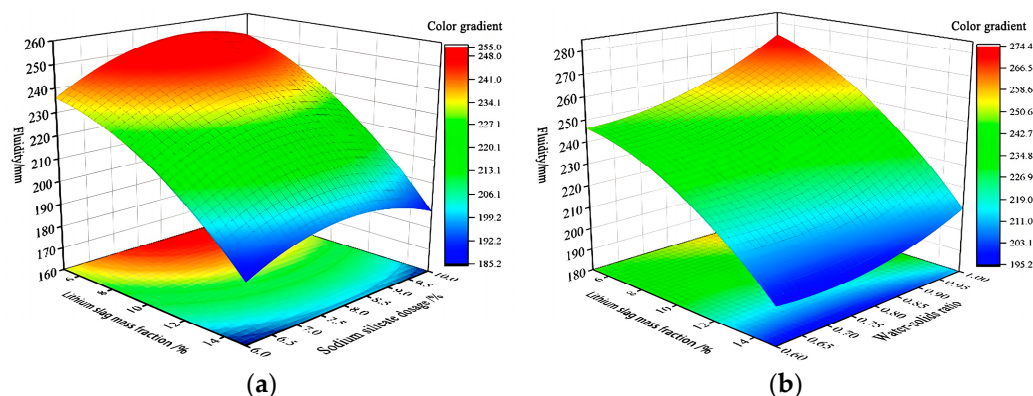


Figure 9. Fluidity 3D response surfaces diagram. (a) 3D response surfaces diagram for the influence of the interaction term x_1x_2 on fluidity Y_1 ; (b) 3D response surfaces diagram for the influence of the interaction term x_1x_3 on fluidity Y_1 .

Figure 9a shows fixing activation lithium slag mass fraction x_1 , fluidity Y_1 minimum at sodium silicate dosage x_2 of 6%. Fixed sodium silicate dosage x_2 , fluidity Y_1 maximum is at activation lithium slag mass fraction x_1 of 5%, and minimum is at activation lithium slag mass fraction x_1 of 10%. According to the engineering requirements of the fluidity Y_1 [19,20], activation lithium slag mass fraction x_1 should be taken in (7–8%), i.e., approximately the middle value of its range (5–10%). Figure 9b shows that by fixing water–solid ratio x_3 , fluidity Y_1 maximum occurs in 8–9% of sodium silicate dosage x_2 .

In summary, activation lithium slag mass fraction x_1 takes (7–8%), sodium silicate dosage x_2 is 8–9%, and water–solid ratio x_3 is 0.6:1; the fluidity Y_1 is more in line with the engineering requirements.

Three-dimensional response surfaces of gelation time Y_2 are shown in Figure 10, which are all parabolic surfaces with openings upward or downward to the ridges, proving that x_1x_2 and x_1x_3 have a significant effect on gelation time Y_2 . This is consistent with the analysis conclusion of p -values in Table 8.

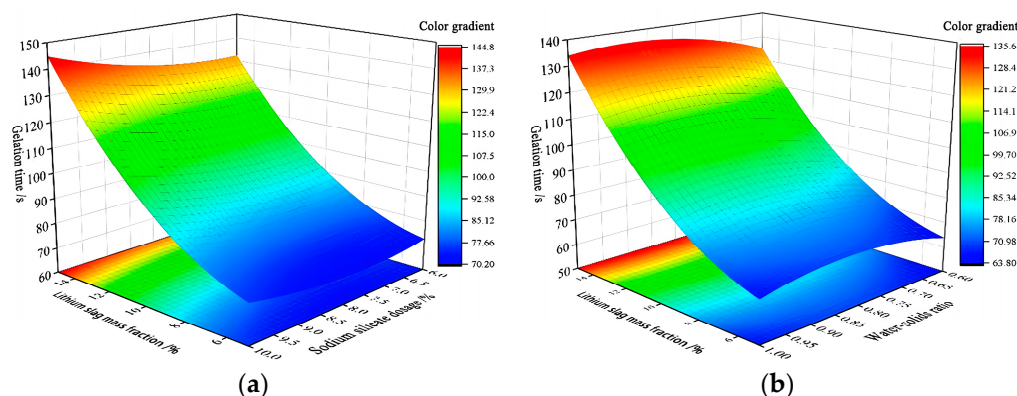


Figure 10. Gelation time response surfaces diagram. (a) 3D response surfaces diagram for the influence of the interaction term x_1x_2 on gelation time Y_2 ; (b) 3D response surfaces diagram for the influence of the interaction term x_1x_3 on gelation time Y_2 .

Figure 10a shows that fixing sodium silicate dosage x_2 , gelation time Y_2 is the longest when activated lithium slag mass fraction x_1 is 15%, and the shortest when it is 5%. When activated lithium slag mass fraction x_1 exceeds 10%, gelation time Y_2 will be too long, which will reduce the early strength of the cementitious material, so the optimal value of activated lithium slag mass fraction x_1 occurs in the range of 5–10%. With fixed activated lithium slag mass fraction x_1 , gelation time Y_2 is shortest when sodium silicate dosage x_2 is about 8–9%. Figure 10b shows that fixing sodium silicate dosage x_2 , gelation time Y_2 is the longest when water–solid ratio x_3 of 0.6:1 or 0.8:1. Fixing water–solid ratio x_3 , gelation time

Y_2 is the longest when sodium silicate dosage x_2 of 10%, and the shortest when it is 6%. In summary, when the activated lithium slag mass fraction x_1 takes (7–8%), sodium silicate dosage x_2 is 8–9%, and water–solid ratio x_3 is 0.6:1, gelation time of composite cementitious material will be more reasonable [31,33].

Three-dimensional response surfaces of water evolution rate Y_3 are shown in Figure 11, which are all parabolic surfaces with openings upward or downward to the ridges, proving that x_1x_2 and x_1x_3 have a significant effect on water evolution rate Y_3 . This is consistent with the analysis conclusion of p -values in Table 8.

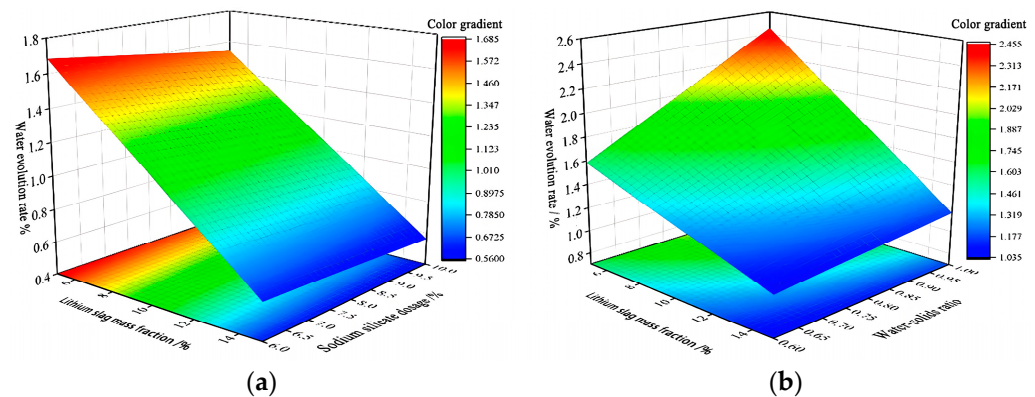


Figure 11. Water evolution rate response surfaces diagram. (a) 3D response surfaces diagram for the influence of interaction term x_1x_2 on water evolution rate Y_3 ; (b) 3D response surfaces diagram for the influence of interaction term x_1x_3 on water evolution rate Y_3 .

Figure 11a shows that fixing sodium silicate dosage x_2 and activated lithium slag mass fraction x_1 of 6%, the water evolution rate Y_3 is maximum; fixing activated lithium slag mass fraction x_1 and sodium silicate dosage x_2 has almost no effect on water evolution rate Y_3 . Figure 11b shows that fixing sodium silicate dosage x_2 , water evolution rate increases slowly with the increase in water–solid ratio x_3 ; sodium silicate dosage x_2 is 8–9%, and water evolution rate Y_3 maximum occurs when water–solid ratio x_3 is 0.6:1.

In summary, the water evolution rate Y_3 is more in line with the engineering requirements, when activated lithium slag mass fraction x_1 is in the range of 7–8%, sodium silicate dosage x_2 is 8–9%, and water–solid ratio x_3 is 0.6:1 [11,16].

Three-dimensional response surfaces of 3d compressive strength Y_4 is shown in Figure 12, which are all parabolic surfaces with openings upward to the ridges, proving that x_1x_3 and x_2x_3 have a significant effect on 3d compressive strength Y_4 . This is consistent with the analysis conclusion of p -values in Table 8.

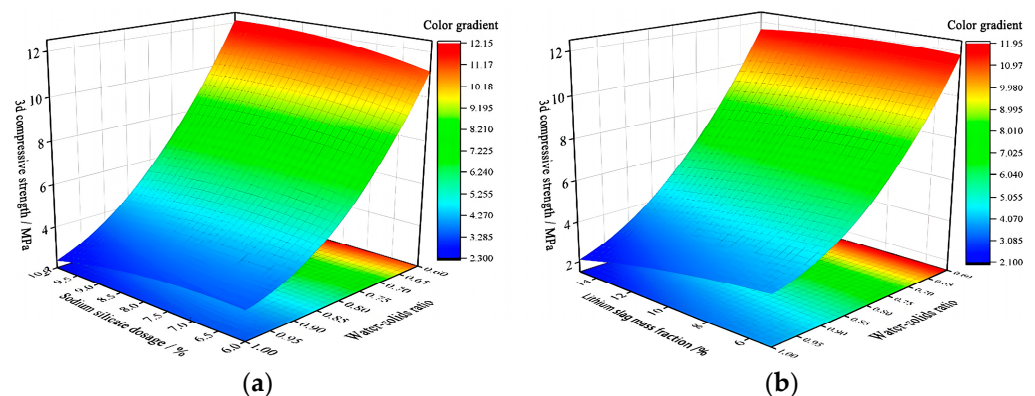


Figure 12. 3d compressive strength Y_4 response surfaces diagram. (a) 3D response surfaces diagram for the influence of interaction term x_1x_3 on 3d compressive strength Y_4 ; (b) 3D response surfaces diagram for the influence of interaction term x_2x_3 on 3d compressive strength Y_4 .

Figure 12a shows that fixing water–solid ratio x_3 , 3d compressive strength firstly increases and then decreases with activated lithium slag mass fraction x_1 increasing, and reaches the maximum at around 7%. Fixed activated lithium slag mass fraction x_1 , with the increase in water–solid ratio x_3 , 3d compressive strength is decreasing. Figure 12b shows that fixing the water–solid ratio x_3 , the 3d compressive strength Y_4 increases with the increase in sodium silicate dosage x_2 . Fixed water–solid ratio x_3 , 3d compressive strength reaches its maximum at 8–9% of sodium silicate dosage x_2 .

In summary, when activated lithium slag mass fraction x_1 is the middle value of (5–10%), sodium silicate dosage x_2 is at 8–9%, and water–solid ratio x_3 is 0.6:1, the 3d compressive strength Y_4 this maximum.

Three-dimensional response surfaces of 28d compressive strength Y_5 are shown in Figure 13, which are all parabolic surfaces with openings upward or downward to the ridges, proving that x_1x_3 and x_2x_3 have a significant effect on 28d compressive strength Y_5 . This is consistent with the analysis conclusion of p -values in Table 8.

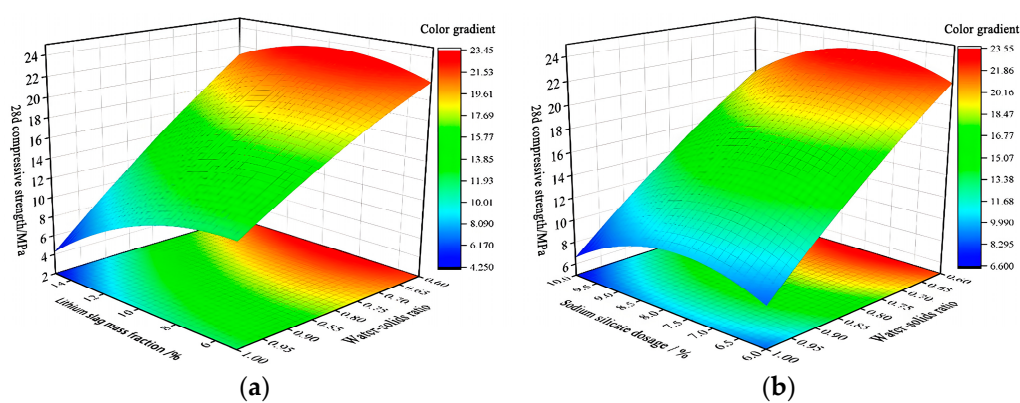


Figure 13. 28d compressive strength Y_5 response surfaces diagram. (a) 3D response surfaces diagram for the influence of interaction term on 28d compressive strength Y_5 ; (b) 3D response surfaces diagram for the influence of interaction term on 28d compressive strength Y_5 .

Figure 13a shows that by fixing water–solid ratio x_3 , 28d compressive strength Y_5 is maximized at about the middle of its range where activated lithium slag mass fraction x_1 is (5–10%). Fixing activated lithium slag mass fraction x_1 , 28d compressive strength Y_5 is maximized at a water–solid ratio x_3 of 0.6:1. Figure 13b shows that fixing sodium silicate dosage x_2 , 28d compressive strength Y_5 maximum occurs at a water–solid ratio x_3 of 0.6:1. Fixing the water–solid ratio x_3 , sodium silicate dosage x_2 in the range of 8% to 9% maximizes the 28d compressive strength.

In summary, 28d compressive strength Y_5 is maximized when water–solid ratio x_3 is taken as the middle value of (5–10%), sodium silicate dosage x_2 is 8–9% and water–solid ratio x_3 is 0.6:1.

This section focuses on identifying the key independent variables and their interaction terms that affect the performance indexes of the cementitious materials. Parametric conditions are provided for the analysis of subsequent work

3.3. Response Surface Optimal Proportioning Design

According to the effect results of activated lithium slag mass fraction x_1 , sodium silicate dosage x_2 and water–solid ratio x_3 on each response value of the composite cementitious material, BBD-RSM was used to regression fit each response value, calculate the optimal parameter values of the numerical regression model, and optimize the multi-parameter and multi-response values. Among them, the optimization range and criteria are shown in Table 9. The optimum ratio was finally obtained to be activated lithium slag mass fraction x_1 7.32%, sodium silicate dosage x_2 of 8.81% and water–solid ratio x_3 0.6:1. This result was, respectively, substituted into the mathematical model equations of each response value in Equations (2)–(6), and the results were that fluidity is 235.69 mm, gelation time is 73.54 s,

water evolution rate is 1.123%, and 3d and 28d compressive strengths, respectively, are 11.54 MPa and 22.9 MPa.

Table 9. Response optimization standards.

		Optimization Objective	Low Level	High Level	Importance
Independent variable	x_1 /%	Range	5	15	+++
	x_2 /%	Range	6	10	+++
	x_3	Range	0.6	1	+++
Response value	Y_1 /mm	Maximum	179	276.5	+++
	Y_2 /s	Minimum	61.33	140.66	+++
	Y_3 /%	Minimum	0.33	1.79	+++
	Y_4 /MPa	Maximum	2.4	12.2	+++
	Y_5 /MPa	Maximum	4.59	22.1	+++

Note: ‘+++’ indicate ‘significant’.

3.4. Optimal Ratio Test Verification Results and Analysis

3.4.1. Mechanical Properties of Grouted Consolidated Body in Crushed Rock Body

Figure 14a shows mechanical properties of ALS and OPC. As can be seen from the figure, the compressive strength, elastic model and split tensile strength of ALS have been improved by 34.33%, 36.43% and 34.98%, respectively, compared with that of OPC.

Figure 14b shows all compressive and tensile stress-strain curves of ALS and OPC went through a compaction stage, elastic-plastic stage and damage stage. From the figure, it is obvious that compressive and tensile deformation of ALS is significantly improved, with the improvement values of 37.78% and 40%, respectively. Figure 14b shows all compressive and tensile stress-strain curves of ALS and OPC went through a compaction stage, elastic-plastic stage and damage stage. From the figure, it is obvious that compressive and tensile deformation of ALS is significantly improved, with the improvement values of 37.78% and 40%, respectively.

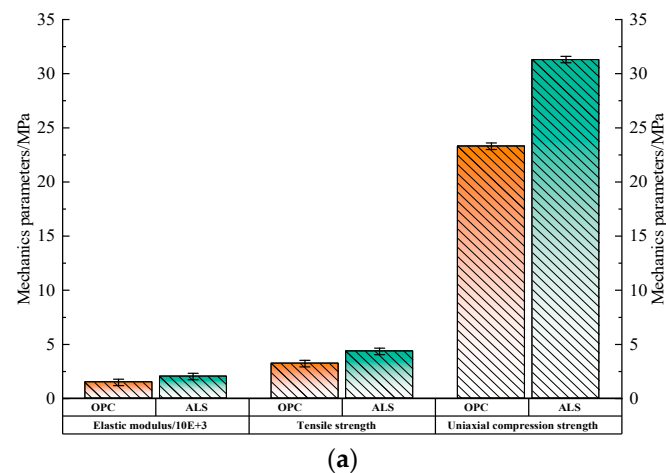


Figure 14. Cont.

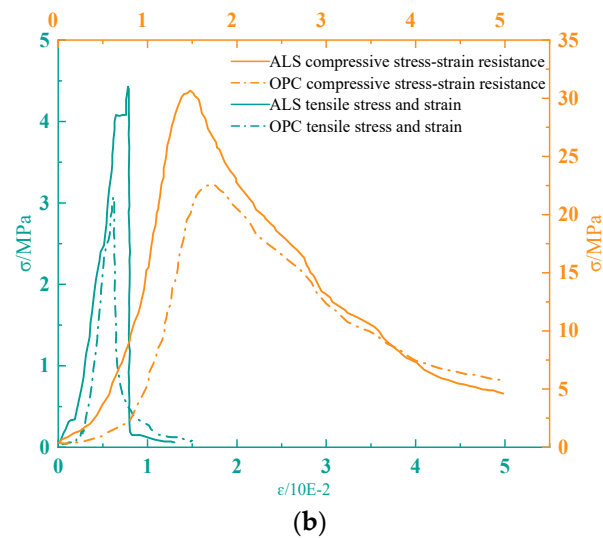


Figure 14. Comparison of mechanical properties of *ALS* and *OPC*. (a) Comparison of uniaxial compressive strength, splitting tensile strength and elastic modulus of *ALS* and *OPC*; (b) Comparison of stress-strain curves of *ALS* and *OPC*. Abbreviations in figure: *ALS*—grouted consolidated bodies of activated lithium slag composite cement-based cementitious materials; *OPC*—grouted consolidated bodies of ordinary Portland cement cementitious materials.

3.4.2. Comparison of Macroscopic Rupture Characteristics of Grouted Consolidated Bodies

Figure 15a shows damage morphology of *ALS* and *OPC* under uniaxial compression. The damage morphology of these two cementitious materials grouted consolidated bodies are basically same in uniaxial compression process, showing “/” type damage morphology. With axial load increasing, micro-cracks were produced in specimen surface, and skin gradually falls off. When axial load reaches the peak pressure, a large number of macro-cracks are rapidly produced internally in the specimen, and these cracks continue to extend and expand until run through, and finally cause damage to the specimen. However, the *ALS* specimen has fewer fine cracks on outer surface under the peak pressure, penetrating cracks are narrower, and the overall damage structure is more complete. The *OPC* specimen has fewer fine cracks, but penetrating cracks are wider and obvious. Therefore, the uniaxial compressive capacity of *ALS* specimens is relatively better.

Figure 15b shows *ALS* specimen splitting tensile damage morphology is relatively single, mainly for the “|” type, the specimen damage degree is low, and the gangue aggregate cemented denser. *OPC* specimen shows multiple penetrating cracks, the damage degree is larger, the internal gangue aggregate pulls off more serious, fracture surface is flatter, and most of the surface is ruptured in the gangue and cementitious materials cementation. Therefore, it is proved that *ALS* has stronger cementing force with gangue aggregate.

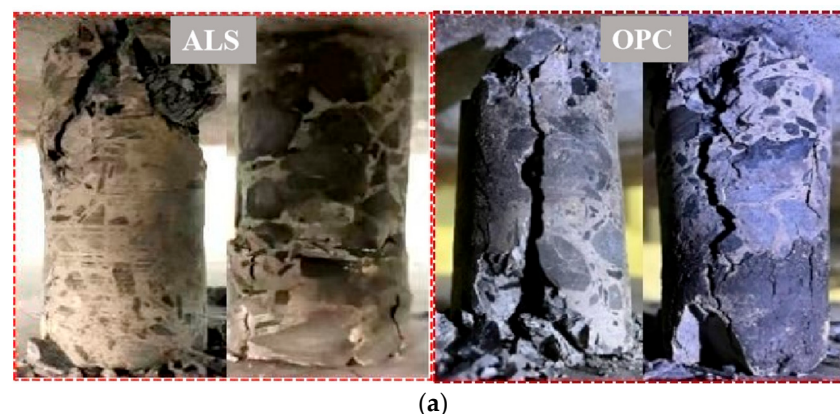


Figure 15. Cont.

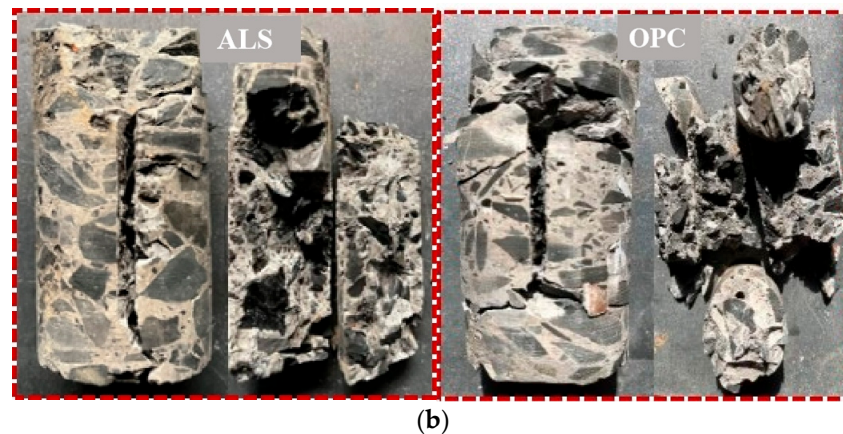


Figure 15. Damage morphology of *ALS* and *OPC*. (a) Compression damage pattern of grouted nodular body specimens of *ALS* and *OPC* under uniaxial compression; (b) Compressive damage patterns of grouted nodular body specimens from *ALS* and *OPC* under splitting tensile action. Abbreviations in figure: *ALS*—grouted consolidated bodies of activated lithium slag composite cement-based cementitious materials; *OPC*—grouted consolidated bodies of ordinary Portland cement cementitious materials.

3.4.3. Microstructure Characteristics of Grouting Consolidated Body

Figure 16 show the *SEM* images of *ALS* and *OPC* samples under uniaxial compression, respectively. It can be seen that the microstructural integrity of *ALS* specimens is higher than that of *OPC* specimens, and their internal structures are denser. It shows that activated lithium slag replaces part of the cement by the alkali excitation of water glass, which can improve the mechanical properties of the solidified body and make the slurry and aggregate denser, and also proves the scientificity of optimal ratios researched out in this paper.

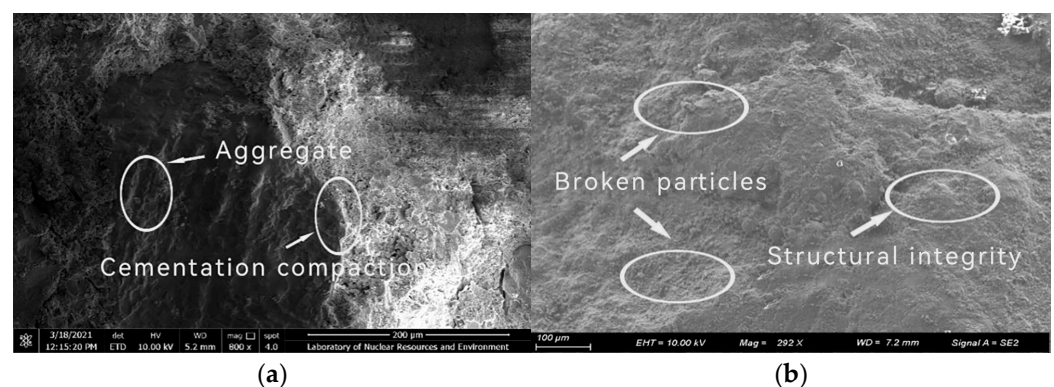


Figure 16. Micro-topography of samples under uniaxial compression. (a) *ALS* micro-topography of samples under uniaxial compression; (b) *OPC* micro-topography of samples under uniaxial compression.

3.5. Summary

This chapter determines that the optimal activation temperature of lithium slag is 700 °C. This result is consistent with literature [18,19]. *BBD-RSM* test determines the optimal ratio of lithium slag composite cementitious material as follows: activated lithium slag mass fraction 7.3%, sodium silicate dosage 8.8%, and the water–solid ratio 0.6:1. In addition, this chapter carries out the uniaxial compressive test, modulus of elasticity, splitting tensile strength, and *SEM* test, and verifies that the effect of lithium slag composite cementitious material on grouting reinforcement of crushed gangue is better than ordinary Portland cementitious material, which also verifies that the optimal ratio studied in this paper is scientific, thus supporting the research.

4. Conclusions

In this study, based on the BBD-RSM test, the ratio of activated lithium slag composite cement-based cementitious material was optimized and the best ratio was obtained. It is also verified that under this optimal ratio, the grouting reinforcement effect of activated lithium-slag-sodium silicate composite cement-based cementitious material on crushed coal gangue is superior to that of ordinary Portland-cement-based cementing materials. The specific contributions and conclusions are as follows:

(1) The optimal calcination temperature of lithium slag was determined to be 700 °C. At this calcination temperature, the content of active components Al_2O_3 and SiO_2 within lithium slag is the highest. This provides an important reference for improving activity of lithium slag volcanic ash.

(2) The regression mathematical models between active lithium slag mass fraction, water glass dosage and water–solid ratio and the mobility, water evolution rate, gelling time, 3d compressive strength and 28d compressive strength were established, and the accuracy of these regression models was verified. This provides important theoretical basis and reference direction for the ratio optimization of industrial-solid-waste-cement-based composite cementitious materials.

(3) The optimal ratio of lithium-slag-cement-based composite cementitious material was determined as 7.3% of active lithium slag mass fraction, 8.8% of water glass dosage, and water–solid ratio of 0.6:1. With this ratio, the fluidity of this cementitious material was 235.69 mm, gelation time was 73.54 s, water evolution rate was 1.123%, 3d and 28d compressive strengths, respectively, was 11.54 MPa and 22.9 MPa.

(4) The uniaxial compressive strength, modulus of elasticity, and tensile strength at break of activated lithium slag cementitious material solidified body were increased by 34.33%, 36.43%, and 34.98%, and the compressive deformation and tensile deformation were enhanced by 37.78% and 40%, respectively, relative to that of ordinary Portland cement. It is proved that the reinforcing effect of lithium slag composite cementitious material on crushed gangue is better than that of ordinary Portland cement. This finding provides a new type of high-performance cementitious material for underground engineering perimeter rock reinforcement.

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