

Article

Research on the Mechanical Properties and Micro-Evolution Characteristics of Coal Gangue-Based Composite Cementitious Materials

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Abstract

With the rapid development of industry, landfill and other environmental problems have arisen due to the coal mining and industrial solid waste generated during coal extraction and industrial production. In this study, coal gangue was utilized as the filling aggregate, along with industrial solid waste as the principal constituent, supplemented by cement, to develop a novel type of cementitious material and address environmental problems arising from the storage of solid waste. The impacts of sodium silicate, lime, and cement on the excitation characteristics and micro-evolution of steel slag–slag-based composite cementitious materials were investigated through experimental proportioning. The mineral composition, chemical composition, particle size distribution, microstructure, and hydration products of the filling materials were analyzed through XRD, XRF, a laser particle size analyzer, and SEM. The results show the following: (1) When the mass ratio of steel slag, slag, cement, sodium silicate, and lime is 30:38:15:2:15, the compressive strength of the Cemented Gangue Filling Body (CGFB) reaches the optimum level. At this juncture, the compressive strength of CGFB at 3 days is 2.16 MPa, and that at 28 days is 4.18 MPa. (2) Na_2SiO_3 and lime can activate the latent active substances within slag and steel slag, generating C-S-H gel and Aft through hydration reaction. (3) As the curing time escalates, the microstructure of the filling body becomes increasingly compact, and the porosity decreases from 10.5% to 3.8%. This study not only presents a new technical means for the resource treatment of solid waste such as coal gangue but also provides powerful support for the development and application of mine filling materials.

Keywords: coal gangue; composite activator; compressive strength; microstructure; hydration reaction mechanism



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1. Introduction

As a traditional energy source, coal plays an important role in industry and life. As new energy has not yet formed a sufficient substitution, the coal-based energy pattern cannot be changed in the short term [1]. From the perspective of global energy consumption, coal has the function of a ballast stone. In countries that have achieved carbon peaks, the

proportion of coal consumption has generally declined steadily, but it has remained above 20% for a long time, and coal-fired power generation is generally higher than 20% [2]. However, extensive mined-out areas have been formed during coal mining, which can lead to problems such as roadway roof collapse, underground water inrush, mining-induced seismicity, and surface subsidence [3]. According to incomplete statistics, China discharges about 795 million tons of coal gangue every year, causing $6.56 \times 10^8 \text{ m}^2$ of land damage, which is a key source of risk to mine safety and the ecological environment [4]. Controlling the accumulation of coal gangue and improving the utilization rate of coal gangue has become a key issue in the green and sustainable development of the coal industry. Therefore, the effective comprehensive utilization of coal gangue aggregate is imperative [5,6].

In order to solve the above problems, coal gangue filling technology has been widely employed in many coal mines. This technology can effectively control surface subsidence, improve recovery rates, and yield significant social and economic benefits [7–10]. The core purpose of filling technology in mining is to transport the filling materials to the underground goaf together to support the structure. Filling materials are generally composed of a binder, an aggregate, and water [11]. At present, the filling cost accounts for 20% of the total mining cost, and the cementitious material accounts for 75% of the filling cost, which seriously hinders the further application of this technology in coal mines [12]. Traditional cementitious materials are mainly based on Portland cement, which involves energy consumption during production. The cement industry is one of the largest sources of CO₂ emission, accounting for 5–8% of global anthropogenic carbon emissions [13,14]. In the context of the ‘dual carbon’ goal, cement prices and filling costs are expected to continue rising. Therefore, it is crucial to find alternative economical, green, and stable cementitious materials to replace cement.

In recent years, solid wastes such as steel slag [15], slag [16–18], desulfurization gypsum [19,20], fly ash [21,22], and construction waste powder have been widely used in the solidification process of engineering slurries [23]. Steel slag is a by-product of the steelmaking process. The annual amount of steel slag in the world is 150–250 million tons [24]. China is the world’s largest producer of steel slag. According to statistics, the annual output of steel slag in China exceeds 100 million tons, and its utilization rate is less than 30% [25]. Most steel slag is stored or landfilled, occupying valuable land resources and causing environmental pollution. Common chemical components in steel slag include SiO₂, Fe₂O₃, CaO, Al₂O₃, and MgO [26,27]. Blast furnace slag is a waste product from blast furnace smelting, which is rapidly cooled by cold water to form a sponge-like pumice. The material forms a unique glass-like structure through a high-temperature melting process. Its chemical composition is similar to that of Portland cement clinker and has potential reactivity. Therefore, it is an important raw material for preparing cementitious materials [28–30]. Gijbels Katrijn et al. [31] studied the role of phosphogypsum in alkali-activated abrasive blast furnace slag. The results showed that the incorporation of phosphogypsum accelerated the initial setting time and delayed the final setting time. At the same time, sodium hydroxide improves the compressive strength of the material and the development of the amorphous phase. Tian et al. [32] prepared a green road geopolymer as a grouting material by adding water glass as an activator and obtained satisfactory mechanical strength and initial fluidity. Liu et al. [33] used quicklime to regulate alkali-activated slag as a binder and analyzed its early hydration. Wang et al. [34] described the composition and structure of blast furnace slag and its early water. The above studies have discussed the feasibility of steel slag, slag, water glass, and lime in the preparation of cementitious materials, but most of them focus on the application of single solid waste, and there is a lack of research on the incorporation of aggregates. In addition, the research

on the preparation of cementitious materials by using a variety of solid wastes under the action of composite excitation materials is still insufficient.

In this paper, a new type of coal gangue filling cementitious material was prepared by using a chemical activator to activate the potential active substances in various solid wastes and supplemented by a small amount of cement, thus converting industrial solid waste materials into valuable cementitious raw materials. The sensitivity of different materials was analyzed by an orthogonal test. The degree of hydration reaction and product type were observed by scanning electron microscopy. The pore structure characteristics of microscopic images at different curing times were analyzed by computer graphics processing technology [35]. The research results provide an important theoretical reference for the treatment of solid waste and coal gangue.

2. Experimental Materials and Methods

2.1. Experimental Materials

The coal gangue utilized in the experiment was carefully selected from a coal mine in Shaanxi, China. The steel slag and slag were sourced from Hebei Province, China, while lime powder with a CaO content greater than 90% was purchased from the market. The chemical composition is shown in Table 1, the mineral composition is shown in Figure 1, and the particle size composition is shown in Figure 2. The cement used is 42.5 ordinary Portland cement produced by Shandong Shanshui Cement Group Co., Ltd., Jinan, China. The water glass was purchased from the market as instant sodium silicate powder with a modulus of 1–3.4. In this study, coal gangue was used as a filling aggregate. The influence of sodium silicate, quicklime, and cement on the mechanical properties and micro-evolution characteristics of the filling body and the early excitation characteristics of steel slag–slag-based composite cementitious materials were investigated.

Table 1. Chemical composition of the materials.

Material	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	K ₂ O	CaO	MgO	TiO ₂	Na ₂ O
Coal gangue	55.05	24.64	9.12	6.06	3.18	1.45	1.45	1.06	0.32
Steel scoria	13.5	4.49	18.8	0.74	0.26	25.8	3.82	0.76	0.29
Slag	29.6	16.3	0.34	2.23	0.42	40.3	8.2	1.26	0.52
Quicklime	5.28	1.54	0.26	0.23	0.06	91.1	1.17	0.08	0.06

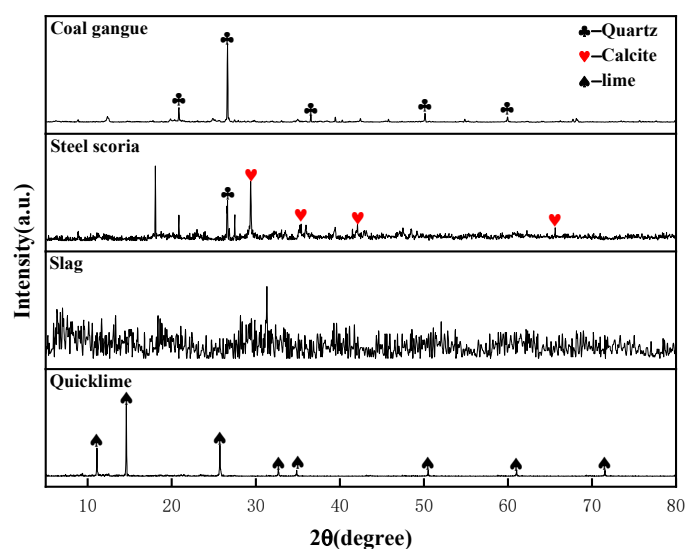


Figure 1. XRD spectrum of filling material.

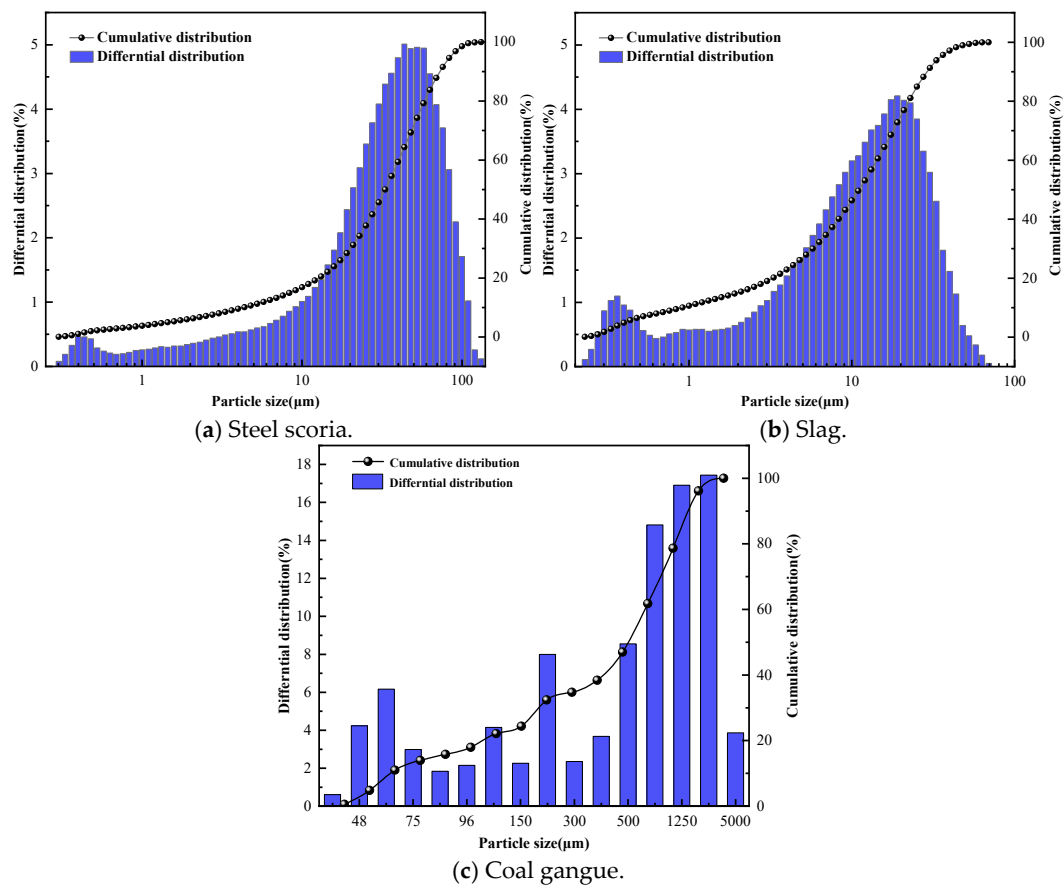


Figure 2. Particle size distribution of coal gangue.

Figure 3 shows the micro-morphology of the filling raw materials. Steel slag particles are irregular in shape with rough surfaces; larger particles are attached to smaller ones, with no holes or cracks, and particle distribution is not concentrated. Slag mostly appears as blocky crystals with irregular shapes, no holes or cracks, and smooth, glassy surfaces with a few small particles attached. Cement particles have a non-uniform size distribution, irregular shapes, and rough surfaces with fine particles attached. Quicklime particles are mainly amorphous aggregates. Coal gangue is mostly flaky and massive, with uneven surfaces, irregular internal structure, disordered particle arrangement, varying particle sizes, and a high fine particle content. Particles are loosely arranged with large pores; layered coarse particles have relatively smooth surfaces and large interparticle pores.

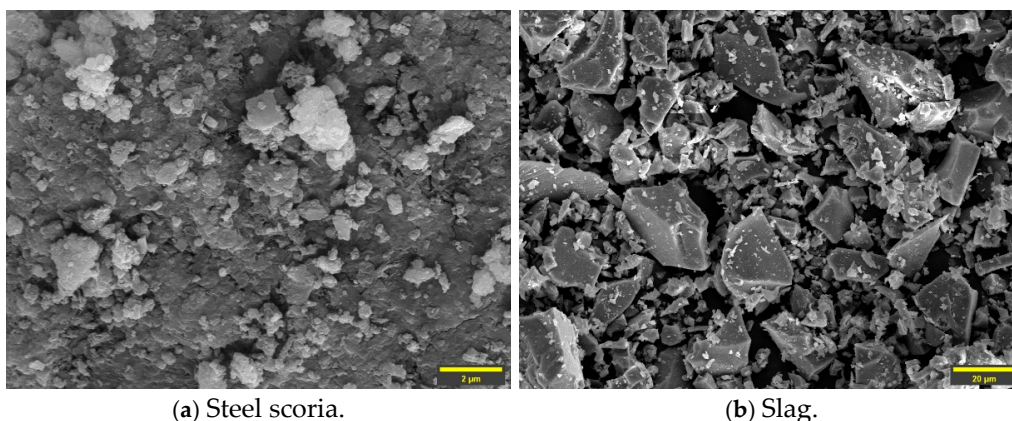


Figure 3. Cont.

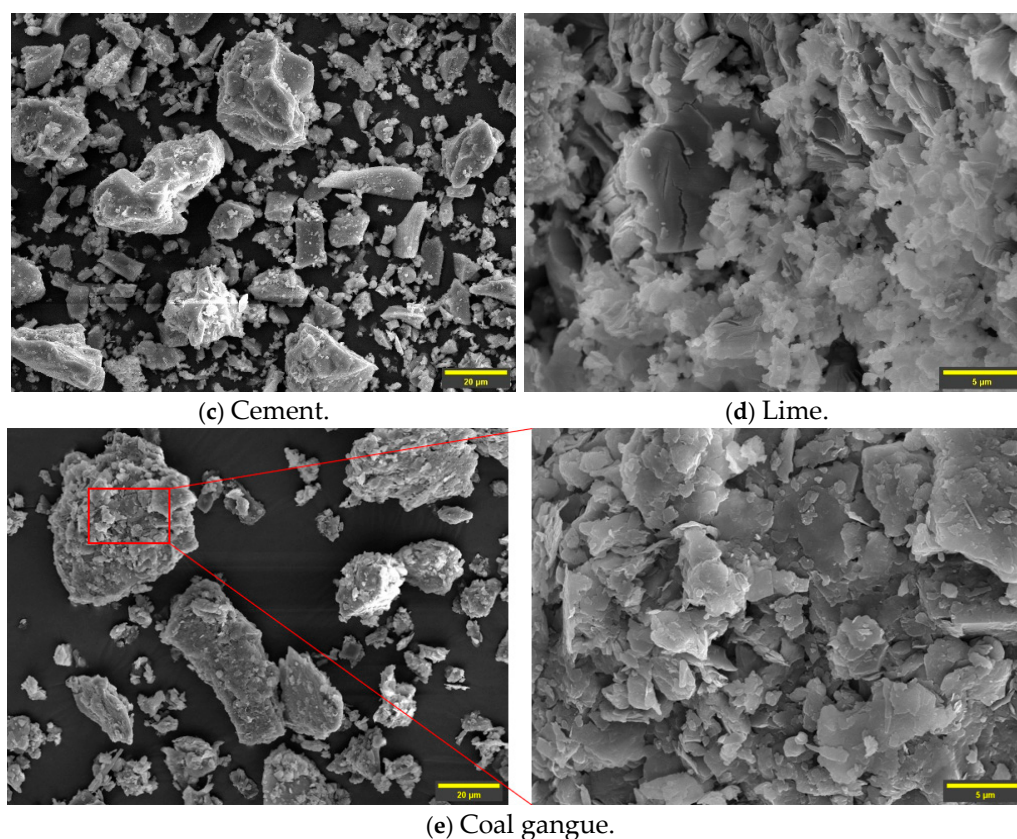


Figure 3. Microscopic morphology of the filling raw material.

2.2. Orthogonal Design

In order to study the excitation mechanism of sodium silicate, lime, and cement in steel slag–slag-based cementitious materials, the orthogonal design method is used to design the ratio of the composite activator by using four factors and three levels in the orthogonal table L9 (3^4). The cement material is 4.25# Portland cement, which served as the control group. In the experiment, the cementitious raw materials were added according to the mass percentage of the binder. Based on previous experimental research and cost control, the steel slag content is fixed at 30%, the cement content is less than 35%, the water glass content is 1–2%, the lime content is 5–15%, and the slag content is determined by several other factors. The specific values for the levels are shown in Table 2.

Table 2. Summary of test scheme.

Sample ID	Content of SS (%)	Content of S (%)	Content of NaSiO ₃ (%)	Content of Q (%)	Cement (%)
S1-L5-C15	30	49	1	5	15
S1.5-L10-C15	30	43.5	1.5	10	15
S2-L15-C15	30	38	2	15	15
S1.5-L5-C25	30	38.5	1.5	5	25
S2-L10-C25	30	33	2	10	25
S1-L15-C25	30	29	1	15	25
S2-L5-C35	30	28	2	5	35
S1-L10-C35	30	24	1	10	35
S1.5-L15-C35	30	18.5	1.5	15	35
Cement	0	0	0	0	100

Note: The amount of coal gangue is 4 times the mass of all the above materials. The ratio of glue to bone is 1:4.

2.3. Sample Preparation

The preparation procedure for the samples is in accordance with the “Standard for Basic Performance Test Methods of Building Mortar” (JGJ/T 70-2009) [36]. The sample was prepared using a standard triple test mold with a size of 7.07 cm × 7.07 cm × 7.07 cm. Before preparing the sample, a layer of oil film is brushed on the inner wall of the test mold to facilitate demolding. According to the experimental scheme, the weighed filling material is poured into a mixed container, stirred for 5 min to form a uniform filling slurry, and then injected into the standard triple test mold. After the initial setting, the test block is scraped flat, and the test block is placed at a temperature of 20 ± 1 °C and a relative humidity of 50%. The specific production process is shown in Figure 4.

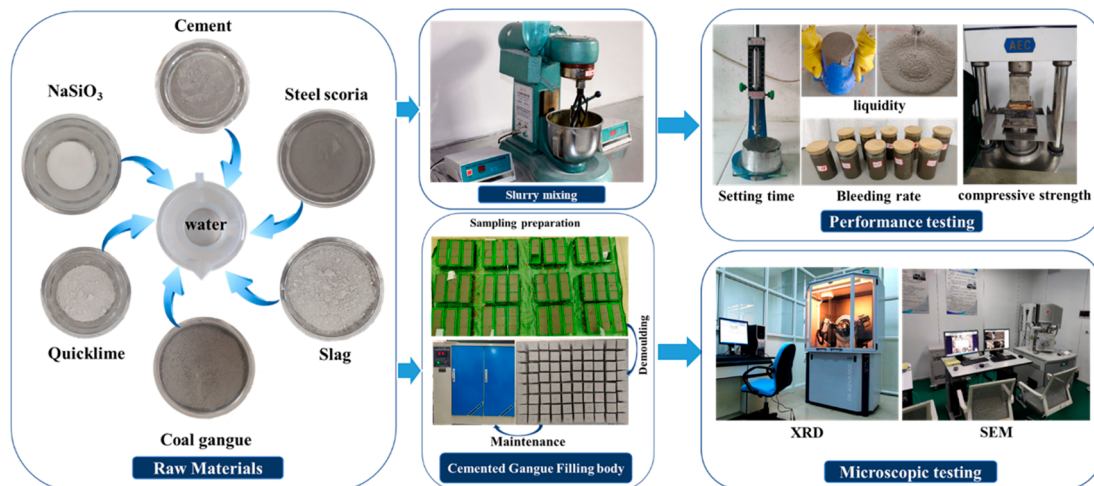


Figure 4. Preparation and related test process of CGFB.

2.4. Testing Methods

2.4.1. Setting Time

The setting time was determined according to the “Cement standard consistency water consumption, setting time, stability test method” (GB/T 1346-2011) [37]. The initial and final setting times of the filling slurry were tested using a Vicat apparatus.

2.4.2. Flowability

The fluidity of the slurry was measured according to the “cement mortar fluidity determination method” (GB/T 2419-2005) [38]. A slump bucket with a diameter of 100 mm at the upper end, a diameter of 200 mm at the lower end, and a height of 300 mm was used to test the flow properties of the filling slurry.

2.4.3. Compressive Strength

The uniaxial compressive strength of the filling body is carried out according to the cube compressive strength test standard in the ‘Standard for Basic Performance Test Methods of Building Mortar’ (JGJ/T 70-2009). The loading speed was 0.25–1.5 kN/s.

2.4.4. Mineral Phase

In order to study the mineral composition in the material, the main mineral components in the material were analyzed by the XRD method. After obtaining the JAW file by XRD, Jade 6.5 analysis software was used to compare the measured tailing map with the standard comparison card to determine the main mineral components in the material. The X-ray diffractometer parameters were as follows: Cu target, scanning range of 10–70°, working voltage and current of 40 kV and 40 mA, step size of 0.02°, angle measurement

accuracy of $2 \pm 0.01^\circ$, angular resolution of $\text{FWHM} \pm 0.1$, and angular reproducibility of $\pm 0.0001^\circ$.

2.4.5. Microstructure

The microstructure morphology was observed by a quanta 250 field emission environmental scanning electron microscope. The instrument parameters were as follows: acceleration voltage (high-vacuum): 1.0 nm (SE) at 30 kV, 3.0 nm (SE) at 1 kV; acceleration voltage (low-vacuum): 1.4 nm (SE) at 30 kV; environmental vacuum: 1.4 nm (SE) at 30 kV. The magnification can be adjusted in the range of 10~100,000 times. In order to prevent charge accumulation on the surface of the sample, a thin layer of gold was coated on the surface of the sample using a gold sprayer before SEM observation. By observing the microstructure and internal structure of the sample, the shape of the sample and its change process can be understood.

3. Results and Discussion

3.1. Setting Time

The setting times of CGFB with different activator contents are shown in Figure 5. The names given represent the percentages of cementitious materials in the CGFB formula; for example, S1-L5-C15 included 1% sodium silicate content, 5% lime content, and 15% cement content. On the whole, the initial setting time of CGFB was 140~155 min, and the final setting time was 170~210 min. This shows that the filling body can reach the initial self-care state within 4 h and has a certain strength [39]. This is of great significance in improving the efficiency of mining. It was worth noting that the setting time of CGFB was mainly influenced by the dosages of sodium silicate and lime. A higher amount of sodium silicate shortens the setting time, whereas an increase in lime content prolongs it.

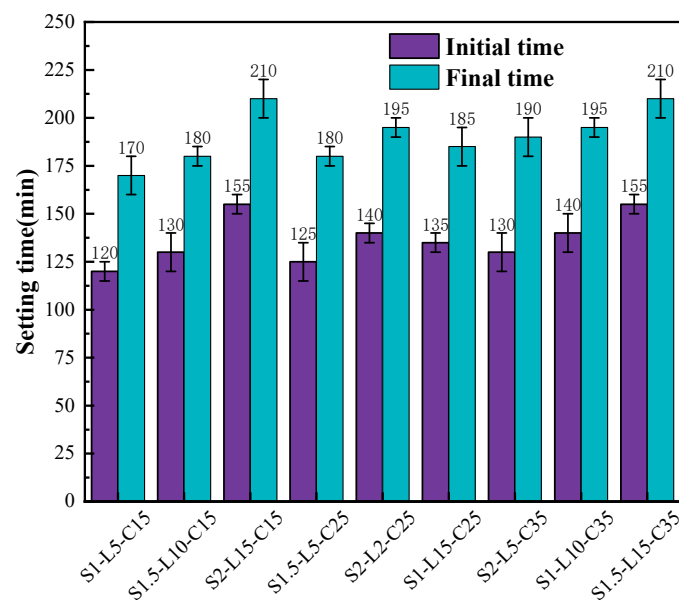


Figure 5. Effect of composite activator dosage on the setting time of CGFB.

3.2. Flowability

The stability of filling slurry pipeline transportation is crucial for the filling process [40]. After the filling slurry is transported to the empty area by the pipeline, it is necessary to continue to maintain good fluidity in order to achieve complete filling in the empty area and a better roof contact rate. Therefore, the filling slurry requires good and stable fluidity to meet the requirements of stable pipeline transportation. Figure 6 reflects the fluidity of

filling slurry under different activator conditions. The overall slump is between around 231 and 252 mm, which basically meets the requirements for mine backfilling. It should be noted that the slump of CGFB was primarily influenced by the dosages of sodium silicate and lime. A higher amount of sodium silicate resulted in poorer fluidity, while an increase in lime content led to an improved setting time.

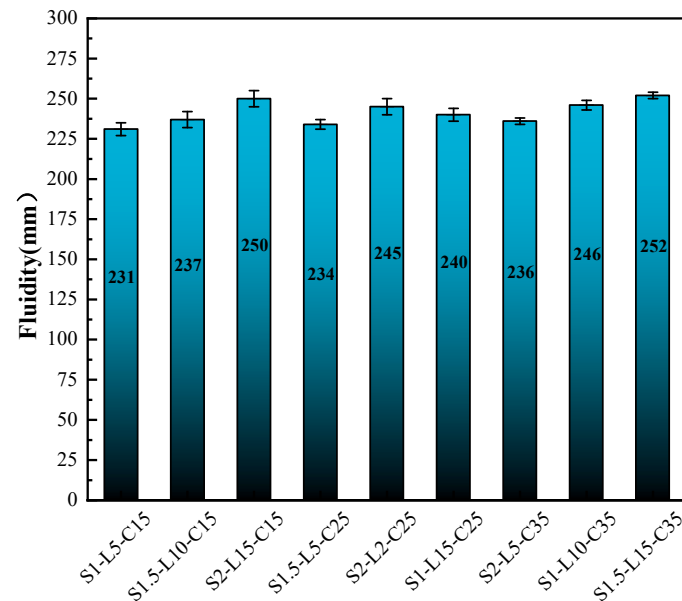


Figure 6. Fluidity of fresh mortars.

3.3. Mechanical Strength

As shown in Figure 7, the uniaxial compressive strength of different curing ages under nine different activator content conditions was tested. From the experimental results, it can be seen that the maximum compressive strength of the filling body can reach 0.74 MPa in 1 day. At this time, the ratio of the activator is water glass/quicklime/cement = 1.5:10:15, that is, the S1.5-L10-S15 group. The maximum compressive strength at 3 days, 7 days, and 28 days is 2.16 MPa, 3.1 MPa, and 4.18 MPa, respectively. Except for the strength at 3 days, which is close to that of regular cement, the strength at other ages is obviously better than that of regular cement. It can meet the strength requirements of the mine for the filling body [41]. It is worth noting that, on the whole, the higher the cement content, the lower the later strength of the filling body, which indicates that the quality of the filling body was better when a certain activator was added within a certain range, the slag content was increased, and the cement content was reduced. Not only does this approach employ slag solid waste and reduce environmental pollution, air pollution, and the waste of land resources caused by slag storage, it also reduces the use of cement, which not only reduces the filling cost to a certain extent but also reduces energy consumption in the cement production process and reduces carbon emissions. It is of great significance for environmental protection and the construction of green mines and waste-free mines.

Aiming to determine the compressive strength of the filling body after 3 days and 28 days of curing, quadratic polynomial regression analysis was carried out with the amount of activator (water glass, lime) and the amount of cementing agent as the factors, and a regression model were established to predict the early and late compressive strength of the filling body. The response surface method was used to analyze the response surface of the two interacting factors.

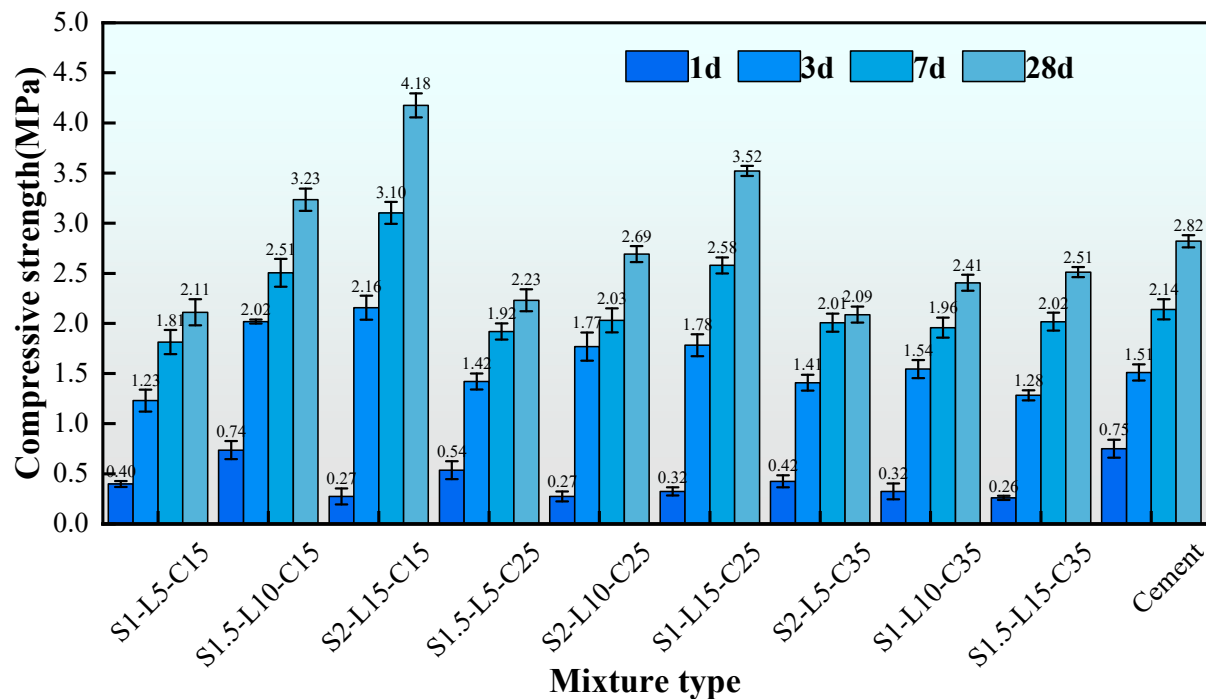


Figure 7. Compressive strength of mortars.

The content of water glass, lime, and cementing agent were taken as the research object, and the compressive strength of the filling body at 3 days and 28 days of curing age was taken as the investigation index. The multiple regression analysis–quadratic polynomial regression method in the DPS data processing system was used to establish the regression equations for the 3-day and 28-day compressive strength of the backfill, as shown in Equations (1) and (2):

$$R_{3d} = -0.3579 + 0.3544X_2 - 0.0092X_2^2 - 0.0053X_2X_3 \quad (1)$$

$$R_{28d} = 0.5147 + 0.3308X_2 + 0.04X_3 - 0.0082X_2X_3 \quad (2)$$

where X_1 represents the amount of water glass, X_2 represents the amount of lime, and X_3 represents the amount of cement.

The determination coefficients of the regression equation are $R_{3d}^2 = 0.9826$ and $R_{28d}^2 = 0.9916$, respectively, indicating that the equation has a high fitting rate and strong reliability. Based on the two fitting equations mentioned above, the optimal mix proportion conditions for the backfill at 3 days and 28 days can be determined.

Based on the regression model for the compressive strength of the filling body at 3 days and 28 days, the influence of the interaction between the lime content and cement content on the compressive strength of the filling body was analyzed. Taking the lime content and cement content as X-axis coordinates and Y-axis coordinates, and taking the 3-day and 28-day compressive strength of the filling body as Z-axis coordinates, the response surface stereo analysis diagram and contour map are drawn (as shown in Figure 8). It can be seen from Figure 8 that when the content of cement and lime is 15% and 15%, respectively, the compressive strength of the cemented backfill reaches the maximum at 3 days and 28 days. It is further explained that under this composite activator system, the amount of cement can be reduced, the consumption of solid waste can be increased, and the utilization rate of solid waste can be high.

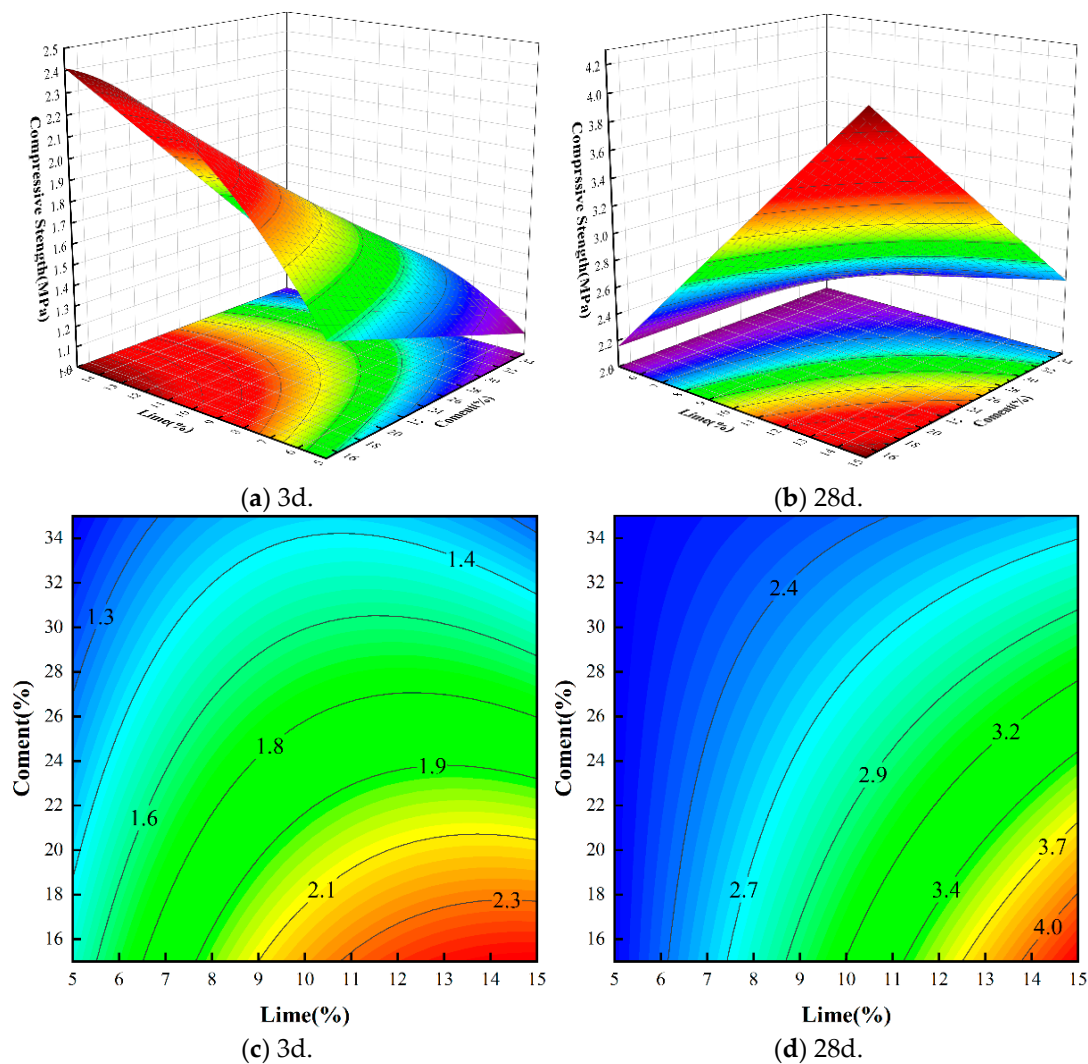


Figure 8. The effect of interaction on the 3-day and 28-day strength of the filling body.

3.4. Hydration Products and Microstructure

According to the hydration products of the filling body at different ages in Figure 9, it can be seen that when the hydration reaction was carried out for 1 day, the main hydration products were ettringite (AFt) and calcium silicate hydrate (C-S-H). From the XRD analysis results, it can be seen that there was unreacted quartz (SiO_2). Due to the formation of hydration products such as AFt and C-S-H gel, the backfill material acquires certain early-age strength. When the hydration reaction proceeded to 3 days, the main hydration products were predominantly ettringite and hydrated calcium silicate, and there was still unreacted quartz, but the XRD diffraction peak of quartz was obviously reduced. Compared with the XRD diffraction pattern after 1 day of the hydration reaction, the characteristic peak of the XRD diffraction pattern after 3 days of the hydration reaction was more obvious, indicating that the hydration product was more stable after 3 days of the hydration reaction. When the hydration reaction proceeded to 28 days, the AFt and C-S(A)-H gel in the hydration products were significantly reduced, and there was no characteristic peak in the XRD diffraction pattern. At this time, there were more hydration products, mainly mullite, hydrated aluminum calcium sulfate, and a small amount of calcium sulfate, aluminum calcium sulfate, etc. By 28 days, the hydration reaction was essentially complete, and the hydration products had filled the pores within the backfill, resulting in significantly higher compressive strength.

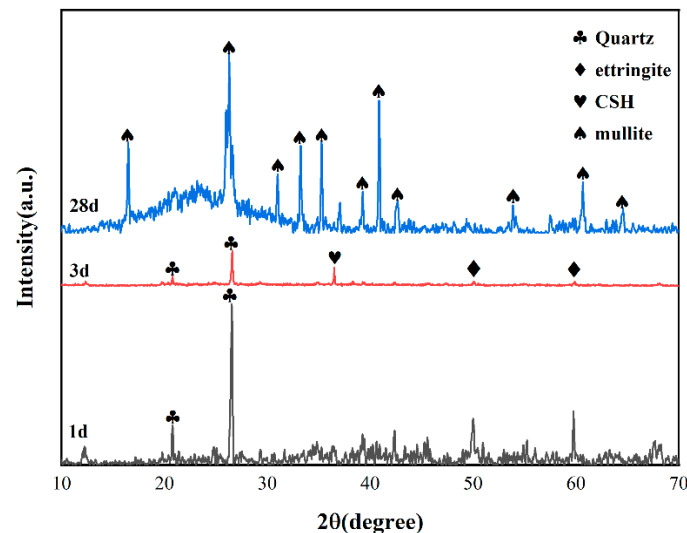


Figure 9. S2-L15-C15 hydration products at different ages.

Figure 10 shows the micro-morphology of the S2-L15-C15 group cemented backfill after curing for 1, 3, 7, and 28 days. It can be seen from the images that after 1 day of curing, the cementitious material had already begun to partially hydrate. The cementitious system was mainly composed of fine needle-like ettringite crystals, which were intertwined with each other, providing the filling body with a certain early strength. However, during the initial stage of hydration, the hydration products were poorly developed, and many of the fine needle-like ettringite crystals were not interconnected. A significant number of voids were present between them, which also explains why the early strength of the filling body was relatively low. By 3 days of curing, the cementitious material had undergone further hydration, and the microstructure formed a three-dimensional network consisting of flocculent C-S-H gel and acicular ettringite. Nevertheless, the hydration reaction was not yet complete, and the morphology of the hydration products remained underdeveloped. Voids and micro-cracks were observed in the matrix formed by the overlapping hydration products. As a result, the strength of the backfill continued to increase.

With ongoing hydration, at 7 days, the amount of long rod-shaped ettringite and C-S-H gel increased in the microstructure. These products interwove and bonded the loose and fragmented coal gangue particles into an integrated whole, resulting in a progressively denser structure. Compared to the microstructure at 1 day, the number of large voids was significantly reduced, the porosity was lower, and the integrity of the filling body was improved. At 28 days of curing, the hydration products continued to grow, and the structure evolved from an initial three-dimensional network into a layered and stacked morphology. The content of acicular ettringite decreased, while the amount of C-S-H gel increased, presenting as irregular masses and flakes that were closely interconnected without a specific orientation. Compared with the samples after 1, 3 and, 7 days, the samples after 28 days showed fewer pores and cracks. Macroscopically, this was reflected in the superior mechanical properties of the backfill material.

A series of pore parameters were obtained by using Image J 2.1.0 software to binarize the SEM image [42]. The fixed threshold method was used for binarization processing, and the threshold was selected as 56. The pixels whose gray value was greater than or equal to the threshold were set to 255, and the others were set to 0. Then the pores were extracted, rendered, and calculated. No less than three regions were selected for microscopic void analysis in each period. The processing results are shown in Figure 11 and Table 3. It can be seen from the calculation results that as the curing time increases, the microscopic porosity of the filling body decreases, the porosity is 10.5% at 1 day, and the porosity is

reduced to 3.8% at 28 days. Regarding the macroscopic performance, the compressive strength of the filling body gradually increases with the extension of the curing time. The compressive strength of the filling body at 3 days was 1.89 MPa higher than that at 1 day, and the porosity was reduced by 4.9%. Compared with 3d, the compressive strength of the filling body at 7 days had increased by 1.94 MPa, and the porosity had decreased by 1.3%. Compared with the strength at 7 days, the compressive strength at 28d had increased by 1.08 MPa, and the porosity had decreased by 0.5%.

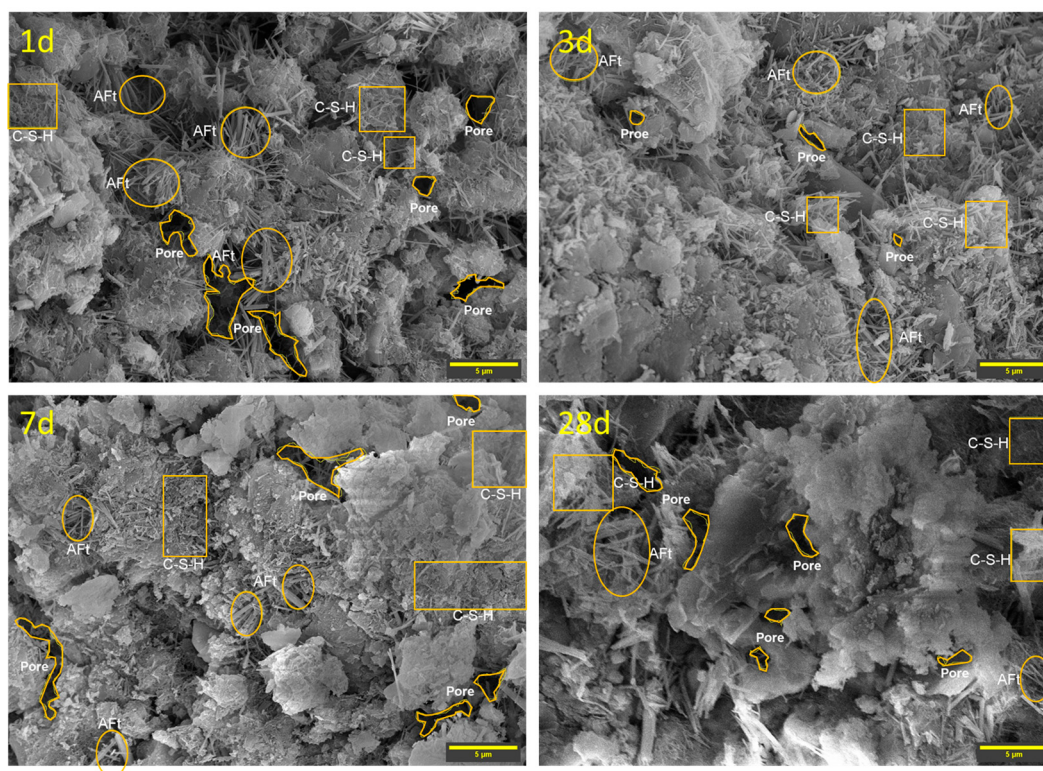


Figure 10. S2-L15-C15 micro-morphology of cemented backfill at different ages.

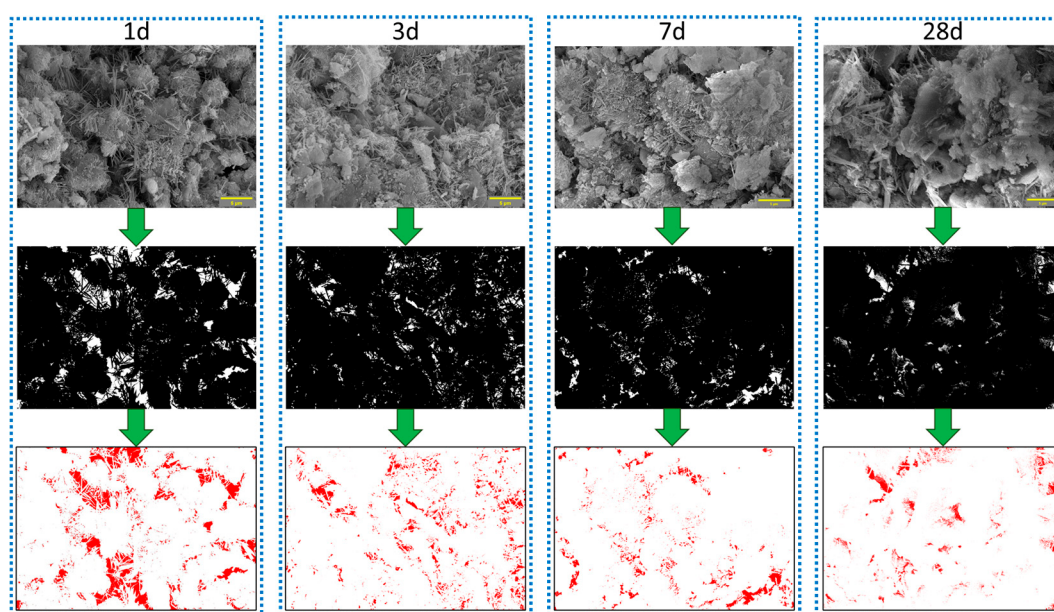


Figure 11. SEM images of S2-L15-C15 group after digital image processing.

Table 3. Porosity of specimens.

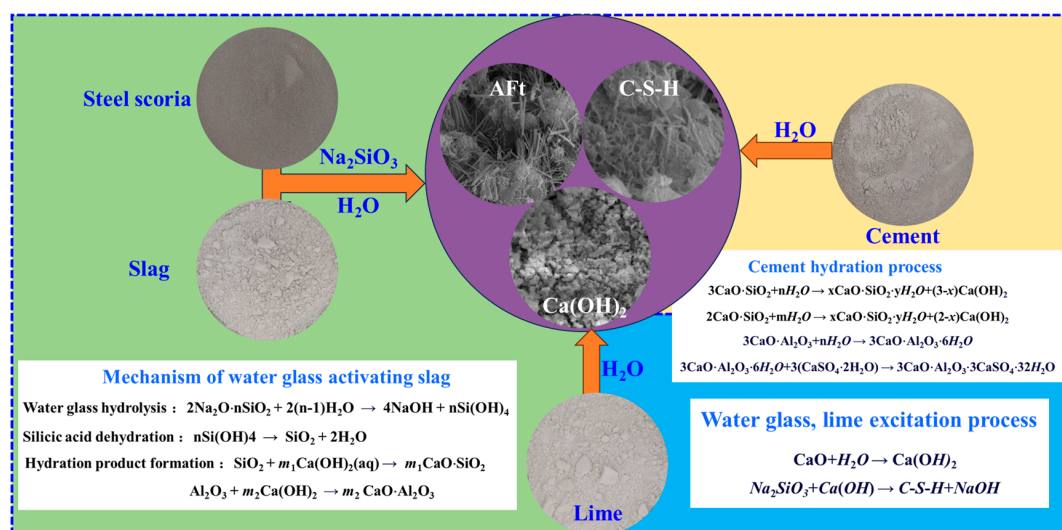
Sample Number	1 d	3 d	7 d	28 d
Porosity / %	10.5	5.6	4.3	3.8

3.5. Mechanism Analysis

In this study, the alkali activation mechanism was used to stimulate the potential active substances in slag and steel slag. Slag powder can show good hydraulicity only under the excitation of clinker hydration product Ca(OH)_2 [43]. Therefore, in the early stage of hydration, the slag powder only plays a role of filling and compaction, and the early strength of the filling body is low. Therefore, the addition of some cement under the action of water glass excitation causes the cement to rapidly undergo a hydration reaction and improve the early strength of the filling body.

The cement hydration reaction is a complex process [44]. The reaction of various mineral components with water was designed, mainly involving the hydration of tricalcium silicate (C_3S), the hydration of dicalcium silicate (C_2S), and the hydration of tricalcium sulfate (C_3A). Among them, C_3S is one of the most important mineral components in cement. The hydration reaction is the main process of cement hardening, and the reaction produces C-S-H, which is a gel-like substance and contributes significantly to the strength of cement. At the same time, Ca(OH)_2 is generated. The hydration reaction of C_2S was similar to that of C_3S , but the hydration rate was slower, and C-S-H gel and Ca(OH)_2 were also formed. The hydration reaction of C_3A was rapid and exothermic, and its hydration products were greatly affected by the concentration and temperature of calcium oxide in the liquid phase. The hydration products included AFt or monosulfide hydrated calcium sulfoaluminate (AFm).

The water hardening process of slag is divided into two steps [45]. With the increase in slag content, the content of cement clinker decreased, and the amount of calcium hydroxide generated by clinker hydration also decreased accordingly, resulting in a decrease in the early strength of slag cement. After the addition of water glass and lime, lime reacts with water to form Ca(OH)_2 , and $\text{Na}_2\text{O} \cdot n\text{SiO}_2$ has a dual role [46]. Hydrolysis occurred in water, producing a large amount of OH^- , and the general pH value could reach 13.0, which was essentially equivalent to strong alkali excitation. The addition of water glass increased the content of $[\text{SiO}_4]^{4-}$, promoted the formation of gel, and accelerated the hydration reaction of the reactants [47]. The main hydration reaction mechanism is shown in Figure 12.

**Figure 12.** Main hydration reaction mechanism diagram.

3.6. Environmental and Economic Benefit Analysis

The developed coal gangue-based composite cementitious material offers significant low-carbon, environmental, and economic advantages, aligning with global sustainability goals and China's "dual carbon" policy. By utilizing industrial solid wastes (steel slag, slag) as primary raw materials and reducing cement consumption, the material significantly lowers CO₂ emissions associated with traditional cement production. The alkaline activation process avoids high-energy calcination, further reducing its carbon footprint. The material consumes large amounts of solid waste (up to 68% in the optimal mix), mitigating land occupation, soil pollution, and ecological risks caused by waste accumulation. It provides a sustainable outlet for industrial by-products that would otherwise require disposal. Replacing over 50% of cement with low-cost wastes substantially lowers material costs, which account for a major portion of backfill expenses. This enhances the economic feasibility of mine backfill applications and supports broader adoption.

This material supports national green mining and waste-free mine initiatives, promoting circular economy practices and contributing to sustainable resource utilization in the mining sector.

4. Conclusions

A cementitious material was prepared by using water glass and lime to stimulate the potential active substances in steel slag and slag along with the addition of a certain amount of cement. It exhibited characteristics such as quick setting, early strength, and low cost, making it suitable for broken and easily weathered coal gangue. For coal mine filling, it significantly improved the filling effect, reduced the filling cost, consumed a large amount of solid waste, and mitigated environmental issues such as soil pollution and land occupation caused by solid waste storage. In this paper, the factors affecting the mechanical properties of CGFB were demonstrated in detail, and a mechanism for improving the mechanical strength of CGFB was revealed from the perspectives of the hydration process and microstructure. The main conclusions are as follows:

- a. When the mass ratio of steel slag, slag, cement, water glass, and lime was 30:38:15:2:15, the CGFB achieved the largest compressive strength, good setting, and good block and flow performance. Under these mix proportions, the compressive strength of CGFB reached 2.16 MPa at 3 days and 4.18 MPa at 28 days. The initial setting time was 155 min, the final setting time was 210 min, and the slump was 250 mm.
- b. The high early strength of CGFB can be attributed to the hydration reaction process of cement being greatly accelerated under the stimulation of water glass, which promoted the formation of the hydration product C-S-H. Under the dual activation of water glass and lime, the potential active substances in steel slag and slag were stimulated, resulting in higher later strength in the CGFB.
- c. With the increase in curing age, the microstructure of the CGFB became denser, the micro-porosity gradually decreased, hydration products continued to develop, the network of C-S-H became more compact, and the length and diameter of rod-like AFt increased. Macroscopically, these changes were reflected in the performance evolution of the filling body over different curing periods.
- d. Based on computer image processing technology, the pore characteristics of SEM images were analyzed and compared with the macro compressive strength. The results show that as the oxidation age of the filling body increases, the porosity becomes lower and lower, and regarding the macroscopic performance, the compressive strength becomes higher and higher.

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