

Original Research Report

Evaluation of coal gasification slag modification technology based on multivariate pozzolanic activity evaluation method: Activity enhancement method and mechanism

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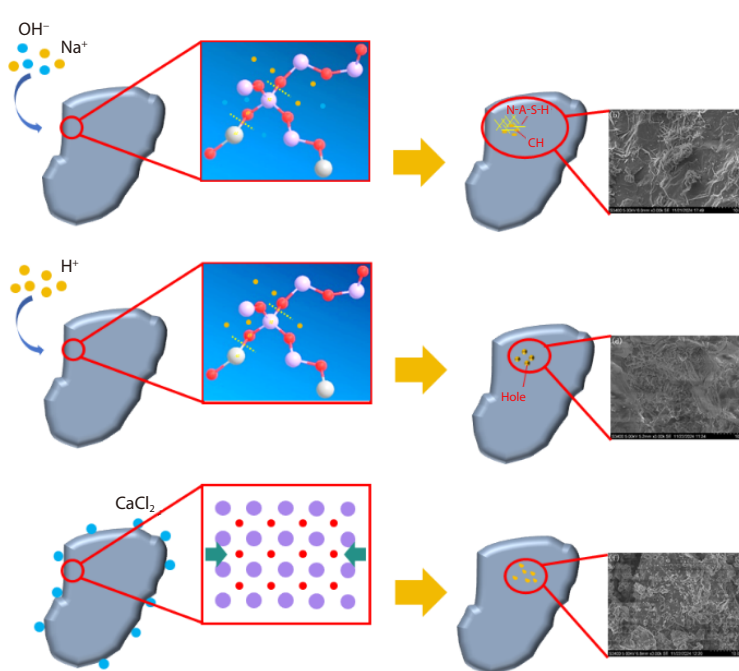
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Abstract: The massive stockpiling of coal gasification slag poses significant environmental hazards, necessitating urgent resource utilization. When used in cement-based materials, it can partially replace cement, thereby reducing carbon emissions. This paper employs different pretreatment methods to enhance the hydration activity of coal gasification slag and compares modification techniques using various evaluation methods. The results indicate that, in terms of evaluation methods, the Rietveld whole-pattern fitting method, ion leaching method, and quality loss method can rapidly assess pozzolanic activity; the combined application of these methods can simultaneously ensure high accuracy and low time consumption. Regarding modification techniques, the modification methods adopted in this study can alter the amorphous composition, ion dissolution, and reactivity of coal gasification slag. Under the experimental conditions of this study, alkali dissolution and CaCl_2 modification can effectively enhance pozzolanic activity, resulting in stronger mechanical properties. Specifically, the compressive strength growth rates of cement with coal gasification slag modified by NaOH at 7 d and 28 d can reach 13.5% and 6.5%, respectively, while those modified by CaCl_2 can reach 9.0% and 13.1% at 7 d and 28 d, respectively, demonstrating significant effects. Therefore, these methods can be considered as viable means for modifying coal gasification slag to improve its resource utilization efficiency.



Keywords: coal gasification slag, modification, activity, evaluation, mechanism

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1. Introduction

Coal is the primary energy source in China, occupying a pivotal position, while coal gasification technology represents a key pathway for the clean utilization of coal. However, this process generates 15% to 20% of coal gasification slag (CGS)^[1–3]. Coal gasification slag is a solid residue formed during a series of chemical and physical reactions between coal and a gasifying agent under specific temperature and pressure conditions, incorporating inorganic minerals from the coal along with residual carbon particles. It is classified into coarse slag and fine slag. According to reports, the amount of coal gasification slag generated by coal combustion is relatively large^[4–6], yet its utilization rate remains low. Massive stockpiling not only occupies land but also poses environmental safety risks and hinders the development of coal chemical technology^[7–9].

Coarse slag accounts for approximately 80% of the total volume of coal gasification slag and has a relatively low carbon content, whereas fine slag contains a higher carbon content and forms a porous structure under high temperatures due to process influences^[10,11]. Additionally, coal gasification slag contains silica and alumina, with its main mineral phases consisting of silicates and aluminosilicates, exhibiting potential pozzolanic activity^[12–15]. Therefore, it can be utilized as a building material product.

Fu et al.^[16] investigated the influence of coal gasification slag content on the properties of cement-based materials. Their findings indicated that low-dosage coal gasification slag exhibits nucleation and pozzolanic effects in cement-based materials, which are beneficial for hydration reactions and enhance the compressive strength. However, when the coal gasification slag content exceeds 30%, the hydration product content decreases, and the microstructure becomes loose, resulting in poor mechanical properties. Li et al.^[17] studied the hydration mechanism of coal gasification slag in cement. Their results showed that when fine slag is used in cement-based materials, its high carbon content hinders hydration reactions, whereas the use of coarse slag allows for the detection of hydration products such as ettringite and C-S-H gel formation, thereby promoting hydration reactions and improving mechanical properties. Zhao et al.^[18] explored the application of calcined coal gasification slag in cement-based materials and found that calcination enhances the hydration activity of coal gasification slag. Furthermore, researchers have employed chemical modification^[19–22], physical modification^[23–25], and synergistic modification^[26] to improve the hydration activity of coal gasification slag, thereby increasing its substitution rate in cement-based materials.

However, current modification methods for coal gasification slag are relatively limited, and there is a lack of systematic research on the impact of different modification approaches on the properties of coal gasification slag, making it difficult to significantly improve its utilization efficiency. Additionally, research on coal gasification slag, as well as other solid wastes, often employs traditional activity index evaluation methods to assess pozzolanic activity^[27–30], which are time-consuming and result in slow experimental outcomes.

Therefore, this study compares the effects of different modification methods on the physicochemical properties of coal gasification slag and utilizes various pozzolanic evaluation methods to assess and compare the modification processes of coal gasification slag, including the accuracy and timeliness of the evaluation method. Compared with existing studies, this work clearly identifies the limitations of single-method evaluation, as well as the necessity and core parameters of adopting multi-criteria evaluation methods.

This research will provide diverse perspectives on the utilization of coal gasification slag and establish a rapid evaluation method for pozzolanic activity, offering an effective approach for the rapid identification of pozzolanic activity in coal gasification slag and other solid wastes.

2. Materials and methods

2.1. Materials

The raw materials used in the experiment included coal gasification slag, P.I 42.5 Portland cement, NaOH, KOH, HCl, Na₂SO₄, and CaCl₂. Among them, the coal gasification slag was obtained from a chemical plant in Shanxi Province, China, with a density of 2.7 g cm⁻³. The chemical composition and physical properties of the coal gasification slag are presented in Tables 1 and 2, respectively. The experimental results reveal that the primary chemical constituents of the coal gasification slag are Al₂O₃ and SiO₂, with contents of 31.55% and 39.11%, respectively, followed by CaO and Fe₂O₃, with contents of 7.97% and 3.43%, respectively. The loss on ignition (LOI) of the coal gasification slag is 12.68%. Fig. 1 shows the initial morphology of the coal gasification slag, exhibiting a porous block-like structure.

Table 1. Chemical composition of coal gasification slag (wt%).

Al ₂ O ₃	SiO ₂	CaO	Fe ₂ O ₃	K ₂ O	TiO ₂	MgO	Na ₂ O	LOI
31.55	39.11	7.97	3.43	0.30	1.05	0.99	1.87	12.68

Table 2. Physical properties of coal gasification slag.

Sample	Density (g cm ⁻³)	pH	Moisture content (%)
Coarse slag	2.7	9.76	1.52



Fig. 1. The initial morphology of the coal gasification slag.

The physical properties of the cement are presented in Table 3. The specific surface area of the P.I 42.5 Portland

Table 3. Physical properties of cement.

Specific surface area (m ² kg ⁻¹)	Density (g cm ⁻³)	Standard consistency water requirement (%)	Setting time (min)		Flexural strength (MPa)			Compressive strength (MPa)		
			Initial	Final	3 d	7 d	28 d	3 d	7 d	28 d
370	3.10	25.5	117	175	5.9	7.3	9.1	28.1	42.8	56.2

cement is 370 m² kg⁻¹, with a 7 d flexural strength and compressive strength of 7.3 MPa and 42.8 MPa, respectively, and those at 28 d of 9.1 MPa and 56.2 MPa, respectively.

2.2. Methods

2.2.1. Coal gasification slag modification method

The experiment employed acids, alkalis, and salts to modify the coal gasification slag separately, with the specific modification protocols outlined in Table 4. For the acid and alkali solutions, both were prepared at a concentration of 0.5 mol L⁻¹ and mixed with the coal gasification slag at a liquid-to-solid ratio of 2:1, followed by washing, drying, and grinding. After washing, the washing solution should be neutral. In the case of salt modification, the coal gasification slag was combined with the chemical reagents, followed by drying to a constant weight, and then ground. The grinding duration was uniform across all samples, lasting 30 min. The detailed modification process is illustrated in Fig. 2.

2.2.2. Size distribution

The particle size distribution was primarily determined using a laser particle size analyzer (Mastersizer 2000). The sample (50–100 mg) was ultrasonically dispersed in an anhydrous ethanol bath for 5 min and then transferred to the measurement cell. The average value was taken from three test results.

2.2.3. Composition and microstructure

The mineral composition was determined using an X’Pert Pow-

der X-ray diffractometer (XRD) manufactured by JEOL Ltd. (Japan). The instrument operated at a voltage and current of 40 kV/40 mA, with a continuous scan using a Cu target. The scanning angle ranged from 5° to 80°, with a scanning speed of 2° min⁻¹, to obtain sufficiently fine diffraction data and meet the accuracy requirements of Rietveld refinement calculations.

Chemical bonds were analyzed using infrared spectroscopy (FTIR). Initially, the coal gasification slag sample and KBr were mixed in a ratio of 1:100 and manually ground in a dry and clean agate mortar for 5 min. The mixture was then placed into a pellet mold and subjected to a press at approximately 20 MPa for 5 min. The resulting pellet was placed on an infrared workbench, and the Thermo Scientific OMNIC operating system was used to set the scan count to 64 and the resolution to 32 cm⁻¹ before initiating the test.

Microscopic morphology was observed using a scanning electron microscope (SEM). The sample was first affixed to conductive tape and then subjected to gold sputtering for approximately 30 to 40 s before testing. The acceleration voltage was set to 5 kV, the working distance was 3 mm, and the magnification was 3000 ×.

The quality loss test employed a muffle furnace (MF) for calcination. Samples were removed at specific temperatures for weighing, and the weight loss was calculated accordingly; six parallel test specimens were prepared for the same sample. The temperature ranges were verified using DTG analysis.

Table 4. Modification methods and conditions for coal gasification slag.

Sample	Activator Reagents	Modification conditions	Grinding time
CGS	/	/	30 min
CGS-SH	NaOH	0.5 mol L ⁻¹ & the liquid-solid ratio is 2:1	30 min
CGS-PH	KOH	0.5 mol L ⁻¹ & the liquid-solid ratio is 2:1	30 min
CGS-HA	HCl	0.5 mol L ⁻¹ & the liquid-solid ratio is 2:1	30 min
CGS-SS	Na ₂ SO ₄	4%	30 min
CGS-CC	CaCl ₂	4%	30 min

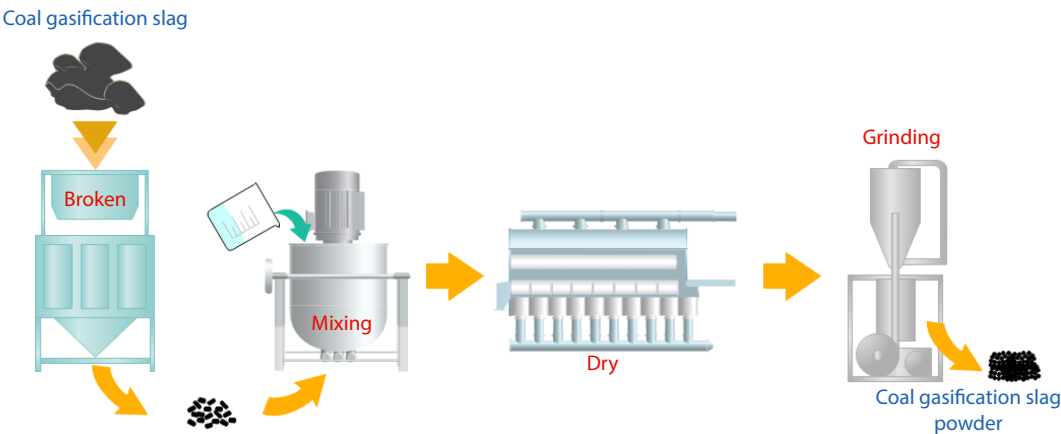


Fig. 2. Schematic diagram of coal gasification slag modification process.

2.2.4. Ion release

Weigh 1 g of modified coal gasification slag and prepare 100 mL of a 1 mol L⁻¹ NaOH solution to simulate the alkaline environment of cement hydration. Place the coal gasification slag into the prepared NaOH solution and stir it on a 20 °C thermostatic magnetic stirrer for 1 h, 3 h, and 6 h. Filter the mixed solution at the specified stirring times through a 0.42 µm filter paper into a 10 mL container. Then, dilute the filtered solution with a 5% nitric acid solution until the pH is less than 2. Finally, conduct an inductively coupled plasma (ICP) experiment to test the ion concentrations of Si, Al, and Ca. As the dilution process results in a solution volume exceeding 100 mL, the total mass of ions must be calculated, and the volumetric concentration of ions is then determined based on a 100 mL volume.

2.2.5. Compressive strength

To prepare the mortar, blend 135 g of modified coal gasification slag, 315 g of cement, 1350 g of standard sand, and 225 g of water, which was conducted in accordance with the Chinese National Standard GB/T 1596-2005, "Fly Ash Used for Cement and Concrete". The tests were conducted in accordance with the Chinese National Standard GB/T 17671-2021,

"Test method of cement mortar strength (ISO method)". Pour the mixture into a mold measuring 40 mm × 40 mm × 160 mm, cure it for 24 h, then remove the test block and immerse it in water for curing until the specified age is reached. Finally, three test blocks were taken out for testing.

3. Results

3.1. Physical and chemical properties of modified coal gasification slag

3.1.1. Size distribution

As evident from Fig. 3, the particle size distribution of the modified coal gasification slag primarily falls within the range of 0.1 µm to 100 µm. From the differential curve, it can be observed that the distribution curves of the modified coal gasification slag samples (CGS-SH, CGS-PH, CGS-HA, CGS-SS, CGS-CC) are closer to a normal distribution compared to the control group (CGS). The larger particles are more easily ground, resulting in a higher percentage content at the main peak position, whereas the control group still exhibits a shoulder peak. Additionally, the cumulative distribution curves indicate a leftward shift for the modified coal gasification slag, suggesting particle refinement.

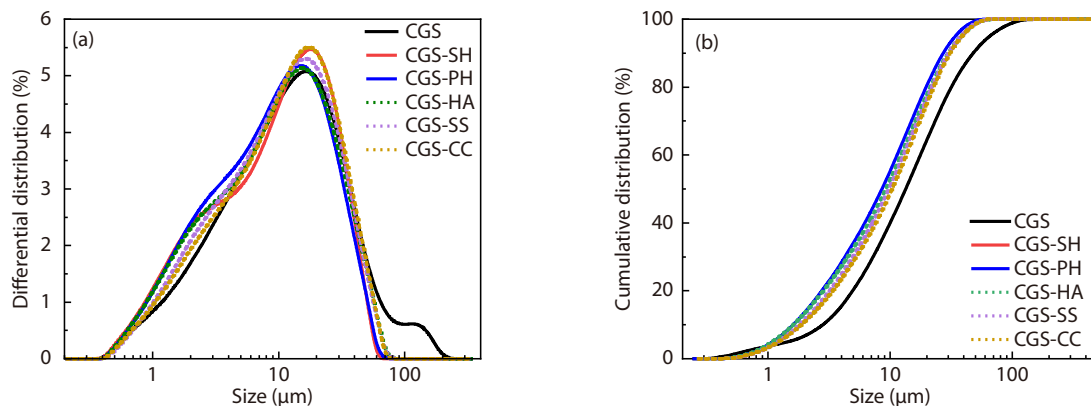


Fig. 3. Particle size distribution of coal gasification slag. (a) Differential distribution, (b) Cumulative distribution.

As can be seen from the data in Table 5, after grinding, the particle size parameters D_{10} , D_{50} , and D_{90} all decrease, with notable reductions observed in the CGS-SH, CGS-PH, and CGS-HA experimental groups. This is because the coal gasification slag modified by acid leaching or alkali dissolution exhibits defects in the crystalline structure of its aluminosilicate glass matrix. Under alkali dissolution or acid leaching conditions, bonds such as Si–O–Si, Si–O–Al, Al–O–Al, and Ca–O within the structure break and create vacancies, resulting in

Table 5. Characteristic particle size of coal gasification slag (µm).

Sample	D_{10}	D_{50}	D_{90}
CGS	2.037	10.932	38.310
CGS-SH	1.566	9.566	28.285
CGS-PH	1.614	8.596	27.204
CGS-HA	1.614	9.219	29.846
CGS-SS	1.819	9.754	30.124
CGS-CC	1.874	10.385	30.882

improved grindability under the same grinding time. Meanwhile, the characteristic values of the coal gasification slag modified by salts (CGS-SS, CGS-CC) also decrease, but to a lesser extent. This is because Na₂SO₄ and CaCl₂ adsorb onto the surface of the coal gasification slag particles, forming an adsorption film that weakens or neutralizes the van der Waals forces between the particles or the electrostatic charges on their surfaces, thereby enhancing the grinding efficiency.

3.1.2. Phase composition

As shown in Fig. 4, the main mineral phases of coal gasification slag modified under different chemical conditions consist of anorthite and mullite, which are largely similar to those of the control group. Furthermore, for coal gasification slag modified by alkali dissolution (CGS-SH, CGS-PH) or acid leaching (CGS-HA), the intensity of the mullite diffraction peak at a diffraction angle of $2\theta \approx 26^\circ$ slightly decreases compared to the control group. The observed reduction in the mul-

lite mineral phase in the coal gasification slag may be due to the corrosive effects of residual acids or alkalis during the drying process, as shown in Table 6.

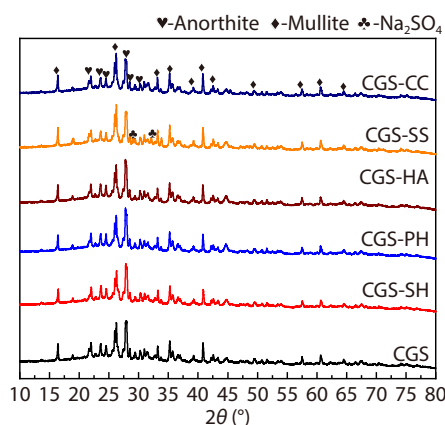


Fig. 4. XRD patterns of coal gasification slag.

Table 6. The phase content of different CGS.

Sample	Anorthite	Mullite
CGS	59.091%	35.141%
CGS-SH	63.580%	31.986%
CGS-PH	61.828%	33.592%
CGS-HA	61.578%	32.528%
CGS-SS	57.925%	37.009%
CGS-CC	56.503%	38.193%

For the CGS-SS, new diffraction peaks corresponding to Na_2SO_4 crystals appear at diffraction angles of $2\theta \approx 29^\circ$ and $2\theta \approx 33^\circ$. Additionally, the intensity of the mullite diffraction peak at $2\theta \approx 26^\circ$ is higher for the modified coal gasification slag (CGS-SS, CGS-CC) compared to the control group, while the intensity of the anorthite diffraction peak at $2\theta \approx 27^\circ$ is lower. This suggests that under the combined action of mechanical energy and chemical activators, part of the amorphous anorthite structure is disrupted and cleaved into substances similar to mullite.

From Fig. 5, it can be observed that the absorption bands at wavenumbers 3431 cm^{-1} and 1633 cm^{-1} correspond to the stretching vibrations and bending vibrations of

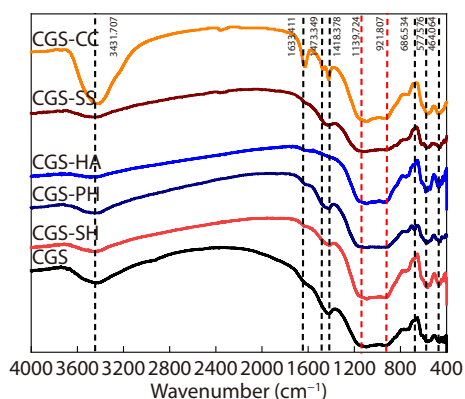


Fig. 5. FTIR patterns of coal gasification slag under different modification conditions.

H-O-H , which are associated with the bound water within the coal gasification slag. The bands at 1418 cm^{-1} and 1473 cm^{-1} correspond to the symmetric stretching vibrations of the C-O bond, related to the residual carbon in the coal gasification slag. The absorption peaks appearing in the low wavenumber region below 1200 cm^{-1} are primarily attributed to the vibrations of silicate and aluminate groups. Within the wavenumber range of 1139 cm^{-1} to 921 cm^{-1} , the symmetric stretching vibrations of Si-O bonds in the amorphous silicate tetrahedra (Q^2 , Q^3 , Q^4) of the coal gasification slag are observed. The peak at 686 cm^{-1} is caused by the bending vibration of Si-O-Si bonds, while the peak at 577 cm^{-1} corresponds to the deformation vibration of Si-O-Al, and the peak at 464 cm^{-1} is associated with the in-plane bending vibration of Si-O, all of which are related to the amorphous aluminosilicate glass phase.

For the CGS-SH and CGS-HA, the bending vibration peak of Si-O-Al at 577 cm^{-1} and the characteristic peak at 464 cm^{-1} are enhanced, indicating the breaking or recombination of Si-O-Al and Si-O bonds. Additionally, the intensity of the characteristic peaks in the range of 1139 cm^{-1} to 921 cm^{-1} is increased for CGS-SH and CGS-HA, suggesting the depolymerization of the amorphous aluminosilicate glass phase in the coal gasification slag. Therefore, the modification of coal gasification slag by CGS-SH and CGS-HA can effectively alter the structure of the aluminosilicate glass phase.

For the CGS-PH, there is almost no change at 577 cm^{-1} and 464 cm^{-1} , but a new characteristic peak appears at 686 cm^{-1} , indicating the breaking and recombination of Si-O-Si bonds in the aluminosilicate after modification, leading to an increase in active sites.

The characteristic peaks observed at 1633 cm^{-1} , 1473 cm^{-1} , and 1418 cm^{-1} in the CGS-CC may be related to the formation of CO_3^{2-} . In contrast, the CGS-SS shows almost no change compared to the control group.

3.1.3. Microstructure

Fig. 6 illustrates the microstructures of coal gasification slag under different modification conditions. From Fig. 6a, it can be observed that the particle surface is generally smooth with a small number of tiny particles adhering. These tiny particles are primarily composed of soluble substances, mullite, residual carbon, and other materials.

In Fig. 6b and c, it is evident that after alkali dissolution modification, the needle-like mullite crystals remain largely unchanged. However, the surface of the coal gasification slag particles is partially covered with an amorphous gel-like substance and hexagonal flake-like structures of $\text{Ca}(\text{OH})_2$. This is because, under strongly alkaline conditions, the active substances such as Si, Al, and Ca in the coal gasification slag glass phase continuously dissolve and react with OH^- to form gel-like substances and a small amount of $\text{Ca}(\text{OH})_2$. Due to the relatively low Ca content in the coal gasification slag, the dissolution amount in an alkaline environment is low, leading to direct combination with OH^- . Consequently, the dissolved Si and Al from the glass phase cannot effectively combine with Ca to form gel products. Instead, they combine with Na^+ ions to form N-A-S-H gel products to maintain

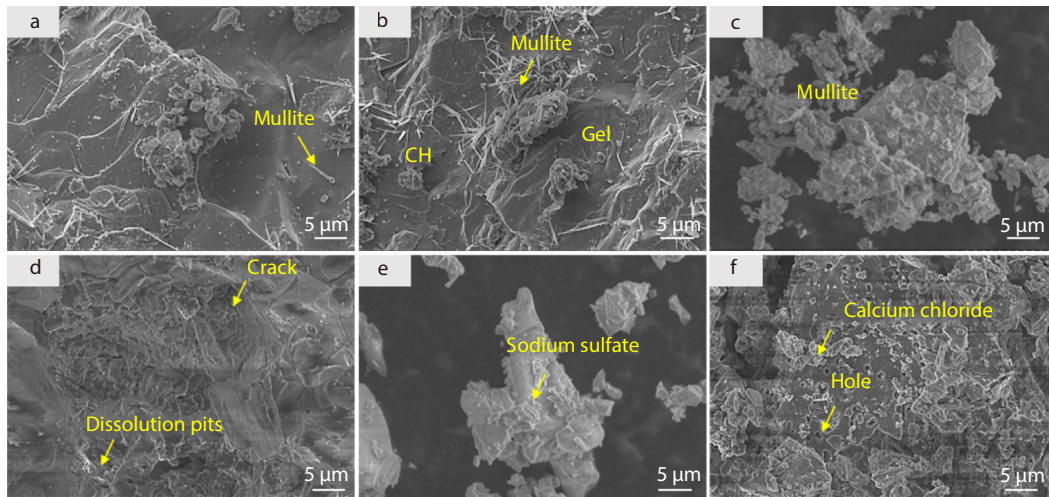


Fig. 6. SEM images of coal gasification slag under different modification conditions. (a) CGS, (b) CGS-SH, (c) CGS-PH, (d) CGS-HA, (e) CGS-SS, (f) CGS-CC.

charge balance.

Fig. 6d shows that the surface of the coal gasification slag modified by acid leaching is uneven, with dissolution pits and micro-cracks. From Fig. 6e and f, it can be seen that the surface of the coal gasification slag modified by salts contains some fine crystalline particles, which may be due to the refined sodium sulfate or calcium chloride crystals adhering to the surface of the coal gasification slag particles. The surface of the coal gasification slag modified by sulfates shows no changes, while the surface of the coal gasification slag modified by chlorides exhibits some small dissolution sites. This is because, under the action of mechanical force, vacancies are generated in the silicate structure of the coal gasification slag. The CaCl_2 , due to charge balance effects, substitutes or disrupts the metal ions (such as Ca^{2+} , Na^+ , Al^{3+} , etc.) in these structures, leading to a decrease in structural stability and the appearance of dissolution sites.

3.2. Rietveld whole-pattern fitting

Generally, it is believed that a higher glass phase content in coal gasification slag indicates higher pozzolanic activity. X-ray diffraction (XRD) analysis is a characteristic method for characterizing crystalline structures. To more intuitively analyze changes in the glass phase content of modified coal gasification slag, the EXPGUI-GSAS software was employed to perform Rietveld whole-pattern fitting on the samples. The Rietveld whole-pattern fitting method is a technique for calculating the glass phase content in coal gasification slag, enabling quantitative determination of the contents of the amorphous phase within the slag.

First, 0.9 g of coal gasification slag and 0.1 g of $\alpha\text{-Al}_2\text{O}_3$ standard sample were weighed and placed into an agate mortar. Manual grinding was then carried out for approximately 10 min, during which an appropriate amount of anhydrous ethanol solution was added. Subsequently, the mixture was placed in a drying oven at 40 °C for 3 h of drying. After XRD analysis, the obtained data were subjected to phase structure refinement using the EXPGUI-GSAS software. The amorphous phase was treated as the background, and

the Rietveld whole-pattern fitting analysis method was employed to quantitatively calculate the weight percentages of each phase.

The formula for the quantitative analysis of mass percentages using the Rietveld whole-pattern fitting analysis method is presented as follows:

$$W_a = \frac{m_a}{\sum_n m_n} = \frac{S_a Z_a M_a V_a}{\sum_n S_n Z_n M_n V_n}$$

where W_a represents the mass percentage of the a -th phase; S_n is the scale factor of the n -th phase; Z_n denotes the number of molecules per unit cell of the n -th phase; M_n is the molecular weight of the n -th phase; V_n indicates the unit cell volume of the n -th phase.

$$\text{Corr}(W_a) = W_a \frac{STD_{\text{measured}}}{STD_{\text{known}}}$$

where $\text{Corr}(W_a)$ represents the corrected Rietveld mass percentage of phase a ; STD_{known} is the actual content of the internal standard substance; STD_{measured} is the Rietveld quantitative analysis result of the internal standard substance.

$$W_{\text{amorphous}} = 1 - \sum_{j=1}^n \text{Corr}(W_j)$$

where $W_{\text{amorphous}}$ represents the content of the amorphous phase calculated by the Rietveld method.

Fig. 7 illustrates the Rietveld whole-pattern fitting process for coal gasification slag under different chemical modification conditions. As can be discerned from the figure, the fitting results for each sample exhibit a high degree of accuracy and reliability, indicating that the Rietveld whole-pattern fitting method has been effectively applied to analyze the coal gasification slag under different chemical modification conditions.

Table 7 presents the calculated results of the amorphous phase content obtained from the Rietveld whole-pattern fitting. It can be observed that the CGS-SH exhibits the highest

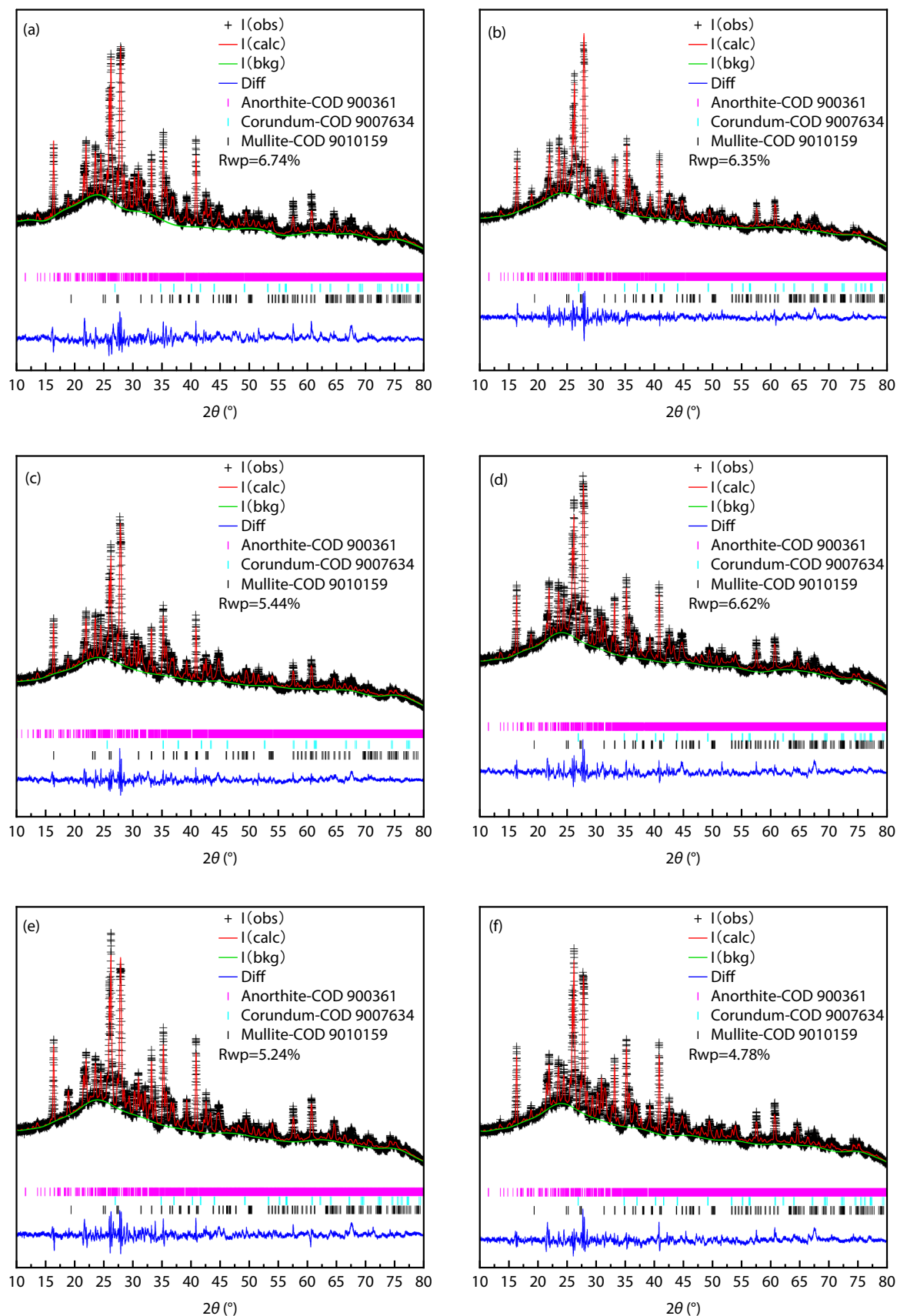


Fig. 7. The Rietveld refinement of XRD patterns. (a) CGS, (b) CGS-SH, (c) CGS-PH, (d) CGS-HA, (e) CGS-SS, and (f) CGS-CC.

amorphous phase content, showing an increase of 11.96% compared with the control group, followed by CGS-PH. The

increase in the amorphous phase of the coal gasification slag modified by alkali dissolution can be attributed to the fact

Table 7. The calculation results of amorphous phase content from Rietveld refinement.

Sample	CGS	CGS-SH	CGS-PH	CGS-HA	CGS-SS	CGS-CC
Content	35.65%	47.62%	46.31%	34.53%	41.45%	39.77%

that a large amount of Si and Al active substances, along with a small amount of Ca substances, are leached out from the aluminosilicate glass matrix of the coal gasification slag in an alkaline environment.

In contrast, the CGS-HA shows a slight decrease in the amorphous phase. This is because, under acidic conditions, H^+ ions can effectively depolymerize the alkaline bonds such as Al–O, Ca–O, and Fe–O in the aluminosilicate glass matrix, thereby disrupting the network structure of the amorphous aluminosilicate and resulting in a loss of about 1.1% in the amorphous phase content. On the other hand, the CGS-SS and CGS-CC exhibit a slight increase in the amorphous phase. This is due to the fact that under the combined action of mechanical force and chemical effects, during the phase transformation process, the particle lattices undergo deformation and dislocation, leading to the formation of unstable crystal structures.

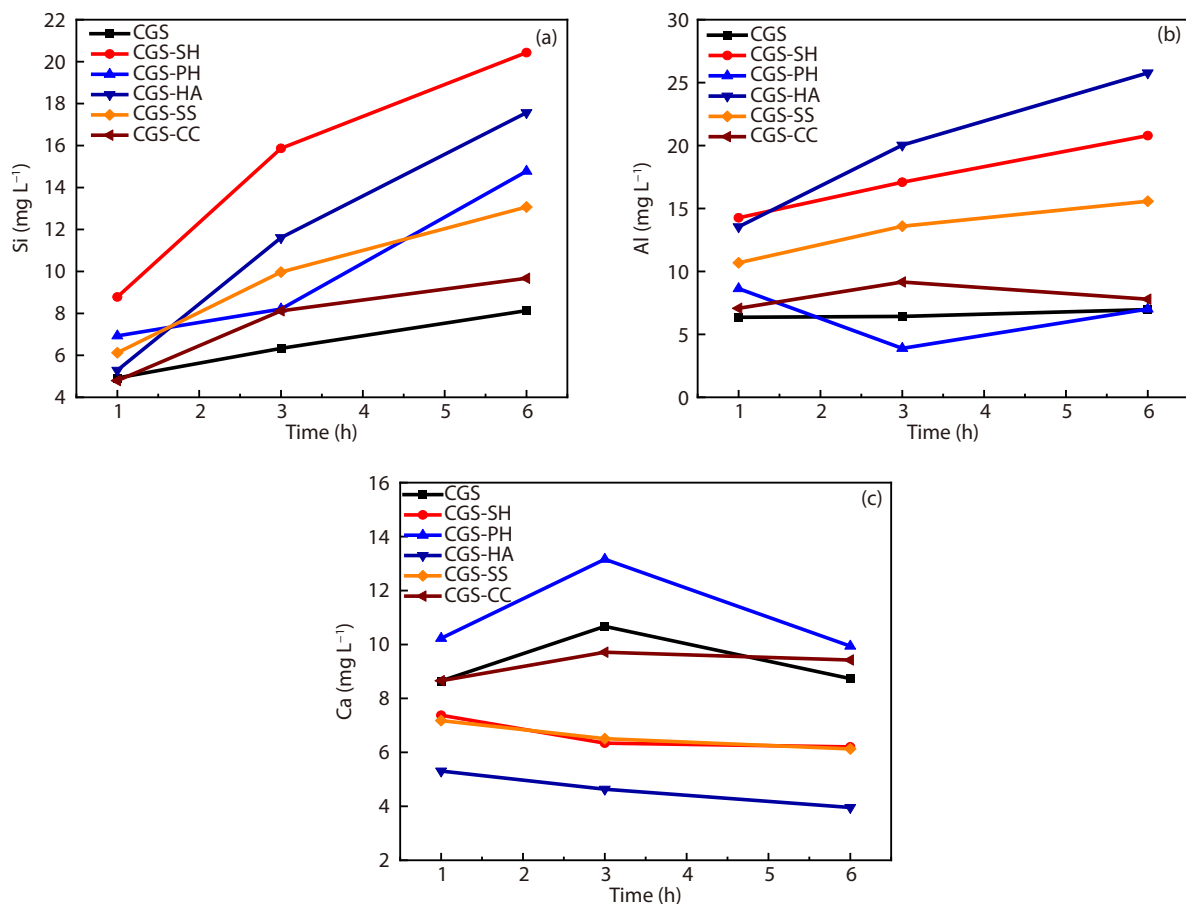
3.3. Ion leaching

Due to the varying degrees of destruction of the aluminosilicate glass phase in coal gasification slag, the release amounts of active components differ. Consequently, by comparing the leaching amounts of silicon, aluminum, and calcium from

coal gasification slag subjected to various chemical modifications, it is possible to evaluate the relative merits of the pozzolanic activity. An inductively coupled plasma optical emission spectrometer (ICP-OES) was employed to determine the contents of silicon, aluminum, and calcium in the solution.

As can be observed from Fig. 8a, with the extension of the leaching time, the Si leaching amounts exhibit a continuous upward trend. Furthermore, when the leaching time is held constant, all the modified coal gasification slags demonstrate varying degrees of enhancement in Si leaching amounts compared to the control group. For instance, when the leaching time is fixed at 6 h, the CGS-SH and CGS-HA exhibit the most favorable Si leaching performance. The Si leaching amounts for CGS-SH and CGS-HA are 20.4 mg L^{-1} and 17.6 mg L^{-1} , respectively, representing increases of 151.9% and 117.3% compared to the control group (8.1 mg L^{-1}), while the Si leaching amounts of CGS-PH, CGS-SS, and CGS-CC increase by 81.5%, 61.7%, and 19.8%, respectively.

As depicted in Fig. 8b, the leaching amount of Al^{3+} ions from CGS exhibits a sluggish increase with the prolongation of leaching time and remains almost unchanged under alkaline conditions. In contrast, for CGS-SH, CGS-HA, and CGS-SS, the leaching amounts of Al^{3+} ions gradually rise as the leach-

**Fig. 8.** Solubility of (a) Si, (b) Al, and (c) Ca in modified coal gasification slag.

ing time extends, with 20.8 mg L⁻¹, 25.8 mg L⁻¹, and 15.6 mg L⁻¹, respectively, increasing by 201.4%, 273.9%, and 126.1% compared to the control group (6.9 mg L⁻¹). For CGS-PH, the dissolution amount of Al³⁺ ions initially decreases and then increases over the leaching time. Although CGS-PH and CGS-SH both belong to alkali-activated samples, the leaching amounts of Si and Al in CGS-PH are far inferior to those in CGS-SH. This can be attributed to the fact that Na⁺ has a higher charge density and a smaller ionic radius compared with K⁺, which facilitates the approach of OH⁻ to Si-O and Al-O bonds. In the case of the CGS-CC, the leaching amount of Al³⁺ ions first increases and then decreases with the prolongation of leaching time. This is because the excess Ca²⁺ ions react with Si⁴⁺ and Al³⁺ ions through polycondensation in the alkaline solution, leading to the formation of gel-like substances.

As illustrated in Fig. 8c, the Ca²⁺ ion concentrations in the CGS-SH, CGS-HA, and CGS-SS exhibit a declining trend. This phenomenon can be attributed to two main factors. Firstly, the leached Ca²⁺ reacts with OH⁻ to form Ca(OH)₂, thereby reducing the Ca²⁺ concentration in the solution. Secondly, the Ca-O bond energy is significantly lower than that of Si-O and Al-O bonds. In the CGS-SH, Ca²⁺ dissolves first, and then interacts with OH⁻, Si⁴⁺, and Al³⁺ in the solution to form gel-like substances. For CGS-PH and CGS, the Ca²⁺ leaching shows an initial increase followed by a decrease. In the initial stage, the leaching of Ca²⁺ from CGS-PH is relatively slow, and the concentration of Ca²⁺ in the solution remains below the solubility curve of Ca(OH)₂, resulting in a temporary increase. However, as the leaching time progresses, the Ca²⁺ in the solution gradually precipitates and aggregates, leading to a subsequent decline in concentration. In the case of CGS-CC, due to the introduction of an excess calcium source into the system, the dissolution curve of Ca²⁺ initially increases and then remains stable.

In summary, the CGS-SH and CGS-HA groups exhibit the most outstanding performance in terms of silicon and aluminum leaching. The CGS-SS group follows with relatively good performance. This superior leaching effect can be attributed to the chemical activation of the Al-O and Si-O bonds within the amorphous aluminosilicate glass matrix. Specifically, the chemical actions disrupt the structure of the aluminosilicate glass matrix, leading to a decrease in the polymerization degree of the aluminosilicate glass matrix. In an alkaline environment, this structural change accelerates the dissolution of silicon and aluminum active substances. Regarding calcium leaching, in contrast to the control group, the calcium leaching amount decreases. This is because during the modification process, Ca²⁺ ions undergo polymerization reactions with other substances.

On the other hand, the CGS-PH and CGS-CC groups show relatively low leaching amounts of silicon and aluminum but relatively high calcium leaching amounts. This indicates that the modification methods employed in these two groups have a limited impact on disrupting the glass matrix structure, which in turn restricts the leaching of silicon and aluminum.

3.4. Quality loss method

The slag contains active minerals such as Al₂O₃ and SiO₂, which endow it with inherent pozzolanic activity. To achieve precise qualitative and quantitative characterization of the pozzolanic activity of the modified coal gasification slag, this study pioneers the use of a quality loss method.

The specific testing procedure is as follows: Initially, the coal gasification slag and Ca(OH)₂ are mixed in a ratio of 4:1. Subsequently, the mixture is stirred evenly under a water-cement ratio of 0.5. After that, the well-stirred mixture is molded at room temperature. Once the specimens are demolded, they are placed in an environment maintained at 80 °C for a curing period of 3 d. To halt the hydration reaction, anhydrous ethanol is employed. After the hydration reaction is terminated, the specimens are dried and then ground into powder for analysis. The remaining amount of Ca(OH)₂ after its reaction with the coal gasification slag can be expressed by the following formula.

$$W_{\text{Ca(OH)}_2 \text{ Residual}} = (m_1/18) \times 74 + (m_2/44) \times 74$$

Consumption of Ca(OH)₂ can be expressed by the following formula.

$$W_{\text{Ca(OH)}_2 \text{ Consume}} = [(1 - W_1) - W_{\text{Ca(OH)}_2 \text{ Residual}}] \times 1000/W_1$$

In the formulas, m_1 represents the mass loss percentage of the mixed paste within the temperature range of 350–450 °C. This specific temperature interval is chosen because it is closely related to the decomposition of Ca(OH)₂, as shown in Fig. 9. m_2 denotes the mass loss percentage of the mixed slurry within the temperature range of 500–700 °C. This range is typically associated with the decomposition of carbonates that may be present in the system, which helps in further distinguishing and quantifying the reaction products and unreacted components. W_1 is defined as the proportion of the pozzolanic material in the mixed slurry, which in this case is 75%.

The calculated consumption amounts of Ca(OH)₂ are listed in Table 8. By quantitatively analyzing the pozzolanic activity according to the consumption amounts of Ca(OH)₂, it is found that the CGS-SH and CGS-HA exhibit the highest Ca(OH)₂ consumption per gram of slag, with values of 109.921 mg and 111.728 mg, respectively. This indicates that these groups possess the strongest pozzolanic activity, which is consistent with the aforementioned analysis results.

3.5. Compressive strength

Fig. 10 and Table 9 illustrate the 7 d and 28 d compressive strengths of cement mortars incorporating different slags. When the curing age reaches 7 d, the cement with CGS-SH exhibits the highest compressive strength, reaching 35.3 MPa, which represents an approximately 13.50% increase compared to the control group (cement with CGS). At a curing age of 28 d, the cement with CGS-CC demonstrates the maximum compressive strength of 52.6 MPa, showing an improvement of nearly 13.11% over the control group. This enhancement can be attributed to the introduction of additional Ca²⁺

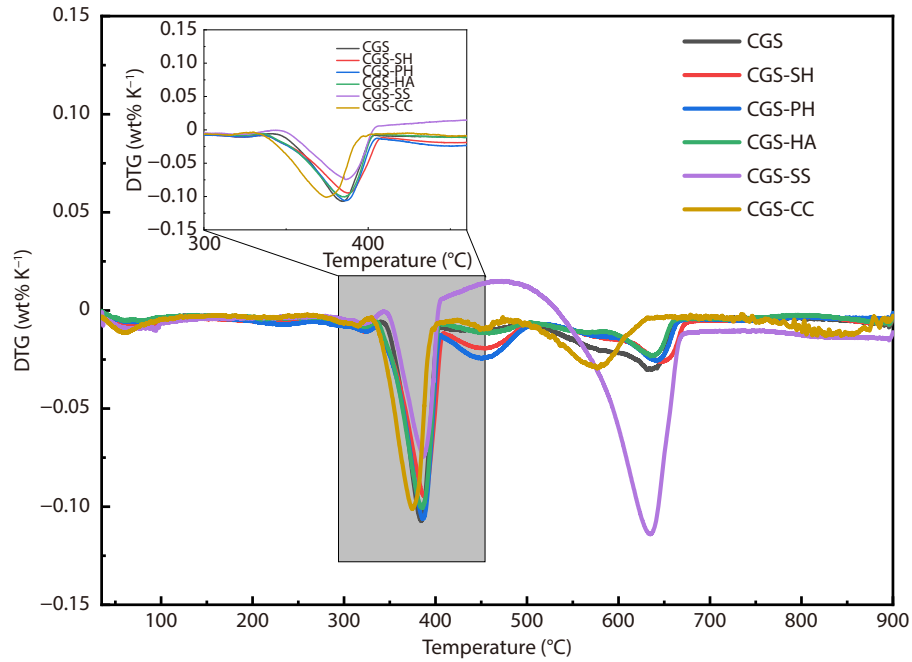


Fig. 9. DTG curves of MCGS- Ca(OH)_2 - H_2O paste.

Table 8. Consumption of Ca(OH)_2 per gram of modified coal gasification slag.

Sample	$W_{\text{H}_2\text{O}}$ (wt%)	W_{CO_2} (wt%)	$W_{\text{Ca(OH)}_2}$ Residual (wt%)	$W_{\text{Ca(OH)}_2}$ Consume (mg)
CGS	3.129	2.943	17.813	95.823
CGS-SH	3.087	2.417	16.756	109.921
CGS-PH	3.340	2.107	17.275	103.004
CGS-HA	3.241	1.960	16.620	111.728
CGS-SS	2.193	6.935	20.679	57.613
CGS-CC	3.269	2.391	17.460	100.533

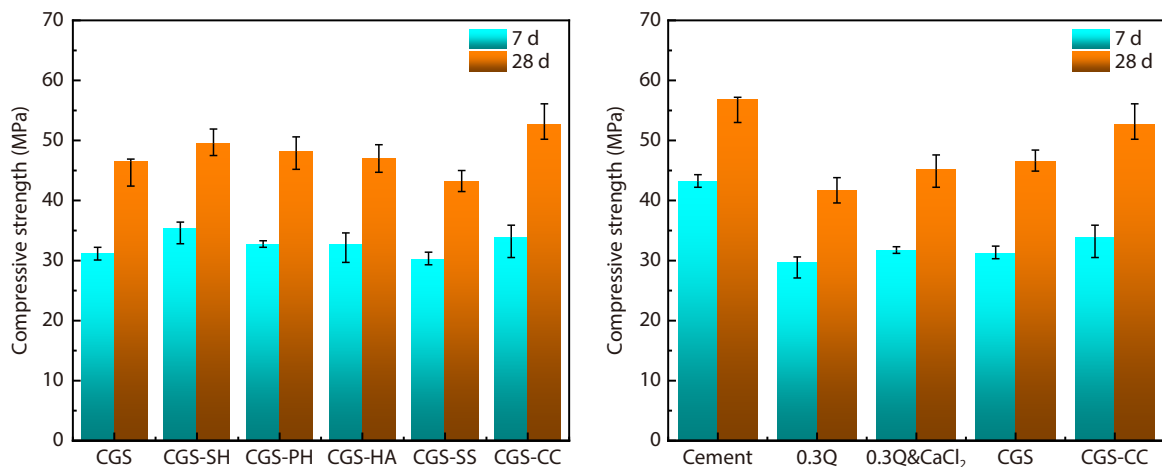


Fig. 10. Compressive strength of different modified coal gasification slags at 7 d and 28 d.

Table 9. Growth ratio of compressive strength for different modified coal gasification slags versus the control group at 7 d and 28 d (%).

Time	CGS-SH	CGS-PH	CGS-HA	CGS-SS	CGS-CC
7 d	13.50	5.14	4.82	-3.21	9.00
28 d	6.45	3.65	1.07	-0.07	13.11

and Cl^- ions into the system.

Furthermore, the CGS-SH consistently outperforms the CGS-PH in terms of cement compressive strength across all curing ages. This observation aligns with previous findings, indicating that the modification effect of KOH is significantly inferior to that of NaOH. The CGS-HA shows relatively modest

increases in compressive strength, with improvements of 4.82% and 1.07% at different curing ages compared to the control group. This limited enhancement is likely due to the excessive destruction of the aluminosilicate glassy phase in the coal gasification slag by the modifier, resulting in the loss of amorphous phases and active substances, which subsequently slows down the strength development in the cement mortar.

In contrast, the CGS-SS exhibits a slight decrease in compressive strength compared to the control group. This phenomenon can be ascribed to the potential excess of SO_4^{2-} ions in the system, leading to the formation of excessive gypsum and ettringite during the later stages of cement hydration. These excessive hydration products disrupt the pore structure of the cement mortar, thereby negatively impacting its compressive strength.

To evaluate the enhancing effect of CaCl_2 on cement, three groups were tested: pure cement, cement with 30% quartz powder replacement (0.3Q), and the same blend with CaCl_2 addition (0.3Q& CaCl_2). The results indicate that CaCl_2 improves the mechanical properties of cement. When the cement content was 70%, CGS exhibited approximately 11% higher mechanical performance compared to 0.3Q, confirming the pozzolanic activity of CGS. After CaCl_2 modification, CGS-CC showed approximately 16% higher mechanical performance than 0.3Q& CaCl_2 , suggesting that the improvement in the hydration activity of coal gasification slag originates from both its intrinsic modification and the effect of the salt.

To further ascertain the extent of the influence of modification methods on compressive strength, an analysis of variance (ANOVA) was employed for the calculations. Given that the effect of curing age on compressive strength is significant, and our primary focus is on analyzing the impact of modification methods on compressive strength, the confidence probability for the modification methods was calculated, as presented in Table 10. Here, SS denotes the sum of squares of deviations, DF represents degrees of freedom, MS stands for mean square, and F is the parameter used to construct the confidence interval. The F-value for the factor "modification method" is 12.25, which is higher than $F_{0.05}$, indicating its significance at a 95% confidence probability.

Table 10. ANOVA on the compressive strength with different modification methods.

Difference source	SS	DF	MS	F	$F_{0.05}$	Confidence probability (%)
Modification method	115.52	4	28.880	12.25	6.39	95
Error	9.43	4	2.3575	/	/	/

4. Discussion

In this study, four distinct and complementary methods were employed to evaluate the pozzolanic activity of the coal gasification slag; it was found that the modification processes could effectively alter the physicochemical properties of the

slag. These changes enhanced the dissolution of reactive SiO_2 and Al_2O_3 , promoted the formation of more stable hydration products, and ultimately improved the pozzolanic activity of slag and the mechanical performance of the cement-based materials incorporating the modified slag.

A comparative analysis of the test cycles associated with different evaluation methods for pozzolanic activity reveals distinct differences in their time-consuming characteristics (Table 11). Among the methods under consideration, the compressive strength method exhibits the longest test cycle. In contrast, the Rietveld whole-pattern fitting method, ion leaching method, and quality loss method offer significantly shorter evaluation cycles. Therefore, these methods can be effectively employed as rapid evaluation techniques for the pozzolanic activity of coal gasification slag.

Table 11. Test cycle for different evaluation methods.

Evaluation methods	Test cycle
Rietveld whole-pattern fitting method	< 1 d
Ion leaching method	< 1 d
Quality loss method	3 d
Compressive strength method	28 d

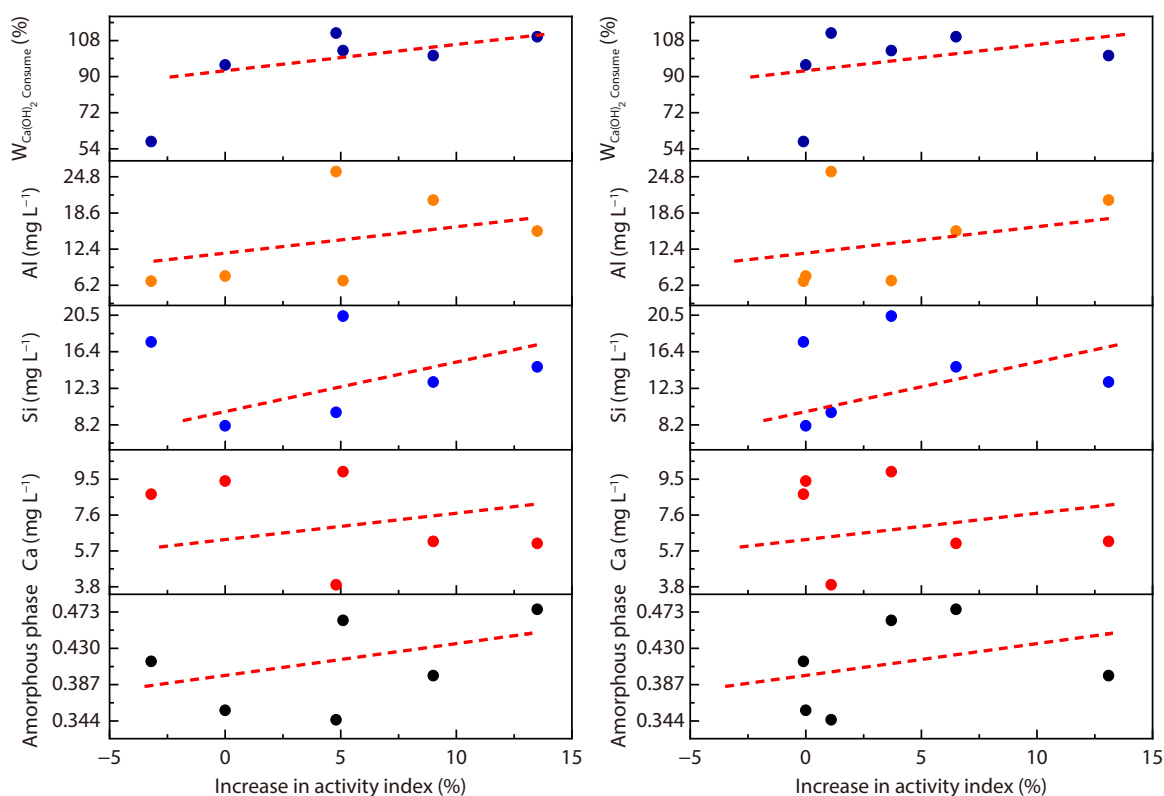
Table 12 and Fig. 11 present a comparison of test results obtained using different evaluation methods. Although the results show a positive correlation, the experimental results indicate that individual methods exhibit deviations when used alone to predict compressive strength. For instance, CGS-CC, despite having a slightly lower amorphous phase content than CGS-PH, demonstrates a higher strength growth rate. Similarly, CGS-HA shows a higher silicon–aluminum dissolution amount compared to the other experimental groups, yet its compressive strength growth rate is lower. Since the coal gasification slag was treated with acid, the amorphous phases in the slag, which are primarily composed of Si–O and Al–O bonds, were dissolved after acid treatment. Consequently, the amorphous content decreased. The dissolution of the amorphous phase converted the original Si–O and Al–O bonds into Si^{4+} and Al^{3+} ions, which are more readily leached in a liquid phase compared to when they are retained within the amorphous matrix. Moreover, CGS-HA exhibits the highest $W_{\text{Ca}(\text{OH})_2 \text{ Consume}}$ value, but its compressive strength is still lower than those of CGS-SH and CGS-CC. Due to its relatively low amorphous phase content, the subsequent pozzolanic reaction may be hindered.

These findings suggest that any single method among the Rietveld whole-pattern fitting method, the silicon–aluminum dissolution method, and the quality loss method may yield biased predictions when used independently. When these methods are used simultaneously, the operation is simple, no extra-long curing age is required, and meanwhile, considerable accuracy can be guaranteed. For example, CGS-PH exhibits a high amorphous phase content and calcium hydroxide consumption, with a high ion dissolution amount, so its hydration activity is significantly improved.

Through a comprehensive comparison of various modification methods, distinct differences in the performance enhance-

Table 12. Comparison of results from different evaluation methods.

Sample	Rietveld whole-pattern fitting method	Ion leaching method (mg L ⁻¹)			Quality loss method	Growth ratio of compressive strength (%)	
	Amorphous phase	Ca	Si	Al	$W_{\text{Ca(OH)}_2 \text{ Consume}}$ (mg)	7 d	28 d
CGS	35.65%	8.7	8.1	6.9	95.8	/	/
CGS-SH	47.62%	6.2	20.4	20.8	109.9	13.5	6.5
CGS-PH	46.31%	9.9	14.7	7.1	103.0	5.1	3.7
CGS-HA	34.53%	3.9	17.6	25.8	111.7	4.8	1.1
CGS-SS	41.45%	6.1	13.1	15.6	57.6	-3.2	-0.1
CGS-CC	39.77%	9.4	9.7	7.8	100.5	9.0	13.1

**Fig. 11.** Relationship between the increase in activity and different test results. (a) 7 d, (b) 28 d.

ment effects have been revealed. In terms of early-stage performance, the activation with NaOH demonstrates a significant advantage. However, the specimens modified with CaCl_2 show a continuous increase in strength over an extended curing period, surpassing the strength values of the NaOH-modified specimens at later ages. In contrast, HCl modification has a relatively minor impact on both the early- and late-stage performance of the coal gasification slag-based cementitious materials. The performance enhancement effects of different modification methods are visually presented in Fig. 12.

As shown in the figure, the coal gasification slag modified by NaOH undergoes significant particle refinement during grinding, owing to the corrosive effect of OH^- on the glassy structure. Meanwhile, the high-temperature drying process partially attacks the mullite mineral phase and promotes the breakage and reorganization of Si–O–Al and Si–O–Si bonds in the amorphous phase. This facilitates the polymerization of reactive species within the slag into Ca(OH)_2 and N-A-S-H, thereby increasing the amorphous

phase content and enhancing the silicon–aluminum dissolution. For the slag modified by HCl, the corrosive effect of H^+ on the aluminosilicate glass induces the breakage and reorganization of Si–O–Al and Si–O–Si bonds, resulting in the formation of etching pits on the slag surface. This disrupts the aluminosilicate glassy structure, reduces the amorphous content, but increases the silicon–aluminum dissolution. For the slag modified by CaCl_2 , electrostatic adsorption during grinding enables a certain degree of particle refinement, while mechanochemical effects cause lattice deformation and dislocation in some particles, forming unstable crystal structures. This leads to an increase in the amorphous phase content and enhanced silicon–aluminum dissolution.

In summary, different chemical activators modify coal gasification slag through distinct mechanisms, and most methods enhance its pozzolanic activity and improve comprehensive utilization efficiency. This further enables the resource utilization of coal gasification slag for the preparation of low-carbon cementitious materials.

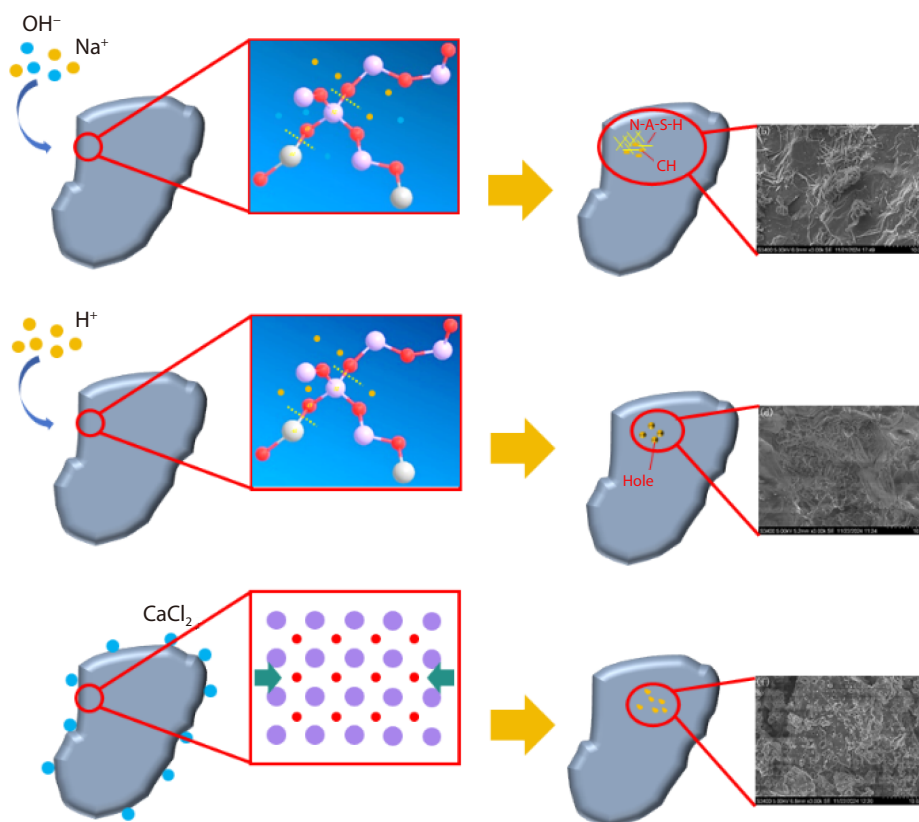


Fig. 12. Schematic diagram of different modification methods to enhance hydration activity.

Although this study primarily focuses on the activity evaluation methods, it also presents several types of modification approaches for coal gasification slag. From the perspective of cost, industrial alkali has the highest price, while salt exhibits a relatively low cost. In terms of process operability, the acid-base modification process involves soaking, washing, and drying, which is relatively complicated and generates waste liquid. Therefore, when chemical methods are employed for slag modification, environmental benefits must also be taken into account. When waste liquid is generated, it can be concentrated and reused for the modification of coal gasification slag, so as to realize full-process circulation. From the perspective of application scenarios, when the chemically modified coal gasification slag is applied in structural buildings, the corrosion effect of salt ions on steel bars and other components still needs to be considered.

5. Conclusion

This study compared the impacts of different modification methods on the structural characteristics of coal gasification slag and evaluated the pozzolanic activity of the modified coal gasification slag. Under the experimental conditions of this study, the following conclusions can be drawn.

(1) For coal gasification slag modified by NaOH, Na_2SO_4 , and CaCl_2 , compared with the control group, the amorphous phase content increased. Its ions are more prone to leaching, and more $\text{Ca}(\text{OH})_2$ is formed. For CGS modified by CaCl_2 , the 28 d compressive strength increased by nearly 13.11%. However, for CGS modified by NaOH, the 7 d compressive strength exhibits the most significant enhancement.

(2) The Rietveld whole-pattern fitting method, ion leaching method, and quality loss method can be effectively employed as rapid evaluation techniques for the pozzolanic activity of coal gasification slag.

(3) For the chemical modification of coal gasification slag, the selection should comprehensively consider the cost, process maturity, and actual application scenario requirements. Chemical reagents with low cost, simple process, good environmental benefit, and minor impact on the structure are preferred.

The above conclusions are obtained under the experimental conditions of this study, and the industrial application effect needs to be further verified by pilot tests.

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Data availability

All data needed to support the conclusions in the paper are presented in the manuscript. Additional data related to this paper may be available from the corresponding author upon request.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Zhibing Liu is employed by No. 3 Engineering Co., Ltd of CCCC Third Harbor Engineering Co., Ltd.

Author contribution statement

Yafeng Rui: Investigation, Data curation, Writing – original draft. **Tianyong Huang, Fengdong Liu:** Methodology, Conceptualization, Writing – review & editing. **Guiquan Zhang, Changlong Wang, Zhibing Liu:** Resources.

Use of AI statement

None.

References

- [1] Tang, H., He, J., Fu, L., et al. Supergravity separation: An innovative strategy for efficient cleaning and upgrading of coal gasification slag waste. *Waste Management*, **2025**, 205: 114973. <https://doi.org/10.1016/j.wasman.2025.114973>.
- [2] Deng, X., Chen, L., Zhao, Z., et al. Effect of ultrasonic-hydraulic coupling cavitation pretreatment on carbon extraction from coal gasification coarse slag by flotation. *Fuel*, **2024**, 378: 132898. <https://doi.org/10.1016/j.fuel.2024.132898>.
- [3] Ren, L., Ding, L., Guo, Q., et al. Characterization, carbon-ash separation and resource utilization of coal gasification fine slag: A comprehensive review. *Journal of Cleaner Production*, **2023**, 398: 136554. <https://doi.org/10.1016/j.jclepro.2023.136554>.
- [4] Chai, Z., Liu, B., Lv, P., et al. Recycling of coal gasification fine slag as ultra-high capacity adsorbents for the removal of Rhodamine B dye: Graded synthesis method, kinetics and adsorption mechanism. *Fuel*, **2023**, 333: 126318. <https://doi.org/10.1016/j.fuel.2022.126318>.
- [5] Zhao, W., Zhang, L., Chen, H., et al. Mechanism study on the inhibition of iron precipitation behavior by microstructure transformation of slag during co-gasification of biomass and coal. *Fuel*, **2027**, 429: 140786. <https://doi.org/10.1016/j.fuel.2026.140786>.
- [6] Su, S., Tahir, M. H., Cheng, X., et al. Modification and resource utilization of coal gasification slag-based material: A review. *Journal of Environmental Chemical Engineering*, **2024**, 12(2): 112112. <https://doi.org/10.1016/j.jece.2024.112112>.
- [7] Sun, Y., Fan, P., Yang, J., et al. Study on the mechanism of hydrothermal pretreatment enhancing the flotation of coal gasification fine slag. *Fuel*, **2025**, 399: 135669. <https://doi.org/10.1016/j.fuel.2025.135669>.
- [8] Zhao, X., Yang, K., He, X., et al. Overview of the triple attributes and their connections of coal gasification slag in China: Resources, materials, and environment. *Fuel*, **2025**, 400: 135646. <https://doi.org/10.1016/j.fuel.2025.135646>.
- [9] Guo, F., Guo, Y., Chen, L., et al. Multitudinous components recovery, heavy metals evolution and environmental impact of coal gasification slag: A review. *Chemosphere*, **2023**, 338: 139473. <https://doi.org/10.1016/j.chemosphere.2023.139473>.
- [10] Xuan, W., Liu, W., Yan, S., et al. Preparation of hierarchical porous materials using coal gasification fine slag and the ammonia nitrogen adsorption performance. *Fuel*, **2025**, 399: 135599. <https://doi.org/10.1016/j.fuel.2025.135599>.
- [11] Ma, L., Zhao, G., Zhang, J., et al. Characteristics of iron precipitation and slag melting in the coal gasification and flash ironmaking coupling process. *Chemical Engineering Science*, **2026**, 336: 124548. <https://doi.org/10.1016/j.ces.2026.124548>.
- [12] Liu, X., Jin, Z., Jing, Y., et al. Review of the characteristics and graded utilisation of coal gasification slag. *Chinese Journal of Chemical Engineering*, **2021**, 35: 92–106. <https://doi.org/10.1016/j.cjche.2021.05.007>.
- [13] Hu, Z., Gu, X., Li, Z., et al. Sustainable valorization of coal gasification slag through optimized grinding kinetics: Composite cement compressive strength enhancement and environmental assessment. *Environmental Research*, **2025**, 277: 121601. <https://doi.org/10.1016/j.envres.2025.121601>.
- [14] Liao, S., Xu, H., Zhang, H., et al. Composite energy storage cement-based mortar including coal gasification slag/paraffin shape-stabilized phase change material: Physical, mechanical, thermal properties. *Journal of Building Engineering*, **2024**, 95: 110327. <https://doi.org/10.1016/j.jobe.2024.110327>.
- [15] Yang, P., Suo, Y., Liu, L., et al. Study on the curing mechanism of cemented backfill materials prepared from sodium sulfate modified coal gasification slag. *Journal of Building Engineering*, **2022**, 62: 105318. <https://doi.org/10.1016/j.jobe.2022.105318>.
- [16] Fu, B., Cheng, Z., Wang, D., et al. Investigation on the utilization of coal gasification slag in Portland cement: Reaction kinetics and microstructure. *Construction and Building Materials*, **2022**, 323: 126587. <https://doi.org/10.1016/j.conbuildmat.2022.126587>.
- [17] Li, Z., Zhang, Y., Zhao, H., et al. Structure characteristics and composition of hydration products of coal gasification slag mixed cement and lime. *Construction and Building Materials*, **2019**, 213: 265–274. <https://doi.org/10.1016/j.conbuildmat.2019.03.163>.
- [18] Zhao, Y., Gu, X., Xu, X. Physical-chemical performance of coal gasification slag with calcination activation utilized as supplementary cementitious material. *Construction and Building Materials*, **2024**, 451: 138776. <https://doi.org/10.1016/j.conbuildmat.2024.138776>.
- [19] Sun, X., Sun, R., Liu, D., et al. Preparation of coal gasification coarse slag-based alkaline activator and its activation mechanism in alkali-activated slag. *Cement and Concrete Composites*, **2024**, 152: 105648. <https://doi.org/10.1016/j.cemconcomp.2024.105648>.
- [20] Long, S., Bai, X., Xie, W., et al. Mechanical grinding mechanisms for particle characteristics and cementitious activity of coal gasification coarse slag. *Powder Technology*, **2026**, 482: 122815. <https://doi.org/10.1016/j.powtec.2026.122815>.
- [21] Guo, Q., Huo, B., Yu, K., et al. Using acetic acid as a preconditioner to optimize rheology of alkali-activated coal gasification slag based backfill pastes. *Minerals Engineering*, **2024**, 218: 109040. <https://doi.org/10.1016/j.mineng.2024.109040>.
- [22] Chang, R., Zhang, J., Li, H., et al. Preparation and characterization of cementitious materials based on sulfuric-acid-activated coal gasification coarse slag. *Construction and Building Materials*, **2024**, 426: 136164. <https://doi.org/10.1016/j.conbuildmat.2024.136164>.
- [23] Fang, K., Zhang, D., Wang, D., et al. The impact of coal gasification slag powder on fluidity, rheology and viscoelasticity properties of fresh cement paste. *Journal of Building Engineering*, **2023**, 69: 106237. <https://doi.org/10.1016/j.jobe.2023.106237>.
- [24] Zhang, X., Wang, X., Li, Z., et al. Study on preparation and performance of cement-stabilized macadam containing ground sludge gasification slag (GSGS). *RSC Advances*, **2025**, 15(9): 7139–7148. <https://doi.org/10.1039/d5ra00462d>.
- [25] Yang, P., Liu, L., Suo, Y., et al. Physical-chemical coupling excitation of low activity coal gasification slag solid waste and its application as a backfill cementitious material. *Construction and Building Materials*, **2023**, 401: 132973. <https://doi.org/10.1016/j.conbuildmat.2023.132973>.
- [26] Zheng, Y., Medepalli, S., Wang, T., et al. A multi-scale experimental investigation of the feasibility of using integrated coal gasification combined slag as a supplementary cementitious material. *Journal of Cleaner Production*, **2024**, 449: 141491. <https://doi.org/10.1016/j.jclepro.2024.141491>.
- [27] Sachdeva, N., Shrivastava, N., Shrivastava, S. Pozzolan reaction and strength activity index of dolomite powder incorporated cement mortar. *Materials Today: Proceedings*, **2023**. <https://doi.org/10.1016/j.matpr.2023.05.042>.

- [28] Patil, C., Manjunath, M., Hosamane, S., et al. Pozzolonic activity and strength activity index of bagasse ash and fly ash blended cement mortar. *Materials Today: Proceedings*, **2021**, 42: 1456–1461. <https://doi.org/10.1016/j.matpr.2021.01.251>.
- [29] Yang, J., Yang, X., Wang, X., et al. Influence of mechanical grinding on particle group characteristics and cementation activity of magnesium slag from Xinjiang Tengxiang. *Construction and Building Materials*, **2025**, 487: 142081. <https://doi.org/10.1016/j.conbuildmat.2025.142081>.
- [30] Panzer, M., Scherb, S., Beuntner, N., et al. Effect of sulfate carrier addition on the strength of calcined clay blended cements. *Construction and Building Materials*, **2025**, 477: 140915. <https://doi.org/10.1016/j.conbuildmat.2025.140915>.



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