Formation Mechanism of "Encapsulated" Carbide Slag Composite Alkalinity Sustained-release Particles for the Source Control of Acid Mine Drainage

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Abstract

Acid mine drainage (AMD) has caused serious and long-lasting damage to the environment in many countries. The source control of AMD is considered to be the most direct and effective method of remediation. Carbide slag is an industrial waste which is considered as a potential treatment material for AMD treatment due to the strong alkalinity. However, the application of carbide slag in the source control of AMD encounters difficulties due to its fast alkalinity release rate. This is a first attempt to mix carbide slag with bentonite to prepare alkalinity sustained-release particles for the source control of AMD. Results showed that the gel phase(C-S-H) formed between the interface of carbide slag and bentonite encapsulated the surface of the $\text{Ca}(\text{OH})_2$ which grain decreases from 267nm to 211nm. The optimum preparation conditions are suggested as follows: a mass ratio of bentonite to carbide slag of 3:7, a Na_2CO_3 dose of 10 wt%, and a calcination temperature of 500°C for 1 h. The particles can remove 105 mg/g Cu^{2+} within 12 h, and the loss rate is only 7.8%. Compared with carbide slag, the alkalinity release time of the particles is prolonged by 4 times.

1. Introduction

Mineral resources are a perpetual driving force of social development, but the environmental problems caused by mining have become increasingly prominent and persist for a long time, even after mine closure. Pollutants in mining areas diffuse to the atmosphere^[1], soil^[2] and rivers^[3]. Acid mine drainage (AMD) is characterized by its concealment, strong acidity, high concentrations of heavy metals, and persistence^[4]. The Picher mining area in the United States^[5] and the Carnot mine in France^[6] are typical cases of serious AMD pollution. AMD has caused serious damage to approximately 72000 hectares of lakes and reservoirs worldwide and has become a serious environmental problem worldwide^[7].

The traditional AMD terminal treatment method is generally laborious and time-consuming. Compared with terminal treatment, source control can minimize the formation and diffusion of AMD. The formation of AMD is due to the combined action of microorganisms and oxygen, as well as sulfide oxidation during the cyclic transformation of Fe^{2+} and Fe^{3+} . If one or two formation conditions are blocked, the risk of AMD formation will be effectively reduced, such as live bacteria inhibition^[8], alkaline material filling^[9], anaerobic limestone reaction ditching^[10], waste packaging^[11] and wetland construction^[12]. Anoxic limestone drains (ALDs) were first proposed by Turner and McCoy at 1990^[13]. However, ALDs with limestone can only increase the pH to 8 and cannot completely remove metal ions such as Fe^{2+} and Mn^{2+} ^[14]. Moreover, FeCO_3 and MnCO_3 colloids are easily generated, leading to incongruent dissolution, which shortens the service life of the structure^[15]. Therefore, to overcome the above shortcomings, the development of alternative limestone materials has become the goal of many studies.

Blast furnace slag^[16], fly ash^[17] and serpentinite^[18] have all been considered as a replacement to limestone. Petrik^[19] suggested that fly ash alone is a cost-effective alkaline treatment material, but fly ash increases the effluent turbidity and is not conducive to the separation of metals and raw materials. Turigan^[20]

replaced limestone with low-grade nickel soil, but the nickel soil could buffer the pH to only 4.7 at the highest, allowing very few types of heavy metals to be removed. The main component of carbide slag (CS) is $\text{Ca}(\text{OH})_2$, which has high solubility, large alkalinity release and high removal efficiency for heavy metal ions^[1]. Based on the above characteristics, carbide slag has been used for the fixation of heavy metals in soil and the removal of phosphorus in sewage in recent years^[1]. However, there are few studies on the treatment of AMD with carbide slag instead of limestone. Due to the fast alkalinity release rate of carbide slag, the service life may be shortened. Therefore, it is necessary to modify and reduce the alkalinity release rate. In the presence of silicoaluminate, $\text{Ca}(\text{OH})_2$ reacts with volcanic ash to produce hydration products such as C-S-H, C-A-H and C-A-S-H, which improves the mechanical strength of carbide slag^[1]. Sun^[31] found that the formation of hydration products could slow down the alkalinity release rate of $\text{Ca}(\text{OH})_2$, but an excessive gel content led to a decrease in permeability after hardening^[1]. Therefore, a clay mineral with high permeability, Bentonite, may be the best choice to improve the above-mentioned defects.

In this study, carbide slag was used as the main material, bentonite was used as the Si/Al source, and Na_2CO_3 was used as the activator to granulate the two kinds of powder materials. The hydrated products were used to enhance the mechanical strength of the particles and improve the fast alkalinity release and large sludge volume defects of carbide slag, thereby preparing a new filling material for ALDs and realizing the resource utilization of carbide slag. The effects of the ratio of bentonite to carbide slag, Na_2CO_3 dose and calcination temperature on the particle loss rate and Cu^{2+} removal rate were analysed by single-factor experiments. The effects of various factors on the particle composition and microstructure were characterized by X-ray diffraction (XRD) and scanning electron microscopy (SEM). The optimum preparation conditions for carbide slag composite alkalinity sustained-release particles were determined, and the basicity release rates of the particles and carbide slag were compared.

2. Materials And Methods

2.1 Materials and chemicals

The carbide slag used in this study was provided by Fuxin Acetylene Factory, Liaoning Province, China, and the bentonite was sodium bentonite, which was provided by Wanpeng Mine, Liaoning Province, China. The X-ray fluorescence (XRF) results for determining the composition of the two materials are shown in Table 1. Before the experiment, the two raw materials were ground, passed through a 200-mesh screen, and dried in an oven at 105°C for 2 h.

Table 1
Chemical compositions of the carbide slag and bentonite used in %wt oxide.

Oxide	CaO	SiO ₂	Al ₂ O ₃	Na ₂ O	Fe ₂ O ₃	MgO	TiO ₂	K ₂ O
carbide slag	93.65	2.97	0.82	0.71	0.22	0.15	0.06	-
bentonite	2.24	73.33	13.55	4.25	2.26	3.59	0.12	0.50

A small amount of Na, Al and other metal ions were detected in the chemical composition of carbide slag (Table 1), which may have been derived from the acetylene raw material (calcium carbide) or mixed impurities in the production process. According to the chemical composition of bentonite, a large amount of Na⁺ replaces Ca²⁺, belonging to Na-bentonite (Na-Bent), and contains small amounts of iron, magnesium, potassium and titanium (Table 1), which may be caused by the substitution of the aluminium oxide octahedral structures in montmorillonite by other divalent cations[¶]. The XRD results showed that the main mineral components of bentonite were montmorillonite and quartz, and the main component of carbide slag was Ca(OH)₂.

A copper ion solution was prepared with CuSO₄. HNO₃ and NaOH were used to adjust the pH of the solution. Na₂CO₃ was used as an activator for the preparation of the particles. The above chemical reagents were analytically pure.

2.2 Preparation of the granular composites

The preparation of composite particles mainly includes raw material mixing, particle forming and high-temperature roasting. First, bentonite and carbide slag were mixed according to mass ratios of 1:9 ~ 9:1. Additionally, to study the effect of Na₂CO₃ on the particles, 0 ~ 10% Na₂CO₃ was added to the raw materials. To ensure that the raw materials met the plastic requirements of machine processing, distilled water was added to the raw materials, the moisture content was controlled at 60%, and the raw materials and water were mixed by hand for 15 min to ensure the full dispersion and dissolution of the mixture. Then, the mixture was machine processed into small cylindrical particles with a diameter of 2 mm and a length of 3 mm. Finally, the formed particles were calcined at 200 ~ 800°C and then cooled to room temperature. In order to compare the influence of calcination temperature on the particles, uncalcined particles were prepared at room temperature and stored in sealable plastic bags.

2.3 Copper removal experiment

A series of particles were prepared according to different mass ratios of bentonite to carbide slag, doses of Na₂CO₃, and calcination temperatures. By comparing the removal rates of copper ions by particles prepared under different conditions, the treatment effect of particles on copper-containing wastewater was analysed. The pH was adjusted to 3.2 (± 0.05) with 10% HNO₃ and 10% NaOH. Briefly, 0.20 g of composite particles were placed into a 250 ml beaker, and 100 ml of simulated wastewater at a concentration of 300 mg/L was added. The solution was treated for 12 h under static conditions. The

residual Cu^{2+} concentration in the solution was determined by flame atomic spectrophotometer (Japan, HITACHI Z-2000) at 324.8 nm wavelength.

2.4 Characterization of granular composites

To characterize the mechanical strength of the particles, the percentage of mass loss of the particles in water to the original mass was measured, namely, the loss rate. The specific operation involved taking the same mass of particles in a 250 mL conical flask, adding 100 mL of distilled water, and placing the flask in a shaker at 100 rpm for 12 h. Then, the particles were dried at 105°C for 2 h, cooled at room temperature and passed through a 0.5 mm mesh sieve. The remaining particles were weighed, and the loss rate was calculated. The larger the loss rate is, the worse the mechanical strength of the particles.

The morphology and structure of the different particles were characterized by SEM (German Nova 400 Nano). The accelerating voltage was 10 kV. Due to the low conductivity of the composite particles, the surface of the particles needed to be sprayed with gold for 3 min before testing.

The mineral composition of the particles was characterized by XRD (Rigaku Ultima IV, Japan). The particles were manually ground into powder and tested by X-ray bombardment with a Cu-K α radiation source. The specific parameter settings were as follows: the incident wavelength was $\lambda = 1.5418 \text{ \AA}$, the power supply voltage was 40 kV, the current was 40 mA, the scanning angle was $5 \sim 90^\circ$, and the angular velocity was $4^\circ/\text{min}$.

3. Results And Discussion

3.1 Effect of the mass ratio of bentonite to carbide slag on the particles

Bentonite and carbide slag were mixed at mass ratios of 9:1 ~ 1:9, and 5 wt% Na_2CO_3 was added. Then, the slag was roasted at 500°C for 1 h to obtain a series of particles. The removal rate of Cu^{2+} and loss rate of particles prepared with different mass ratios of bentonite and calcium carbide are shown in Fig. 1. Increasing the proportion of carbide slag was conducive to the formation of Cu^{2+} precipitates. When the ratio of bentonite to carbide slag decreased from 9:1 to 5:5, the particle loss rate decreased from 40.36–8.98%. However, when the ratio decreased to 1:9, the particle loss rate increased to 40.1%. This indicated that the loss rate could be controlled by changing the ratio.

The loss of three typical particles in water are shown in Fig. 2 (a)–(c). As the contact time with water increased, the 9:1 particles gradually ruptured into small blocks, while the 1:9 particles gradually became spherical. This morphological change indicates that when the ratio of bentonite to carbide slag is greater than 5:5, the internal force is caused by bentonite swelling due to water absorption^[1]. When the ratio is less than 5:5, external forces such as flow shear and friction are concentrated at the corner of the particle, leading to the separation of powder from the particle surface. This separation is the main reason for the increase in loss rate, indicating that the internal cohesion of the particle is insufficient. When the ratio of

bentonite to carbide slag is 5:5, the particle morphology is complete, indicating that the cohesive force inside the particle can overcome the expansion of bentonite, water shear and friction to achieve balance; thus, the loss rate reaches a minimum.

The surface morphologies of the three typical particles are compared in Fig. 2 (d)-(f). As shown in Fig. 2d, the 9:1 particle surface exhibits a smooth, crack-free compact structure. Figure 2e corresponds to the 5:5 particles and obvious small cracks are observed on their surface. These cracks provide buffer space for bentonite to absorb water and expand, thereby reducing the particle loss rate. The surface morphology of the 1:9 particles is shown in Fig. 2f. The surface became rough, and the number of cracks decreased. This structure shows that the particles exposed to the surface more easily fall off in water under the action of shear and friction, as shown by the macro-morphology in Fig. 2c.

The changes in the interlayer spacing of montmorillonite in unburned bentonite, calcined bentonite (500°C) and 9:1 particles are shown in Fig. 3a. No characteristic peaks representing the interlayer spacing were found in the 5:5 and 1:9 particles, indicating that the layered structure disappeared. The d_{001} value of unburned bentonite was 1.06 nm, which is the characteristic peak of sodium montmorillonite. After calcination at 500°C, the d_{001} value decreased to 0.96 nm. This result was consistent with the interlayer spacing of montmorillonite without interlayer-bound water. However, when a small amount of carbide slag was added, there were two weak characteristic peaks within $2\theta = 6-10^\circ$. The d_{001} value of the characteristic peak of the layered structure increased to 1.28 nm. This result is consistent with the d_{001} value of Ca-montmorillonite containing a layer of crystal water^[1], indicating that Ca^{2+} in carbide slag enters the interlayer of montmorillonite, resulting in the transformation of some Na-bentonite to Ca-bentonite. The d_{001} value of another characteristic peak was consistent with that of montmorillonite, which had its lost interlayer-bound water. This part of the bentonite is the main cause of the water swelling and cracking of particles.

Figure 3b compares the phase change of particles at different ratios. The 9:1 particles showed an obvious increase between 18° and 25° , indicating that new crystalline phases were formed, but their crystallinity was too low. The characteristic SiO_2 peaks at 35.89° and 31.28° widened, and a flat and wide peak was observed at 27.79° . Phase analysis showed that SiO_2 was transformed into $\text{NaAl}_2(\text{AlSiO}_3)\text{O}_{10}(\text{OH})_2$ (PDF 24-1047), indicating that the crystallinity of SiO_2 decreased and participated in the formation of silicate. As the ratio was decreased to 5:5, the characteristic peaks of SiO_2 at 28.43° and 31.28° disappeared, but no peaks appeared, indicating that SiO_2 existed in an amorphous form. When the ratio was further decreased to 1:9, the characteristic peak of montmorillonite at 19.88° disappeared, indicating that montmorillonite transformed into an amorphous state.

The above results indicate that the formation of an amorphous gel is conducive to enhancing the mechanical strength of particles, and SiO_2 in bentonite is preferentially converted to an amorphous state over montmorillonite. Therefore, when the proportion of bentonite is greater than 1, the layered structure of montmorillonite is retained, and the particles are more likely to be destroyed due to water absorption

and expansion. When the proportion of bentonite is less than 1, the insufficient production of gel leads to an increase in the loss rate.

3.2 Effect of Na_2CO_3 dose on the particles

It can be seen from Sect. 3.1 that increasing the proportion of carbide slag can effectively improve the removal rate of Cu^{2+} ions, and the formation of amorphous gel is conducive to enhancing the particle strength. According to Provis et al.^[1], since the formation of CSH, CAH, and CASH gels depends on the activation of alkali metal hydroxides or carbonates (i.e., Na_2CO_3). We expect to increase the proportion of calcium carbide slag as much as possible while maintaining a low loss rate. Therefore a series of particles were obtained by increasing the dose of Na_2CO_3 from 0–10% at different ratios (5:5, 4:6, 3:7) and roasting at 500°C for 1 h.

Figure 4 shows the loss rate and Cu^{2+} removal rate of the different particles. The Na_2CO_3 content increased from 0–10%, and the loss rates of the three groups of particles exhibited different degrees of decrease. The 7:3 series of particles decreased the most, from 63.56–7.40%. When 10% Na_2CO_3 was added, the loss rate of the 3:7 particles was 7.40%, which was similar to the loss rate (5.82%) of the 5:5 particles (Fig. 4a). These loss rate results indicate that increasing the amount of Na_2CO_3 can reduce the loss rate.

The removal rate of Cu^{2+} decreased when increasing the Na_2CO_3 dose from 0–10% (Fig. 4b), indicating that the addition of Na_2CO_3 had a negative effect on the removal of Cu^{2+} . However, the copper ion removal rate of the 7:3 particles was better than that of the other particles. The loss rate of the 7:3 particles with 10% Na_2CO_3 was less than 10%.

The surface morphologies of the 7:3 particles with 0% and 10% Na_2CO_3 are shown in Fig. 5. The surfaces of the particles without Na_2CO_3 mainly consisted of large irregular particles stacked together in a loose structure, and the edges were rough (Fig. 5a). This structure led to a high loss rate of particles. The XRD analysis of the particles without Na_2CO_3 (Fig. 6) shows that the composition of the particles included montmorillonite and SiO_2 from the bentonite and $\text{Ca}(\text{OH})_2$ and CaCO_3 from the carbide slag. This indicated that the main composition remain unchanged. A slight bulge in the substrate was observed between 25° and 40° because $\text{Ca}(\text{OH})_2$ can generate amorphous CSH through the pozzolanic reaction^[1]; however, the amount of amorphous CSH was not enough to reduce the loss rate.

When increasing the Na_2CO_3 content to 10%, the particle surface flattened, and cracks with clear edges appeared, indicating that the particles lost water and shrunk; thus, the structure became compact (Fig. 5b). Based on Fig. 6, for the particles with 10% Na_2CO_3 , the characteristic peaks at 19.79° and 21.73° disappeared, and the background hump between 25° and 40° became more obvious than that for the particles without Na_2CO_3 . This result indicates that Na_2CO_3 plays a promoting role in the transformation of montmorillonite and SiO_2 to an amorphous state because Na_2CO_3 can enhance the

reactivity of Al and Si in clay and promote the formation of gels^[1]. Therefore, with an increasing Na₂CO₃ dose, the transformation of SiO₂ and montmorillonite to an amorphous state was promoted, the gel content in the particles increased, and the particle loss rate was effectively reduced.

3.3 Effect of the roasting temperature

When the mass ratio of bentonite to carbide slag was 3:7 and the dose of Na₂CO₃ was 10% of the total mass, a series of particles were obtained after treatment for 1 h at different calcination temperatures to study the effect of calcination temperature on the particles. Regarding the particles prepared at room temperature, the loss rate reached 44.07%, and the removal rate of Cu²⁺ reached 100%. Regarding the particles calcined at 200°C, the loss rate greatly decreased to 18.73%, and the Cu²⁺ removal rate decreased to 83.46% (Fig. 7). This decrease indicates that the mechanical strength of uncalcined particles is poor, and an excessive loss rate leads to the removal of Cu²⁺, which is consistent with the research results of Zhan^[1]. However, an excessive loss rate leads to an increase in effluent turbidity and sludge. When increasing the temperature from 200°C to 500°C, the loss rate of particles decreased from 18.73–8.69%. However, when the calcination temperature was increased to 800°C, the loss rate increased to 19.14%. The removal rate of Cu²⁺ decreased with an increasing preparation temperature. According to Fig. 7, the loss rate of particles calcined at 500°C was the smallest, and the removal ratio of Cu²⁺ was 73.65%. Therefore, 500°C was set as the preparation temperature of the particles.

The XRD patterns of the particles prepared at different temperatures are compared in Fig. 8. In the uncalcined particles, Na₂Ca(CO₃)₂·5H₂O was detected based on the characteristic peaks at 2θ = 13.84°, 37.83° and 32.86°, while the characteristic peaks of Na₂CO₃ disappeared. This result indicates that a hydration reaction between Na₂CO₃ and carbide slag occurs, providing a precursor for the combination of bentonite and carbide slag after calcination. The characteristic peak of SiO₂ from the bentonite disappeared, while the montmorillonite structure was retained. This is because montmorillonite with Al and Si in its crystal structure cannot participate in the volcanic ash reaction^[1]. Therefore, SiO₂ preferentially transforms to an amorphous state over montmorillonite, forming CSH and other hydrates. The formation of hydration products gives the particles a certain mechanical strength, but insufficient production leads to a high particle loss rate. As the calcination temperature was increased to 500°C, the characteristic peaks of montmorillonite at 7.12° and 19.72° disappeared, indicating that the layered structure collapsed, and that the montmorillonite structure was destroyed. This is because the increase in the content of amorphous silicate transferred from Si and Al in the montmorillonite crystal structure with the increase of temperature further decreased the loss rate. This is consistent with the research results of Okano^[1].

The reaction of Ca(OH)₂ with silicoaluminate can be summarized as^[38]:

When the temperature was increased from 500°C to 600°C, the background hump became obvious between 30° and 40°, indicating that new crystalline phases were formed and the crystallinity increased, which was caused by the transformation of the gel to a crystalline state at high temperature^[1]. In the same range, the characteristic peaks of the particles prepared at 800°C corresponded to Ca_2SiO_4 , $\text{Na}_2\text{Si}_3\text{O}_7$ and $\text{Ca}_{12}\text{Al}_{14}\text{O}_{33}$. This result indicated that the pre-product was a silicate gel containing Ca and Na, the crystallinity increased between 600°C and 700°C, and the crystalline phase was formed at 800°C. Therefore, the crystallization of silicate gel decreases the binding force between bentonite and carbide slag and increases the loss rate of particles. Regarding the particles prepared at 600°C, the characteristic peaks of Ca(OH)_2 at 17.82° and 33.97° became flat and wide, and the characteristic peaks of CaO were found, which was due to the dehydration of Ca(OH)_2 to CaO. This finding was consistent with previous conclusions^[1].

Figure 9 shows the SEM images of the surface morphologies of particles prepared at different temperatures. As Fig. 9a shows, the surface morphologies of the uncalcined particles are rough, and the layered structure is clearly visible. Due to the evaporation of free water inside the particles calcined at 200°C, small cracks appeared, and the layered structure became blurred (Fig. 9b). This is consistent with the XRD results. Regarding the particles calcined at 500°C, the surface morphologies became smooth, and the layered structure disappeared. The condensation of hydration products clarified the edge of the crack. Notably, this structure can more closely combine bentonite and carbide slag^[1]. Since Ca(OH)_2 in the particles calcined at 600°C was dehydrated and converted to CaO, the surface morphologies became more smooth (Fig. 9d). However, when the calcination temperature was increased to 800°C (Fig. 9e), many irregularly distributed silicate crystals appeared on the complex surface morphologies of the particles. The crystals filled the original pores and blurred the edges of the surface cracks. A rough surface is not conducive to resisting the flow shear force and friction between particles, which is one of the reasons for the increase in the loss rate. However, the increase in crystallization is not conducive to the removal of Cu^{2+} and leads to a continuous decrease in the Cu^{2+} removal rate.

3.4 Alkali sustained-release property analysis

Based on the above experiments, when the mass ratio of bentonite to carbide slag was 3:7, the dose of Na_2CO_3 was 10% of the total mass, and the particles were calcined at 500°C for 1 h. The prepared particles had the best mechanical strength and Cu^{2+} removal rate. The sustained release properties of the alkali particles were analysed. Figure 10 shows the time it took to achieve a pH balance for 200 mg of particles (containing 126 mg of carbide slag) and 126 mg of carbide slag powder in initial solutions at pH 3. The time for the release of basicity from the optimal particles to reach equilibrium was 180 min, four times that for carbide slag powder (45 min). Therefore, the composite particles demonstrated a good slow-release effect of basicity in water.

The (001), (101) and (110) crystal planes of Ca(OH)_2 in the raw carbide slag powder, uncalcined particles, and calcined particles at 200°C and 500°C were fitted by XRD, and the grain size was calculated by the Tylor formula. The effect of calcination temperature on the grain size of Ca(OH)_2 was compared and analysed. The fitting results are shown in Table 2.

Table 2
Fitting results for the grain size of Ca(OH)_2 .

Crystal planes	(001)		(101)		(110)		Fit Size (nm)
	FWHM	XS(nm)	FWHM	XS(nm)	FWHM	XS(nm)	
carbide slag	0.309	275	0.347	250	0.298	313	267
25°C	0.303	281	0.340	256	0.325	284	268
200°C	0.321	363	0.370	233	0.320	289	249
500°C	0.361	232	0.439	194	0.389	234	211

Table 2 shows that the grain size of Ca(OH)_2 in the carbide slag powder is 267 nm. After mixing with bentonite and Na_2CO_3 in the optimal proportion, the grain size of Ca(OH)_2 in the particles without calcination was 268 nm, and the grain size exhibited little change. After calcination, the grain size of Ca(OH)_2 decreased from 268 nm to 211 nm. This indicates that calcination effectively reduces the grain size of Ca(OH)_2 . This decrease in grain size can make the amorphous gel better encapsulate carbide slag, thus buffering the alkalinity release of the particles.

4. Conclusion

This study is the first attempt to use carbide slag, bentonite and a small amount of Na_2CO_3 to prepare alkalinity sustained-release particles, namely, carbide slag composite alkalinity sustained-release particles. The results showed that the adhesion of particles came from the adhesion of bentonite itself and the formation of hydrated silicate gel. Na_2CO_3 enhanced the activity of montmorillonite and silica in bentonite and played a significant role in promoting the formation of the gel phase. The gel formed between the interface of the carbide slag and bentonite made the two bonds. At room temperature, SiO_2 is preferentially involved in the formation of gels. As the temperature increases, the reactivity of Si and Al in the montmorillonite structure increases to form hydrated silicate in amorphous. Furthermore, the gel lost water and shrunk at high temperature, condensing the particle structure and obtaining good mechanical strength. But at $T > 600^\circ\text{C}$, the gel gradually transforms to the crystalline state, and the particle loss rate increases. The optimum preparation conditions of the composite alkalinity sustained-release particles were as follows: the mass ratio of bentonite and carbide slag of 3:7, the Na_2CO_3 dose of 10% of the total mass, and the calcination temperature of 500°C for 1 h. The fitting results of the grain size showed that the grain size of Ca(OH)_2 decreased from 268 nm to 211 nm, which made the hydrated silicate gel better encapsulate the Ca(OH)_2 and reduced the basicity release rate of the carbide slag by 4

times. Therefore, carbide slag composite alkalinity sustained-release particles can replace limestone as a new filling material in the ALDs which is beneficial for preventing the formation of AMD from the source.

Declarations

Data Availability

All data generated or analysed during this study are included in this published article.

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Author contributions

J. B.: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Writing - original draft, Writing - review & editing. H. Z.: Conceptualization, Methodology, Funding acquisition, Project administration, Writing - review & editing. L. X.: Conceptualization, Funding acquisition, Methodology. All authors have read and agreed to the published version of the manuscript.

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Competing interests

The authors declare no competing interests.

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Figures

Figure 1

Effect of different proportions on particle loss rate and Cu²⁺ removal rate.

Figure 2

Loss of typical particles in water and the SEM images: (a), (d) 9:1 particles, (b), (e) 5:5 particles, and (c), (f) 1:9 particles.

Figure 3

XRD diffraction data: (a) uncalcined bentonite, calcined bentonite (500 °C) and 9:1 particles and (b) 9:1 particles, 5:5 particles and 1:9 particles.

Figure 4

Effect of different Na_2CO_3 doses on the (a) particle loss rate and (b) Cu^{2+} removal rate.

Figure 5

SEM images of the 7:3 particles with (a) 0% and (b) 10% Na_2CO_3 .

Figure 6

XRD patterns of the particles without Na₂CO₃ and with 10% Na₂CO₃.

Figure 7

Effect of the different calcination temperatures on the particle loss rate and Cu²⁺ removal rate.

Figure 8

XRD patterns of the composite particles at different temperatures.

Figure 9

SEM images of the composite particles at different calcination temperatures: (a) 25 °C, (b) 200 °C, (c) 500 °C, (d) 600 °C, and (e) 800 °C.

Figure 10

Comparison of the basicity release rates of the optimal composite particles and carbide slag powder.