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Leaching optimization and dissolution behavior of alkaline anions in bauxite residue

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Abstract: Bauxite residue is a highly alkaline waste containing soluble alkaline anions, which can cause environmental concerns. The optimal leaching conditions, distribution of alkaline anions, types of pivotal alkaline anions and their dissolution behaviors were investigated based on the combination of single factors-orthogonal experiments and leaching stage experiment. Using a two-stage leaching, 86% of the soluble alkaline anions (CO_3^{2-} , HCO_3^{-} , $Al(OH)_4^{-}$, OH^{-}) were leached with a L/S ratio of 2 mL/g, at 30 °C, over 23 h. During the first stage of leaching, approximately 88% of alkaline anions were leached from the dissolution of free alkali (NaOH, carbonate, bicarbonate, NaAl(OH)₄) with the rest originating from the dissolution of alkaline minerals (calcite, cancrinite and hydrogarnet). Supernatant alkalinity was 69.78 mmol/L with CO_2^{2-} accounting for 75%. Furthermore, carbonate leaching was controlled by solid film diffusion using the Stumm Model with an apparent activation energy of 10.24 kJ/mol. Key words: bauxite residue; alkaline anions; carbonate; leaching optimization; dissolution behavior

1 Introduction

Bauxite residue (BR or red mud) is a hazardous alkaline solid waste originating from the Bayer process [1,2], which is used to extract alumina from bauxite ore. Bauxite is digested in a caustic liquor of sodium hydroxide and slaked lime to enhance refining [3,4]. Currently, approximately 120 million tons of BRs are produced per year and the global inventory reached more than 4 billion tons in 2015 [5,6]. Numerous methods for the treatment and reuse of BR have been investigated [7-10], but the volume recycled is still insignificant due to its high alkalinity and salinity [11,12]. Consequently, large volumes of BR are stored in disposal areas (BRDAs), leading to potential contamination of the surrounding environment [13]. The dust formed from the surface of BRDAs, contains elevated concentrations of free alkali (soluble) that may threaten the surrounding ecology [14-16]. Furthermore, storage of residues may

cause dam collapse, whilst dissolution of soluble alkaline compounds will also cause environmental risk [17].

Recently, strategies to regulate alkalinity have included, amendment with gypsum, neutralization using seawater, carbonation sequestration, and waste acid interaction [18-23]. Although these methods may be effective, they are difficult to conduct on a large scale. The main reason restricting large-scale application may be the limited knowledge of dissolution behavior and distribution of soluble alkaline anions prior to BR disposal. Presently, water leaching may be an effective technique in order to investigate dissolution behavior and composition distribution of soluble alkaline anions in residues. These are the two main factors that effectively regulate alkalinity, and a reduction in soluble alkaline anions in the liquid phase would be a desirable environmental management goal [24]. Nevertheless, the majority of current research has focused on sodium leaching [25–27] that may only be dissolved partially by water, with a dealkalization ratio of less than 50% [6].

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This may be caused by existing alkalinity, including free alkali and chemical bonded alkali in the BR [28] with some alkaline compounds being dissolved under an appropriate chemical equilibrium in the solution, as shown in Eqs. (1)-(9).

$$NaOH \rightarrow OH^{-} + Na^{+}$$
(1)

$$NaAl(OH)_4 \rightarrow Al(OH)_4^- + Na^+$$
(2)

 $Na_2CO_3 \rightarrow CO_3^{2-} + 2Na^+$ (3)

$$NaHCO_3 \rightarrow HCO_3^- + Na^+$$
 (4)

$$CaCO_3 \rightarrow Ca^{2+} + CO_3^{2-} \tag{5}$$

$$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{H}_2\text{O} \rightarrow 3\text{Ca}^{2+} + 4\text{OH}^- + \text{Al}(\text{OH})_4^- \tag{6}$$

$$[Na_6Al_6Si_6O_{24}]$$
· $[2NaX \text{ or } Na_2X]$ \rightarrow

$$8Na^{+}+6H_{4}SiO_{4}+6Al(OH)_{3}+8X (X: OH^{-} or CO_{3}^{2-})$$
(7)

$$[Na_{6}Al_{6}Si_{6}O_{24}] \cdot 2[CaCO_{3}] + 26H_{2}O \rightarrow$$

$$6Na^{+}+2Ca^{2+}+6H_{4}SiO_{4}+6Al(OH)_{3}+2HCO_{3}^{-}+8OH^{-}$$
(8)

 $Ca_3Al_2(SiO_4)_x(OH)_{12-4x} \rightarrow$

$$3Ca^{2+}+(6-4x)OH^{-}+xH_4SiO_4+2Al(OH)_3$$
 (9)

Equations (6)–(9) were interpreted from Refs. [29–32].

Consequently, in order to elucidate the dissolution of soluble alkalinity, sodium leaching is not accurate, due to dissolution of chemically bonded alkali and other minerals, which makes it difficult to take both dealkalization specification and technical cost into consideration [33].

The objectives of this work are to investigate the optimal leaching conditions of BR (including L/S ratio, temperature, time and leaching stage), to determine alkaline dissolution behavior and reaction equilibrium, to screen alkaline anions and analyze their leaching kinetics, and to comprehend alkaline anion dissolution behavior, composition distribution and alkalinity contribution in BR. Based on the above, we aim to provide a scientific foundation for the effective regulation of alkalinity in BR prior to disposal.

2 Experimental

2.1 Materials

Raw BR (PRM) was collected from the Guangxi Branch, Aluminum Corporation of China Limited. Samples were firstly thoroughly homogenized, dried at 65 °C for 48 h, and subsequently sieved (100 mesh). Soluble cations were determined using inductively coupled plasma atomic emission spectroscopy (ICP-AES). Mineral composition of the PRM was determined by X-ray powder diffraction (XRD) analysis.

2.2 Methods

The following investigations were conducted to leaching potential: Firstly, single factor assess experiments were used to assess L/S ratio, leaching temperature and leaching time, respectively. L/S ratios were 1, 2, 3, 4, 5, 6 and 7 mL/g, temperatures were controlled at 10, 15, 20, 25, 30, 35 and 40 °C, and time was controlled as 1, 2, 3, 5, 8, 13, 18 and 23 h. For the second investigation, three factors and three levels were set based on the results of the single factor experiments in order to obtain the optimized leaching condition. Finally, the leaching stage experiments (denoted as 1, 2, 3, 4, 5 and 6) were operated using the optimized conditions to investigate the source and content of alkaline anions, which were used to obtain the leaching rate of alkaline anions from the dissolution of free alkali.

Bauxite residue (20 g), was mixed with deionized water in a beaker, the mixture was then stirred vigorously for 15 s, and then sealed with a plastic membrane. The experiment was conducted in a temperature controlled water bath. Leachates were filtered through SHZ-D (III) vacuum suction filters and pH, alkaline anions and aluminum concentration were immediately analyzed. pH was carried out using a PHS-3C and the content of hydroxide (OH⁻) was calculated from pH. Soluble Al was determined by ICP-AES and aluminate (Al(OH)⁻₄) was calculated from the Al concentration [4,26].

Carbonate $(CO_3^{2^-})$ and bicarbonate (HCO_3^-) were determined by double indicator-neutralization titration using H₂SO₄ (0.005 mol/L) [23]. Initially, leachate (5 mL) was diluted with deionized water (10 mL), and phenolphthalein (0.05 mL) was added until the solution was titrated to pH 8.3 (T1). Next, bromophenol blue (0.1 mL) was added and the solution was then titrated to pH 4.1 (T2). From T1 and T2, the concentrations of $CO_3^{2^-}$ and HCO_3^- were determined, respectively.

3 Results and discussion

Sodium salt was the main component of soluble alkali, with Al originating from dissolution of aluminate (Table 1). XRD patterns of raw bauxite residue revealed that the main minerals consisted of calcite (CaCO₃), cancrinite (Na₆CaAlSi(CO₃)O₂₄·2H₂O), hydrogarnet (Ca₃AlFe₂(SiO₄)(OH)₄)), hematite (Fe₂O₃), goethite (FeOOH), diaspore (AlO(OH)), gibbsite (Al(OH)₃) and perovskite (CaTiO₃)) (Fig. 1).

 Table 1 Cation concentrations under leaching of soluble alkali

 in raw bauxite residue (mg/L)

| Na ⁺ | A1 ³⁺ | K^+ | Ca ²⁺ | Mg^{2+} |
|-----------------|------------------|-------|------------------|-----------|
| 1161 | 52.50 | 81.82 | 2.24 | 0.18 |



Fig. 1 XRD patterns of raw bauxite residue

3.1 Effect of L/S ratio

Effects of L/S ratio on basic alkaline parameters (pH, alkaline anion concentration and leachate alkalinity) of BR under the leaching process are presented in Tables 2 and 3 (25 °C, 23 h, the 1st stage leaching). Supernatant pH decreased with increasing L/S ratio, probably due to a dilution effect from the water. Alkaline anions reached a maximum concentration when the L/S ratio was 2 mL/g, and the concentrations of CO_3^{2-} , HCO_3^{-} and $Al(OH)_4^{-}$ reached 37.20, 9.90 and 1.90 mmol/L, respectively. When the L/S ratio continuously increased, the concentration of alkaline anions slowly decreased. And the alkaline anion concentrations were in the following order: $CO_3^{2-} > HCO_3^{-} > Al(OH)_4^{-} > OH^{-}$. Thus, the L/S ratio of 2 mL/g may be used to regulate alkalinity

due to the high concentration of alkaline anions, which is beneficial to the reaction rate.

Leaching amounts of alkaline anions are shown in Table 3, which were used to investigate the effect of L/S ratio on the dissolution behavior of alkaline anions. These anions were largely dissolved when the L/S ratio reached 2 mL/g. According to the investigations, L/S ratios of 2, 4 and 5 mL/g should be considered for the orthogonal experimental conditions.

3.2 Effect of leaching temperature

Dissolution behaviors of alkaline anions related to leaching temperature are presented in Fig. 2 (L/S ratio of 4 mL/g, 23 h, the 1st stage leaching). Carbonate revealed a positive correlation with leaching temperature from 15 to 25 °C (Fig. 2), with 18.2 mmol/L obtained at 25 °C. Concentrations of HCO_3^- , $Al(OH)_4^-$ and OH^- were lower than that of CO_3^{2-} , with no change observed with increasing temperature. This demonstrated that CO_3^{2-} may dissolve continuously with increasing temperature until both dissolution reactions and hydrolysis gradually reached equilibrium after 25 °C. Supernatant pH rapidly increased with increasing temperature (<30 °C) (Fig. 3) eventually stabilizing. In addition, alkaline anion concentrations increased slowly above 25 °C (27.11 mmol/L at 25 °C). This development may be attributed to the dynamic balance of dissolution reactions, ion conversion and adsorption in the mixture above 25 °C. Leaching temperatures of 20, 25 and 30 °C may therefore be considered for the orthogonal experimental conditions.

 Table 2 Effect of L/S ratio on pH, alkaline anions and alkalinity of leachates

| L/S ratio/ (mL·g ⁻¹) | pH | $c(\operatorname{CO}_3^{2^-})/(\operatorname{mmol}\cdot\operatorname{L}^{-1})$ | $c(\text{HCO}_3^-)/(\text{mmol}\cdot\text{L}^{-1})$ | $c(Al(OH)_4^-)/(mmol \cdot L^{-1})$ | $c(OH^{-})/(mmol \cdot L^{-1})$ | Alkalinity*/ (mmol·L ⁻¹) |
|-------------------------------------|------------------|--|--|-------------------------------------|---------------------------------|---|
| 1 | 10.67±0.12 | 31.40±0.70 | 6.40±0.33 | $1.00{\pm}0.07$ | 0.47 ± 0.06 | 39.27±1.03 |
| 2 | 10.45 ± 0.10 | 37.20±0.78 | 9.90±0.36 | $1.90{\pm}0.03$ | $0.29{\pm}0.04$ | 49.29±0.50 |
| 3 | 10.24 ± 0.07 | 22.90±1.21 | 8.30±0.14 | $1.50{\pm}0.03$ | 0.17 ± 0.04 | 32.87±1.13 |
| 4 | 10.14 ± 0.07 | 19.90±0.67 | 6.70±0.22 | $1.30{\pm}0.02$ | $0.14{\pm}0.03$ | 28.04 ± 0.50 |
| 5 | 10.04 ± 0.07 | 16.30±0.37 | 6.40±0.16 | 1.10 ± 0.04 | 0.11 ± 0.02 | 23.91±0.22 |
| 6 | 9.97±0.07 | 12.30±0.64 | 6.30±0.22 | $1.00{\pm}0.02$ | $0.09{\pm}0.02$ | 19.69±0.85 |
| 7 | 9.94±0.08 | 10.90±0.67 | 5.50±0.29 | 0.90±0.03 | $0.09{\pm}0.02$ | 17.39±0.73 |

*Alkalinity = $c(CO_3^{2-})+c(HCO_3^{-})+c(Al(OH)_4^{-})+c(OH^{-})$

| Table 3 | Effect of | of L/S | ratio | on | leaching | amount | of | alkaline | anions |
|---------|-----------|--------|-------|----|----------|--------|----|----------|--------|
|---------|-----------|--------|-------|----|----------|--------|----|----------|--------|

| L/S ratio/(mL \cdot g ⁻¹) | $n(CO_3^{2-})/mmol$ | $n(\mathrm{HCO}_3^-)/\mathrm{mmol}$ | $n(Al(OH)_4^-)/mmol$ | n(OH ⁻)/mmol | Total/mmol |
|---|---------------------|-------------------------------------|----------------------|--------------------------|-----------------|
| 1 | 0.63±0.01 | 0.13±0.01 | 0.02±0.01 | 0.01 | 0.79±0.02 |
| 2 | 1.49±0.03 | 0.40 ± 0.01 | 0.08 ± 0.01 | 0.01 | 1.98 ± 0.02 |
| 3 | 1.37±0.07 | 0.50±0.01 | 0.09 ± 0.02 | 0.01 | 1.97±0.03 |
| 4 | 1.59±0.05 | 0.54 ± 0.02 | 0.10±0.01 | 0.01 | 2.24±0.03 |
| 5 | 1.63±0.04 | 0.64 ± 0.02 | 0.11 ± 0.01 | 0.01 | 2.39±0.02 |
| 6 | 1.48 ± 0.08 | 0.76±0.03 | 0.12±0.02 | 0.01 | 2.37±0.04 |
| 7 | 1.53±0.09 | 0.77 ± 0.04 | 0.13±0.02 | 0.01 | 2.44±0.05 |



Fig. 2 Effect of leaching temperature on change in alkaline anion concentration



Fig. 3 Effect of leaching temperature on change in pH and alkalinity

3.3 Effect of leaching time

Effects of leaching time on the dissolution behavior of alkaline anions are presented in Fig. 4 (L/S ratio of 4 mL/g, 25 °C, the 1st stage leaching). Leaching time appeared to affect CO_3^{2-} concentration, reaching 17.30 mmol/L at 13 h, but taper off after this point (Fig. 4). Concentrations of HCO_3^- , $Al(OH)_4^-$ and $OH^$ altered only slightly with increasing leaching time, being almost completely leached within 1 h. CO_3^{2-} is a critical alkaline anion in BR, but alkaline anions originating from the dissolution of chemically bonded alkali or free alkali may also be involved. pH of leachates persisted at 10.30 with alkalinity of 17.30 mmol/L at 13 h (Fig. 5). Leaching time of 13, 18 and 23 h may be considered for the orthogonal experimental conditions.

3.4 Orthogonal experimental analysis for optimized leaching conditions

Orthogonal experiments were used to optimize alkaline anion leaching conditions (Table 4), and the

results are presented in Table 5. The effect of leaching factors was as follows: leaching temperature > L/S ratio > leaching time (Table 5). This implied that leaching temperature was the main factor to influence leaching rate as demonstrated by dissolution and diffusion of alkaline anions, which is closely related to temperature.



Fig. 4 Effect of leaching time on changes in alkaline anion concentration



Fig. 5 Effect of leaching time on change in pH and alkalinity

Table 4 Factors and levels of orthogonal experiment

| Level | Residue mass/g | $L/S \text{ ratio/} (mL \cdot g^{-1})$ | Temperature/ °C | Time/h |
|-------|-------------------|--|--------------------|--------|
| 1 | 20 | 2 | 20 | 13 |
| 2 | 20 | 4 | 25 | 18 |
| 3 | 20 | 5 | 30 | 23 |

3.5 Dissolution equilibrium of multiple leaching stages

With increasing leaching stage, the amount of alkaline anions rapidly reduced (Fig. 6(a)). Amounts of CO_3^{2-} and HCO_3^{-} reached 1.52 and 0.49 mmol in leachates at the first stage, respectively. However, after the third stage, these alkaline anions showed negligible

| Table | 5 Ort | hogonal | experiment | results |
|-------|-------|---------|------------|---------|

| No. | Residue mass/g | L/S ratio/ (mL·g ⁻¹) | Temperature /°C | Time/h | Leaching amount*/ mmol |
|-----|-------------------|-------------------------------------|--------------------|--------|------------------------------|
| 1 | 20 | 2 | 20 | 13 | 1.58 |
| 2 | 20 | 2 | 25 | 18 | 1.89 |
| 3 | 20 | 2 | 30 | 23 | 2.21 |
| 4 | 20 | 4 | 20 | 18 | 2.00 |
| 5 | 20 | 4 | 25 | 23 | 2.21 |
| 6 | 20 | 4 | 30 | 13 | 2.34 |
| 7 | 20 | 5 | 20 | 23 | 2.03 |
| 8 | 20 | 5 | 25 | 13 | 2.19 |
| 9 | 20 | 5 | 30 | 18 | 2.32 |
| | | 1.673 | 1.703 | 1.820 | |
| R | | 1.940 | 1.857 | 1.857 | |
| | | 1.953 | 2.007 | 1.890 | |
| | | 0.290 | 0.420 | 0.113 | |

*Leaching amount= $n(CO_3^{2-})+n(HCO_3^{-})+n(Al(OH)_4^{-})+n(OH^{-})$



Fig. 6 Effect of leaching stage on amount of total alkaline anions (a) and free alkaline anions (b)

changes. According to alkali dissolution equilibrium in the solid-liquid phase, alkaline anions from dissolution of free alkali were completely leached after the sixth stage. The concentrations of alkaline anions generated from the dissolution equilibrium of the chemically bonded alkali are shown in Table 6. Dissolutions of chemically bonded alkalis (CaCO₃, Na₆CaAlSi(CO₃)O₂₄. 2H₂O, Ca₃AlFe₂(SiO₄)(OH)₄) were unaffected by the higher concentration of alkaline anions when soluble alkalinity was completely removed. Only a few alkaline anions were leached at the 6th stage. Concentrations of CO_3^{2-} , HCO_3^{-} , $Al(OH)_4^{-}$ and OH^{-} were 3.10, 3.80, 0.21, 0.04 mmol/L with pH reaching 9.57, respectively. Assuming the dissolution balance of chemically bonded alkali would not be affected by leaching stages, the contents of alkaline anions originating from the dissolution of free alkali were calculated using the following equations:

$$F_{\mathbf{a}_{\mathbf{a}}} = L_{\mathbf{s}_{\mathbf{a}}} - c_{\mathbf{b}} \tag{10}$$

$$c_{\rm b} = L_{\rm s_6} \tag{11}$$

$$F_{\rm a} = \sum_{n=1}^{5} F_{\rm a_n} = \sum_{n=1}^{5} L_{\rm s_n} - 5L_{\rm s_6} = \sum_{n=1}^{5} L_{\rm s_n} - 5c_{\rm b}$$
(12)

$$R_n = \frac{F_{a_n}}{F_a} \times 100\%$$
(13)

where *n* is the leaching stage (denoted as 1, 2, 3, 4, 5, and 6); F_a is the total concentration of alkaline anions from the dissolution of free alkali; c_b is the concentration of alkaline anions from the dissolution of chemically bonded alkali; L_s is the concentration of alkaline anions from the different leaching stages; and $R_n(\%)$ is the leaching ratio.

Calculated results are shown in Table 6. Alkalinity of the liquid phase in the BR was improved by alkaline anions from the dissolution of free alkali. The effect of leaching stage on the dissolution of free alkali is shown in Fig. 6(b). During the first stage, the concentration of CO_3^{2-} and HCO_3^{-} reached 1.40 and 0.34 mmol in leachates, respectively. Alkaline anions were almost unchanged after the third stage. Alkalinity reached 69.78 mmol/L (Table 6), and the leaching ratio was calculated using Eq. (13) (Fig. 7). Leaching ratio reached 67% during the first stage, reducing to 19%, 9%, 4%, 2% and 0%, at the second to sixth stages, respectively. The total leaching ratio was 86% within two leaching stages. Table 6 reveals that the critical alkaline anion from dissolution of free alkali was CO_3^{2-} and its concentration reached 52.10 mmol/L, followed by HCO_3^- (13.60 mmol/L).

3.6 Leaching kinetics of critical anions

Due to the highly soluble alkalinity, the Stumm Model may be applied to evaluating leaching kinetics of

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 Table 6 Leaching parameters of chemically bonded alkali and free alkali in bauxite residue

| rubie o Beaching parameters o | Tuble o Dealeming parameters of energies of one of a finite and the and the and the follower | | | | | | | | |
|-------------------------------|--|------------------------------|--|--|------------------------------|-----------------------|--|--|--|
| A 111- | | $c(CO_3^{2-})/$ | <i>c</i> (HCO ₃ ⁻)/ | $c(\operatorname{Al}(\operatorname{OH})_4^-)/$ | <i>c</i> (OH ⁻)/ | Alkalinity/ | | | |
| Alkalı | рп | $(\text{mmol} \cdot L^{-1})$ | $(mmol \cdot L^{-1})$ | $(\text{mmol} \cdot \text{L}^{-1})$ | $(mmol \cdot L^{-1})$ | $(mmol \cdot L^{-1})$ | | | |
| Chemically bonded alkali a | 9.57 | 3.10 | 3.80 | 0.21 | 0.04 | 7.15 | | | |
| Free alkali ^b | 10.47 | 35.00 | 10.40 | 1.73 | 0.26 | 47.39 | | | |
| Free alkali ^c | > 10.47 | 52.10 | 13.6 | 3.62 | 0.46 | 69.78 | | | |

^a Data of chemically bonded alkali calculated from the 6th leaching stage; ^b Data of free alkali through the 1st leaching stage were calculated by Eqs. (10) and (11); ^c Data of free alkali through six leaching stages were calculated by Eqs. (10)–(12)



Fig. 7 Effect of leaching stage on leaching ratio from dissolution of free alkali

critical anions. The Shrinking Core Model (SCM) was used to assess the dissolution process of the solid phase whilst analyzing the leaching process of sodium [6,34]. The critical anion $CO_3^{2^-}$ was the main source of high alkalinity in the liquid phase. It is therefore necessary to analyze its leaching process. The following two expressions of leaching kinetics can be used.

The Stumm Model [35]:

$$\ln\frac{c_x}{c_x - c_t} = K_q t + Z \tag{14}$$

where *t* is the reaction time; c_x and c_t are the concentrations of CO_3^{2-} in dissolution equilibrium and at the time of *t*, respectively; *Z* is a constant; and K_q is the kinetics rate constant.

SCM diffusion model:

$$K_{\rm a}t = 1 - \frac{2\alpha}{3} - (1 - \alpha)^{2/3} \tag{15}$$

where α is the leaching ratio (%); K_a is the rate constant of internal diffusion.

Leaching data at different temperatures exhibited a good fit to the Stumm Model (Fig. 8 and Fig. 9), demonstrating that CO_3^{2-} leaching from dissolution of free alkali was controlled by solid film diffusion. Its rate increased with increasing L/S ratio and temperature, whilst another factor was the diffusion rate of water into interior particles. Based on the diffusion constants at



Fig. 8 Plot of $[1-2\alpha/3-(1-\alpha)^{2/3}]$ vs time at different temperatures



Fig. 9 Plot of $\ln[c_x/(c_x-c_t)]$ vs time at different temperatures



Fig. 10 Plot of $\ln K_q$ vs temperature of water leaching

different temperatures, the plots of $\ln K_q$ versus temperature were established by the Arrhenius equation. Correlation coefficients (R^2) were above 0.99 at different observed temperatures (Fig. 10). The apparent activation energy (E_a) was 10.24 kJ/mol, further illustrating that the diffusion rate of CO_3^{2-} was controlled by solid film diffusion.

4 Conclusions

1) Under the optimized conditions, with a L/S ratio of 2 mL/g, at 30 °C, for 23 h, leaching rates for soluble alkaline anions (CO_3^{2-} , HCO_3^{-} , $Al(OH)_4^{-}$, OH^{-}) of 86% and pH of 9.78 were obtained during a two-stage leaching.

2) Approximately 88% of alkaline anions were leached from the dissolution of free alkali during the first stage, with the remainder originating from alkaline minerals (CaCO₃, Na₆CaAlSi(CO₃)O₂₄·2H₂O, Ca₃AlFe₂(SiO₄)(OH)₄).

3) The alkaline anion CO_3^{2-} accounted for 75% of the total soluble alkalinity (69.78 mmol/L), with HCO_3^{-} accounting for 19%.

4) Carbonate leaching was controlled by solid film diffusion using the Stumm Model, with an apparent activation energy of 10.24 kJ/mol.

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赤泥碱性阴离子浸出优化及溶解行为

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摘 要:赤泥是氧化铝工业生产过程中产生的高碱性固体废弃物。基于单因素-正交实验开展赤泥碱性阴离子浸出特性研究,结合多级浸出实验探讨最佳浸出条件、碱性阴离子分布特征、关键碱性离子类型及其溶解行为。结果表明:在液固比 2 mL/g、浸出温度 30 ℃、浸出时间 23 h、2 次浸出条件下,可溶性碱性阴离子(CO₃²⁻,HCO₃,Al(OH)₄,OH)的最佳浸出率达 86%;赤泥 1 次浸出液中,88%的阴离子来源于可溶性碱(NaOH、碳酸盐、碳酸氢盐、NaAl(OH)₄),12%的阴离子来源于化学结合碱(方解石、钙霞石、水化石榴石);在最佳浸出条件下,可溶性碱性离子浸出总浓度为 69.78 mmol/L, CO₃²⁻约占 75%;碳酸盐溶解反应的表观活化能为 10.24 kJ/mol,这主要受固膜扩散控制。

关键词:赤泥;碱性阴离子;碳酸盐;浸出优化;溶解行为

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