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Influence of Clay Particle Interactions on Leaching Percolation in Ion-Adsorption-Type Rare Earth Ores

Li Wang ¹, Liang Li ¹, Kaizhong Li ^{2,*}  and Li Huang ³

¹ College of Vanadium and Titanium, Panzhihua University, Panzhihua 617000, China; wl003@126.com (L.W.); liliang72@163.com (L.L.)

² School of Minerals Processing and Bioengineering, Central South University, Changsha 410083, China

³ School of Metallurgical Engineering, Jiangxi University of Science and Technology, Ganzhou 341000, China; huangli1101@126.com

* Correspondence: likaizhong1105@163.com

Abstract: Ion-adsorption-type rare earth ores (IRE-ores) are a vital source of rare earth elements globally. The percolation properties of the ore body significantly determine the ease of rare earth extraction using in situ leaching processes. This paper investigates the interactions among clay particles in ion-adsorption-type rare earth ores within aqueous solutions, utilizing methods such as mineral particle aggregation and settling and acid–base adsorption on mineral surfaces. Based on these analyses, this paper elucidates the influence of solution properties on the percolation process of ion-type rare earth ores during leaching. The results indicate that the electrostatic attraction between minerals in aqueous solutions is pronounced, enhancing the interaction and resulting in a notable instability of the aggregates. The aggregation of minerals impacts the viscous effect of water bound to the mineral surface on the solution, thereby affecting the percolation rate. Extremely low concentrations of SO_4^{2-} and CH_3COO^- can act as surface modifiers, reducing the electrostatic attraction between particles and consequently increasing the leaching percolation rate.

Keywords: ion-adsorption-type rare earth ores (IRE-ores); leaching; clay; particle interactions; percolation



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1. Introduction

Ion-adsorption-type rare earth ores (IRE-ores), notably enriched in medium and heavy rare earth elements (REEs), are significant contributors to the global supply of rare earths and support the growth of emerging industries [1]. In IRE-ores, REEs are predominantly adsorbed in an ionic form on clay mineral surfaces, and thus in situ leaching processes commonly employed for extraction [2]. During these processes, a leaching agent (such as ammonium sulfate or magnesium sulfate solution) introduced into the ore body through injection holes may facilitate ion exchange between the adsorbed rare earth ions on the mineral surfaces and the cations in the leaching agent, leading to extraction [3,4]. The complex composition of IRE-ores, along with low rare earth grades and heterogeneous particle sizes, often results in challenges such as a reduced permeability of the ore body, lower rare earth leaching rates, and longer leaching cycles in mining practices [5,6]. Additionally, interactions between the ore body and aqueous solutions might alter the structural integrity of the ore [7], potentially increasing risks such as landslides [8]. Therefore, understanding and improving the leaching and percolation processes in IRE-ores are crucial for enhancing the efficiency of rare earth extraction, refining process flows, and reducing environmental impacts.

The percolation characteristics of leachate in clay minerals are influenced by multiple factors, including ore composition [9], pore structure [10,11], permeability [12], and the properties of the leaching solution [13,14]. Recent studies have advanced our understanding of the factors affecting leaching and percolation in ion-type rare earth ores [15]. It is believed that clay minerals such as kaolinite, halloysite, illite, and montmorillonite in IRE-ores are

primary carriers of REEs [16,17]. High contents of kaolinite and halloysite might reduce the percolation efficiency due to their weak hydrophilicity [18]. The particle size and grading of clay particles also play significant roles in influencing the percolation characteristics, impacting water infiltration [19,20]. A high concentration of fine clay particles in IRE-ores could lead to reduced percolation rates, extended leaching cycles, and decreased rare earth leaching rates [6].

The impact of solution properties on percolation is an area of ongoing research, particularly regarding how ion types, pH values, and other solution characteristics might affect ore permeability [21–23]. For instance, high-salinity solutions might increase the solution viscosity, reducing percolation rates, whereas the presence of carboxylate ions could enhance both the viscosity and wettability of the ore body, potentially increasing the percolation rate. The Deryagin–Landau–Verwey–Overbeek theory (DLVO theory) suggests that solution salinity may compress the double layer on clay particle surfaces, impacting mineral aggregation and water permeability [24]. For example, ions such as Mg^{2+} and NH_4^+ , as opposed to Na^+ , might better maintain the aggregated structure of the ore body and improve permeability [25]. The leaching process, involving ion exchange and surface dissolution of minerals, is complex. Ion exchange at the mineral–water interface might cause the migration of mineral particles, affecting the percolation rate of the minerals. Prolonged leaching might lead to dissolution phenomena on the surfaces of minerals like kaolinite, potentially affecting the ore body’s properties.

Research on optimizing the percolation of IRE-ores has focused on surface modification and external field enhancement. Surface modification involves adding surfactants to the leaching solution to alter properties like mineral surface wettability [26]. External field enhancement, like electrokinetic mining technology, could potentially increase the directed migration rate of the leaching solution [27]. The current understanding of rare earth leaching and solution percolation in IRE-ores, based largely on experimental observations, is continuing to evolve. Techniques such as SEM, TEM, and nuclear magnetic resonance imaging have enhanced our knowledge of the structural characteristics of minerals before and after leaching, but further research is needed to fully understand the underlying mechanisms.

This paper utilizes column leaching to study the percolation behavior of IRE-ores. Analyzing the interactions between clay particles in the soil–water system from a surface chemistry perspective, we seek to elucidate the influence of solution characteristics on the percolation of IRE-ores, contributing to an enhanced understanding of the ion-type rare earth leaching mechanism. This work provides theoretical support for selecting efficient green leaching agents and optimizing leaching solution percolation.

2. Experiments

2.1. Materials

The IRE-ores utilized in this study were obtained from the fully weathered strata of the Guanxi Rare Earth Mine in Longnan, Jiangxi Province. Raw ore samples were sieved to select fractions less than 2 mm in size and subsequently dried at 60 °C for a duration of 48 h prior to their utilization in experimental procedures. The oxygen content in the IRE-ores was analyzed and determined using an oxygen–nitrogen–hydrogen analyzer (ONH 863, LECO, San Jose, MI, USA), and the rest of the elements were determined using an inductively coupled plasma tandem mass spectrometer (ICP-MS, Agilent 8800, Santa Clara, CA, USA) after acid dissolution. The determination of the rare earth content of the ionic phase in the IRE-ores was achieved using the Chinese rare earth industry standard XB/T 619-2015 [28], and was carried out by using ICP-MS after leaching with 20 g/L ammonium sulfate solution.

All chemical reagents were of analytical grade and deionized water was used for solution preparation.

2.2. Experimental Methods

2.2.1. Column Leaching Percolation of IRE-Ores

Percolation experiments were executed within a 48 mm diameter acrylic column, as illustrated in Figure 1. Initially, the column base was lined with two layers of filter paper, followed by the gradual addition of 100 g of the ore sample. An additional two layers of filter paper were placed atop the sample. The ore column was then compacted gently using a 2.5 kg cylindrical iron block, and subsequently, a 1 cm layer of glass sand (particle size range: 0.4~0.6 mm) was layered over the uppermost filter paper. For the leaching process, the leaching agent was introduced via a peristaltic pump at the glass sand's apex, regulating the pump's flow rate to maintain a 2 cm differential between the column's peak liquid level and the ore layer's summit. The percolation rate ($v = m/t$) was determined by collecting and measuring the mass (m) of leachate discharged at the column base at regular intervals (t).

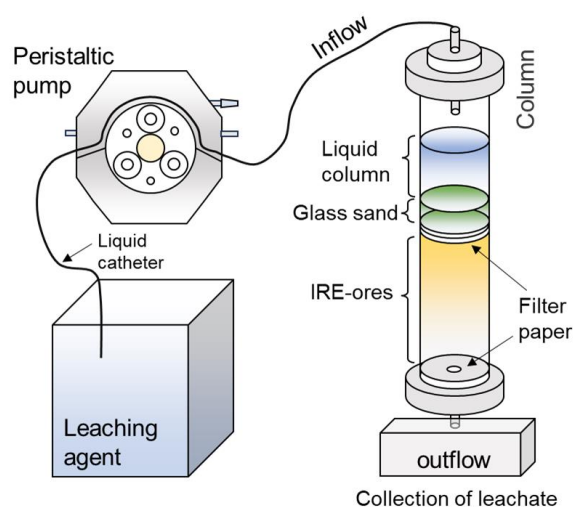


Figure 1. A schematic diagram of the apparatus.

2.2.2. Extraction of Clay Particles from IRE-Ores

Ore samples were amalgamated with deionized water in a 1:2 solid-to-liquid ratio to produce a slurry, which was then pH-adjusted to approximately 8 using NaOH and subjected to ultrasonic dispersion. The dispersed slurry was relocated to a high-settling tank and further diluted to a 1:10 solid-to-liquid ratio with deionized water. After an 8 h settling period at 25 °C, the top 10 cm layer of the slurry (overflow) was siphoned off. This process was iteratively conducted, replenishing the tank to its initial volume with deionized water and extracting the overflow until a clear, transparent supernatant was achieved.

The slurry thus obtained was acidified to a pH of about 4 using 0.1 mol/kg HNO₃, followed by decantation of the supernatant post settling. The residual slurry was then washed several times using sedimentation with deionized water until the conductivity of the slurry was below 20 µs/cm, and subsequently dried at 60 °C. The resultant powder constituted the clay particles of the IRE-ores.

2.2.3. Acid–Base Adsorption on the Surface of IRE-Ores

The acid–base adsorption characteristics of the ore samples were investigated using a potentiometric titrator (ZDJ-5B, INESA Scientific Instrument, Shanghai, China). In this analysis, 3 g of the ore sample was placed in a conical flask along with an electrolyte solution in a 1:10 solid-to-liquid ratio. Following thorough agitation, 0.05 mL of 0.1 mol/kg HCl solution was incrementally added every minute, with concurrent pH monitoring. The quantity of H⁺ adsorbed on the ore's surface was calculated based on pH variations. OH[−] adsorption was gauged in a similar fashion, substituting the titrant with 0.1 mol/kg NaOH solution.

2.2.4. Settling of Clay Particles in IRE-Ores

Suspensions of IRE-ore clay particles were prepared in deionized water across a concentration spectrum of 0.001 to 0.1 g/kg. The absorbance of these suspensions was measured at 810 nm using a spectrophotometer (UV-5500 PC, Shanghai Xiwen Biotech, Shanghai, China), facilitating the construction of a standard curve correlating the suspension concentration with absorbance. Following a 24 h settling period, the absorbance A_1 (and the derived concentration C_1) of the supernatant was measured. A 20 mL sample of the settled suspension was then transferred to a 25 mL colorimetric tube, mixed by inversion thrice, and left to settle for 6 min. The absorbance A_2 (and concentration C_2) of the supernatant was subsequently measured. The settling rate η of the IRE-ore clay particles was computed using $\eta = 100(C_1 - C_2)/C_1$.

2.2.5. Measurement of the ζ Potential of IRE-Ore Surfaces

A suspension of IRE-ore clay particles at a concentration of 0.1 g/kg in deionized water was prepared and ultrasonically dispersed, followed by ζ potential measurements using a Zetasizer Nano ZS90 (Malvern Panalytical Ltd., Malvern, UK).

3. Results and Discussion

3.1. Physicochemical Characterization of IRE-Ores

The total rare earth oxide content and ionic phase rare earth content in the unprocessed raw ore were ascertained to be 0.093% and 0.071%, respectively (refer to Figure 2a). This concentration aligns with the requisite standards for the exploitation and utilization of such rare earth ores, underscoring their significant research potential. The primary chemical constituents identified within the ore include oxygen (44.76%), silicon (23.67%), and aluminum (19.03%), pointing to a mineral composition largely dominated by silicates and aluminosilicates. The X-ray diffraction (XRD) spectrum of the ore, depicted in Figure 2b, indicates a predominance of kaolinite and allophane in the clay fraction, both playing pivotal roles in the ion-type rare earth leaching and percolation processes. Moreover, Figure 2a reveals the presence of trace amounts of iron elements. Recent research has highlighted the role of iron oxide minerals, such as goethite and hematite, in the impact of IRE-ores on rare earth mineralization and ion-exchange leaching, though these were not detectable in the XRD spectrum due to their minimal concentrations.

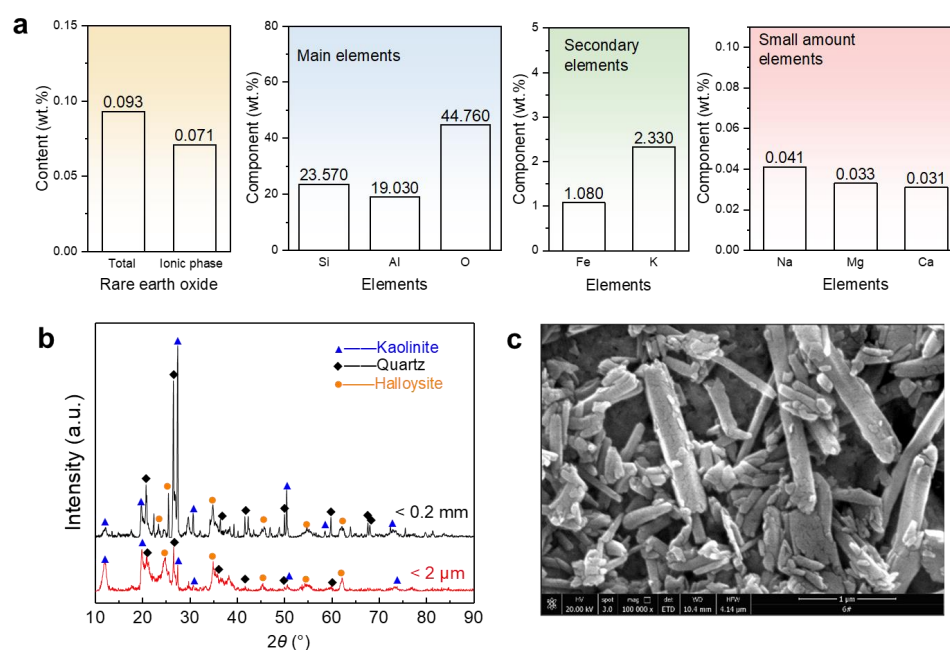


Figure 2. (a) Main chemical composition and the amount of rare earth oxides of the raw IRE-ores, (b) XRD pattern of IRE-ores, (c) SEM image of clay particles (<2 μm) in IRE-ores.

Concerning the clay minerals, due to the large specific surface area, the active sites predominantly reside on the surfaces of the clay colloids (particles less than 2 μm in size) [29]. Screening and sedimentation extraction methods were used to determine that the proportion of clay colloids in ore samples with a particle size of under 2 μm is about 13% (as illustrated in Table 1). These colloids are chiefly characterized by elongated, platy structures (shown in Figure 2c), alongside a considerable presence of nanoparticles, which critically influence the interactions occurring at the soil–water interface during the leaching process.

Table 1. Particle size distribution of the fraction (<0.2 mm) of the IRE-ores.

Particle Size	0.2~0.02 mm	0.02~0.002 mm	<0.002 mm
Mass percent	39.2 wt.%	47.7 wt.%	13.1 wt.%

3.2. Analysis of Leaching Percolation Results in IRE-Ores

The leaching agent concentration is an important factor affecting the extraction of rare earths in the ion exchange leaching process. Figure 3a shows that when ammonium chloride is used as the leaching agent, a concentration of 0.3 mol/L can basically realize the complete extraction of rare earths in the ionic state in IRE-ores (extraction rate of more than 98%). Figure 3b presents the percolation curve for IRE-ores under leaching with a 0.3 mol/kg ammonium chloride solution, primarily delineating two phases. The first phase is the soil–water reaction period, characterized by a linear and rapid decline in the percolation rate as water adsorption occurs in the ore. The second phase is the stable percolation stage, where ore water adsorption nears completion, and the percolation rate gradually decreases. During the leaching process, the concentration of ammonium chloride noticeably influences the average percolation rate in this stable phase (see Figure 3c). Based on the average percolation rate, the sequence from highest to lowest (in terms of ammonium chloride concentration) is observed as 0.3 mol/kg \approx 0.1 mol/kg > 0.5 mol/kg > 0.001 mol/kg. This result is not sufficiently explained solely by the influence of salinity on the solution viscosity or the compression effect on the double layer in saline solutions, as posited by the DLVO theory. Hence, we further explored the leaching process by adjusting the pH of 0.3 mol/L ammonium chloride solutions. Our experimental findings indicated a clear ranking in terms of average percolation rates under different pH conditions, with the order being pH 4.29 > pH 5.84 > pH 5.13 > pH 3.58, as illustrated in Figure 3d.

A comparative analysis of Figure 3c,d demonstrates a notably wider range in average percolation rates in the latter, underscoring the more substantial impact of the solution's pH on percolation rates compared to salinity factors. The active nature of clay minerals is fundamentally attributed to their surface charge characteristics. The solution's salinity and pH level significantly influence the protonation or deprotonation activities on the clay particle surfaces, thereby altering the electrical properties of the mineral surfaces. These alterations impact key mineral characteristics, including surface hydration, ion adsorption, and the dynamics of aggregation and settling. Consequently, it is deduced that the interaction of the leaching solution with the surface of mineral particles plays a predominant role in determining the percolation rate during the leaching process in IRE-ores.

3.3. Analysis of Interactions among Clay Particles in IRE-Ores within Ammonium Chloride Solutions

Figure 4 illustrates the settling curves of clay particles in IRE-ores within ammonium chloride solutions. It is evident that the concentration of ammonium chloride and the pH significantly affect the aggregation and settling of clay particles in the ore. The general analysis is summarized as follows:

- (1) Lower-salinity solutions are more conducive to the aggregation and settling of clay particles in IRE-ores. As the concentration of ammonium chloride increases from 0.001 mol/kg to 0.3 mol/kg, the settling curves generally exhibit a downward trend, contrary to studies related to kaolinite. However, a further elevation in salinity (corresponding to 0.5 mol/kg ammonium chloride solution) results in a noticeable increase in the settling rate of clay particles.
- (2) In low-salinity solutions (0.001 mol/kg and 0.01 mol/kg ammonium chloride), a low pH favors mineral aggregation and settling, which is contrary to previous analyses of kaolinite settling properties. Under acidic conditions, the increase in solution H^+ leads to an increase in positive charge due to protonation of strong aluminate groups on the surface in kaolinite, which should theoretically favor mineral aggregation. However, in relatively higher ammonium chloride solutions, the overall trend aligns with the theoretical expectations, although a slight downward trend still occurs at pH values between 3 and 4.

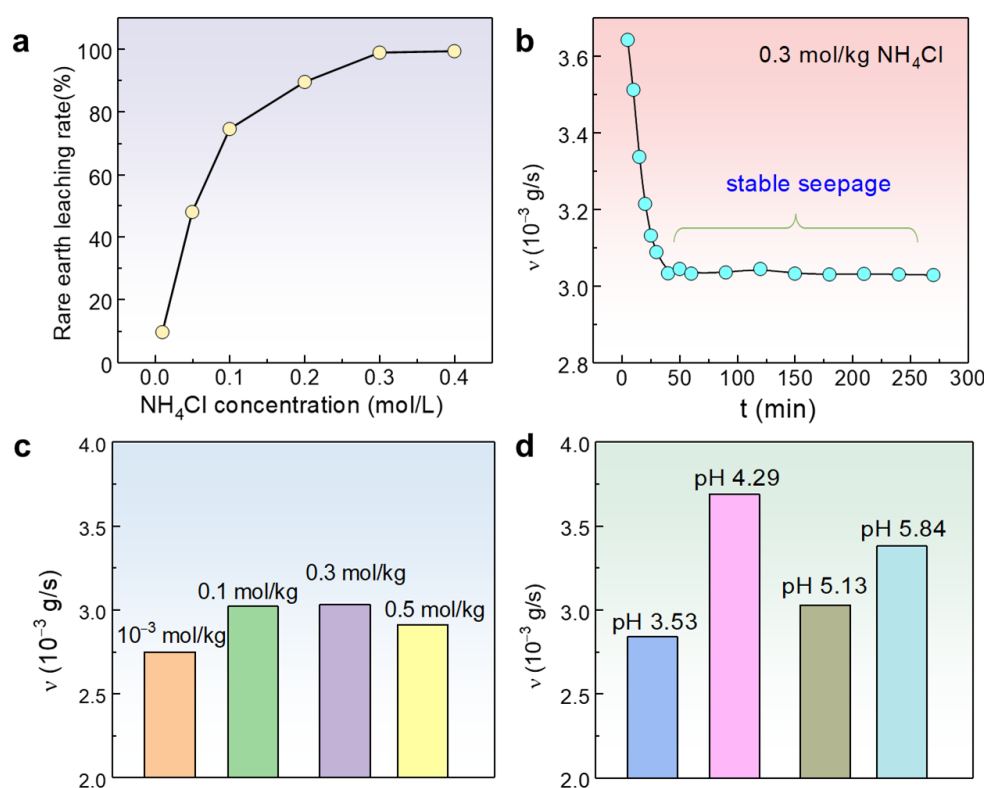


Figure 3. (a) Effect of ammonium chloride concentration on the extraction of ionic phase rare earths from mines, (b) the percolation curve for IRE-ores under leaching with a 0.3 mol/kg ammonium chloride solution, (c) the effect of ammonium chloride concentration on the average percolation rate, (d) the effect of pH on the average percolation rate in 0.3 mol/kg ammonium chloride solutions.

Based on these observations, the anomalous settling behavior of IRE-ore clay particles might be related to the iron oxides present in the ore. Within the experimental pH range of 3 to 6, iron oxides on the particle surface carry a positive charge, enhancing the electrostatic attraction between IRE-ore clay particles, with interactions primarily driven by van der Waals forces and electrostatic attraction. In low-salinity solutions, the thicker double layer on clay particles reduces the van der Waals forces, with electrostatic attraction predominating. The thicker double layer increases the particle collision probability, thereby facilitating aggregation and settling. As the solution's salinity increases, compression of the double layer weakens electrostatic forces, reducing clay particle settling.

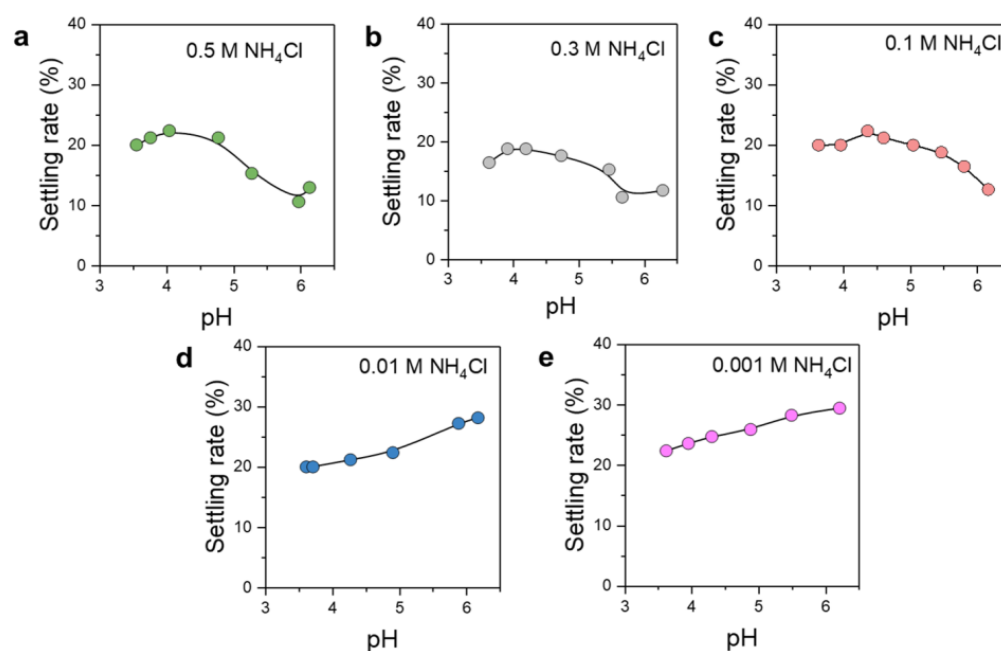


Figure 4. Settling curves of clay particles in IRE-ores within different concentrations of ammonium chloride solution. (a) 0.5 mol/kg (b) 0.3 mol/kg (c) 0.1 mol/kg (d) 0.01 mol/kg (e) 0.001 mol/kg.

Although compression of the double layer enhances the van der Waals forces, they act over short ranges and only exhibit strong attractive forces when the double layer is sufficiently compressed, explaining the sudden increase in clay particle settling in the 0.5 mol/kg ammonium chloride solution. The effect of pH on anomalous clay particle settling involves changes in the surface charge properties of kaolinite and allophane in IRE-ores and encompasses various aggregation mechanisms such as face–face, face–edge, and edge–edge interactions. Additionally, the pH affects the adsorption of iron oxides on mineral surfaces, necessitating further detailed studies, which are beyond the scope of this paper.

To verify the aforementioned hypothesis, studies on the acid–base properties of the mineral surface were conducted. Acid–base titration of clay minerals reflects changes in the variable surface charges. In high-salinity solutions, minerals exhibit an enhanced adsorption capacity for acids and bases, while the opposite is true for low-salinity solutions. Acid–base titration using ammonium chloride solutions involves ammonium hydrolysis, significantly impacting calculations of hydrogen adsorption on mineral surfaces. Figure 5 shows the results of ζ potential measurements of IRE-ore clay particles in ammonium chloride and sodium chloride solutions, indicating that both salts have similar effects on the surface charge of the ore samples. Therefore, sodium chloride solutions were used as a substitute for ammonium chloride in surface acid–base titration analyses, with the results presented in Figure 6a. During acid titration, hydrogen adsorption phenomena were observed on IRE-ore surfaces, but the amount of hydrogen adsorbed did not show a proportional relationship with the sodium chloride concentration, indicating that particle aggregation affects the surface charge properties of minerals and their interactions. During base titration, a larger amount of hydrogen was released from the mineral surfaces, with the amount of hydrogen released generally showing a proportional relationship with the sodium chloride concentration. However, at pH 5.5 to 6, the hydrogen adsorption curves corresponding to 0.5 mol/kg and 0.1 mol/kg sodium chloride intersect, suggesting that mineral aggregation may influence the surface charge properties during base titration.

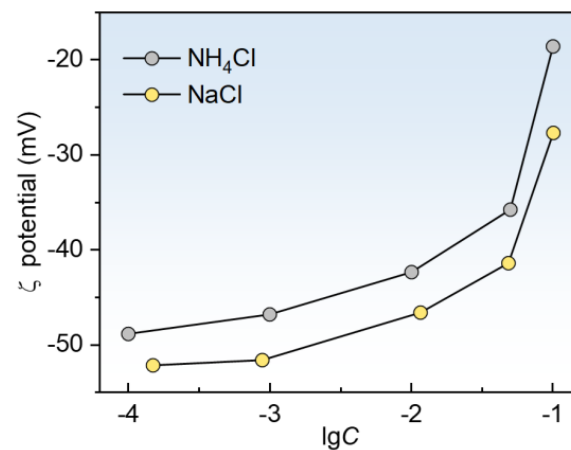


Figure 5. The effect of solution concentration on the ζ potential of IRE-ore clay particles.

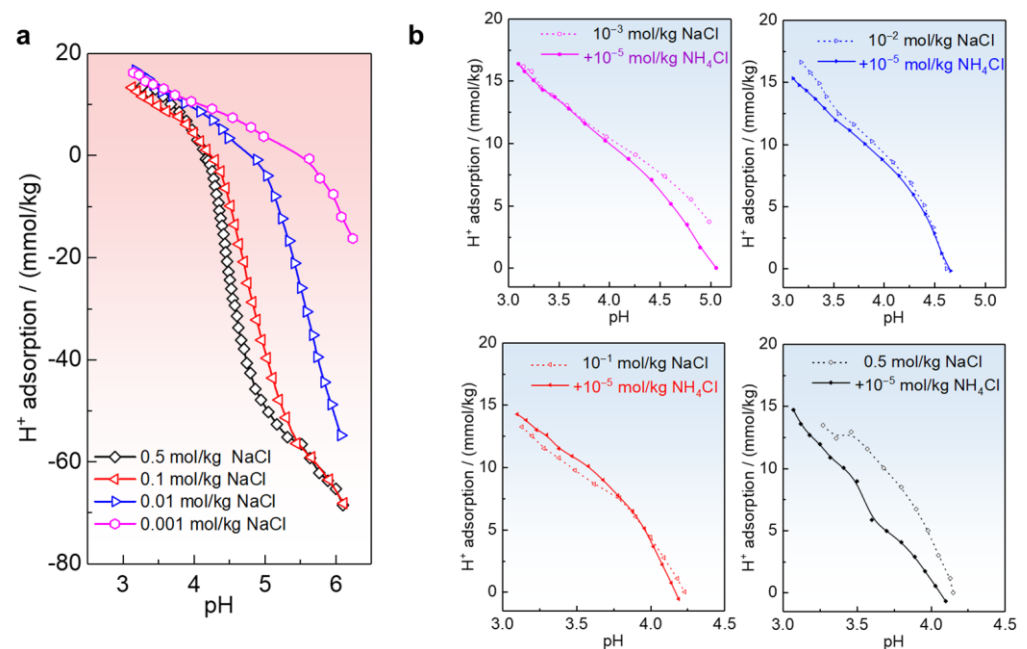


Figure 6. (a) The acid–base titration curves for IRE-ores under sodium chloride solution, (b) the effect of 10^{-5} mol/kg ammonium chloride addition on the acid–base titration curves for IRE-ores.

In the acid–base titration experiments, 10^{-5} mol/kg ammonium chloride was added to examine its effect on hydrogen adsorption during acid titration, as shown in Figure 6b. The addition of 10^{-5} mol/kg NH_4^+ in low-salinity solutions showed an inhibitory effect on hydrogen adsorption on the mineral surface, consistent with previous findings [29]. As the salinity increases, particle aggregation within the double layer is influenced by a combination of van der Waals forces and electrostatic attraction. Under these combined forces, the addition of a small amount of NH_4^+ led to an increase in hydrogen adsorption, as well as a decrease in certain cases.

3.4. Anion Influence on Surface Modification of IRE-Ores and Enhancement in Leaching Percolation

The interactions among clay particles in IRE-ores affect the surface properties of the minerals. Based on this theoretical premise, the impact of anions on the interactions among IRE-ore clay particles, surface acid adsorption, and leaching percolation was investigated by introducing 10^{-5} mol/kg $(\text{NH}_4)_2\text{SO}_4$ and 10^{-5} mol/kg CH_3COOH into the leaching solution. The results are illustrated in Figures 7–9.

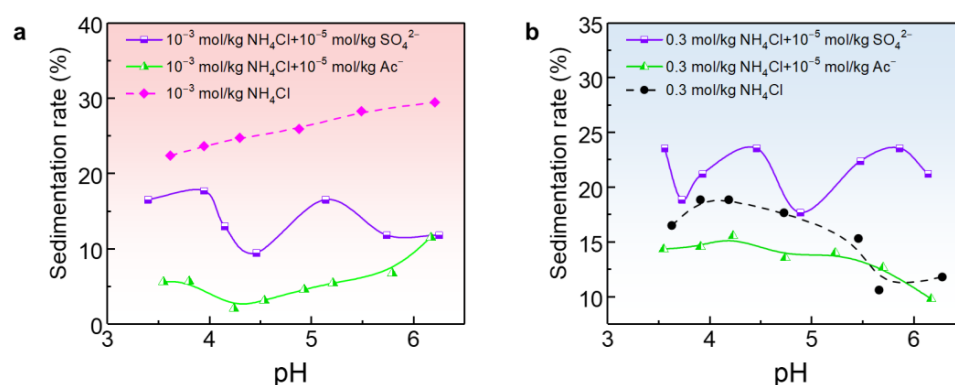


Figure 7. The effect of trace anion additions on the settling curves of clay particles in IRE-ores within ammonium chloride solutions: (a) 0.001 mol/kg ammonium chloride solutions, (b) 0.3 mol/kg ammonium chloride solutions.

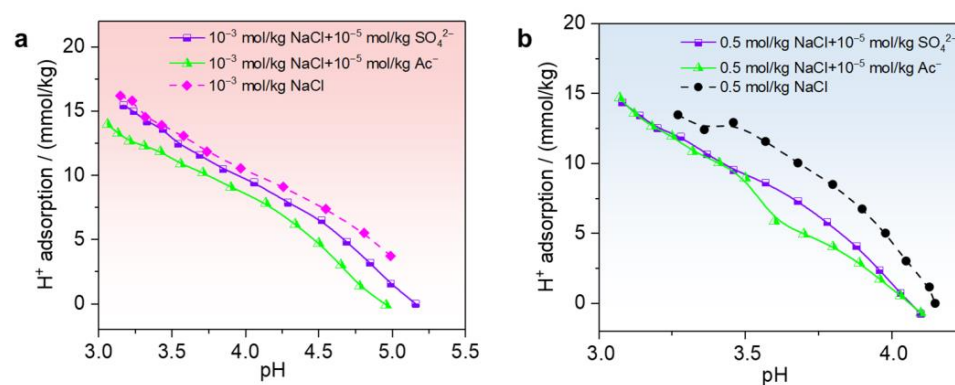


Figure 8. The effect of trace anion additions on the acid–base titration curves for IRE-ores in ammonium chloride solutions: (a) 0.001 mol/kg ammonium chloride solution, (b) 0.5 mol/kg ammonium chloride solution.

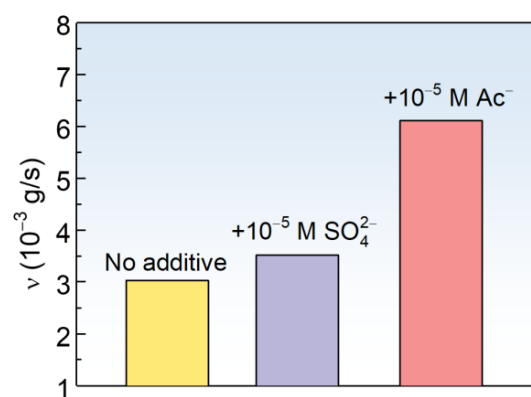


Figure 9. The effect of trace anion additions on the average percolation rate in 0.3 mol/kg ammonium chloride solutions.

SO₄²⁻ exhibits chemical adsorption on the surfaces of clay minerals, occupying positively charged sites and thereby reducing the surface positive charge. In a 10⁻³ mol/kg ammonium chloride solution, the addition of trace amounts of SO₄²⁻ markedly weakened the clay particle aggregation behavior led by electrostatic attraction under low-salinity conditions. However, in a 0.3 mol/kg ammonium chloride solution, despite reducing the electrostatic attraction between mineral surfaces, SO₄²⁻ still demonstrated improved aggregation and settling behavior as electrostatic attraction was not the dominating force. In 10⁻³ mol/kg and 0.5 mol/kg sodium chloride solutions, the addition of minor amounts

of SO_4^{2-} notably decreased the hydrogen adsorption on mineral surfaces. Since SO_4^{2-} occupies hydrogen adsorption sites on mineral surfaces, it remains unclear if the reduction in hydrogen adsorption is related to the weakening of particle aggregation. The addition of SO_4^{2-} in 0.3 mol/kg ammonium chloride leaching solutions increased the percolation rate, indicating that weakening the electrostatic attraction between particles could facilitate the leaching percolation process.

CH_3COO^- (Ac^-) mainly exhibits electrostatic adsorption on clay mineral surfaces, generally not altering the surface charge properties of the minerals. The addition of trace amounts of Ac^- in 10^{-3} mol/kg and 0.5 mol/kg ammonium chloride solutions significantly weakened the aggregation behavior of clay particles, potentially related to the radial adsorption pattern of Ac^- on mineral surfaces. When IRE-ore clay particles interact, the adsorbed Ac^- leads to spatial steric hindrance, inhibiting both electrostatic attraction and van der Waals forces between the particles, thereby reducing the degree of particle aggregation. The introduction of Ac^- into 0.3 mol/kg ammonium chloride leaching solutions more than doubled the percolation rate, suggesting that weakening inter-particle interactions aids the leaching percolation process.

3.5. Mechanism of Clay Particle Interactions on Leaching Percolation in IRE-Ores

The above analyses all indicate that in the leaching process of IRE-ores, interactions among clay particles significantly affect the percolation process. This influence is mainly manifested in the effect of water bound to the surface of the mineral particles on percolation. Bound water on mineral surfaces can be categorized into two types based on the strength of binding: one is the adsorption layer composed of strongly adsorbed hydrated cations and water molecules (inner adsorption layer), constituting strongly bound water. The other is the diffusion layer in the double layer of the mineral surface, consisting of adsorbed hydrated cations and water molecules (outer adsorption layer), known as weakly bound water. For NH_4^+ and Na^+ , they exhibit physical adsorption and do not enter the inner adsorption layer of the mineral surface.

In very low-salinity solutions, the double layer on the surface of IRE-ores is thicker, and due to the electrostatic attraction between mineral particles, aggregation occurs, forming larger clusters (Figure 10a). At this stage, the water bound to the surface of these clusters occupies the diffusion layers of each mineral particle, hindering the flow of the solution on the mineral surface and reducing the percolation rate. However, when the solution's salinity is increased, the double layer on the mineral surface becomes thinner, weakening the interactions between particles, which reduces the formation of aggregates and thus diminishes the viscous effect of the bound water on the mineral surface on the leaching fluid (Figure 10b). With further increases in solution salinity, when the compression of the double layer on the mineral surface becomes significant, van der Waals forces between particles are enhanced (Figure 10c). At this stage, the bound water on the mineral surface is predominantly composed of hydrated cations in the diffusion layer. During mineral particle aggregation, the repulsive hydration forces, electrostatic attraction, and van der Waals forces must be considered. The combined effect of these forces drives mineral aggregation and impacts the leaching percolation process.

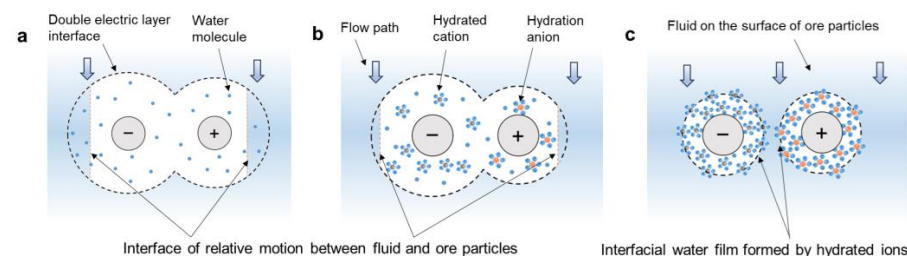


Figure 10. Schematic diagram of the mineral–water interface in the leaching process: (a) pure water or very low-salinity solutions, (b) low-salinity solutions, (c) relatively high-salinity solutions. (Hydrated ions are represented as pentahydrate ions in the figure.)

4. Conclusions

During the leaching process, the stability of IRE-ore aggregates is poor, and the properties of the leaching solution play a crucial role in influencing the stability of these aggregates. When IRE-ore particles aggregate, the electrostatic attraction between them is significant, enhancing the interaction between the minerals. Studies on the stability of IRE-ore aggregates should consider the combined effects of hydration repulsion, electrostatic attraction, and van der Waals forces between the particles.

Given the poor stability of the aggregates, changes in the water body can alter the microstructure of the mineral surfaces in IRE-ores, subsequently impacting the leaching percolation process. Surface modification of the minerals, such as reducing the electrostatic attraction between particles or increasing the spatial steric hindrance to obstruct particle interactions, can effectively enhance the percolation process in IRE-ores. These findings provide theoretical guidance for the green and efficient exploitation of IRE-ores.

Since the ion exchange extraction of rare earths and mineral–mineral interactions take place simultaneously during leaching, the interconnections between the two deserve to be studied in depth in order to improve the leaching efficiency of rare earths.

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