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Soil−water characteristics of weathered crust elution-deposited rare earth ores

Zhong-qun GUO[1], Jian-rong ZHOU[1], Ke-fan ZHOU[1], Jie-fang JIN[1], Xiao-jun WANG[2], Kui ZHAO[2]

1. School of Civil Engineering and Surveying & Mapping Engineering, Jiangxi University of Science and Technology, Ganzhou 341000, China;
2. Jiangxi Key Laboratory of Mining Engineering, Jiangxi University of Science and Technology, Ganzhou 341000, China

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Abstract: The permeability of the weathered crust elution-deposited rare earth ores directly affects the efficiency of in-situ leaching. The soil−water characteristic curve (SWCC) is an important constitutive relation for calculating the permeability of ore body, which is related to many factors. Soil−water characteristic tests of rare earth ore samples considering different factors were carried out by using the pressure plate instrument. Effects of dry density, particle size and solution leaching on water holding behavior and the mechanism were investigated. The experimental observations indicate that with the decrease of dry density, the pore ratio increases gradually, and the saturated water content increases. Under the same matric suction, the water content decreases gradually with the increase of particle size, thus decreasing water holding capacity of ore accordingly. In the same water content, matric suction is inversely proportional to particle size. Under the same matric suction, the water content of ore samples after leaching is less than that of the ore samples before leaching, indicating that solution leaching can decrease water holding capacity of ore.
Key words: weathered crust elution-deposited rare earth ore; dry density; particle size; solution leaching; soil-water characteristic curve

1 Introduction

Rare earth is an important mineral resource of worldwide concern and it is praised as the “industrial vitamins” and “industrial gold”. Weathered crust elution-deposited rare earth (also known as ion-absorbed rare earth) is a special mineral resource in southern China [1]. In these ores, rare earth elements which are adsorbed onto the clay minerals through hydrated cations or hydroxyl hydrated cations are difficult to be enriched by conventional selecting technique [2]. They have the advantages of complete distribution, high content of middle heavy rare earth elements, low radioactivity ratio, high comprehensive utilization value and simple extraction process [3]. Weathered crust elution-deposited rare earth mining has experienced pool leaching, heap leaching and in situ leaching process. Currently, it is mainly exploited by in-situ leaching [4]. The main process of in-situ leaching is shown in Fig. 1. Soil−water characteristics of rare earth ores can reflect difficulties for pores in soil mass to absorb water and predict the permeability of ore body during in-situ leaching [5]. In the process of the leaching of weathered crust elution-deposited rate earth ores, the hydrated cations adsorbed on clay minerals and the ore particle size have been changed. These changes have a significant impact on the water retention characteristics of ores. Studying the effects of different factors on weathered crust

Corresponding author: Zhong-qun GUO, Tel: +86-15216173840, E-mail: guozhongqun_jxust@163.com
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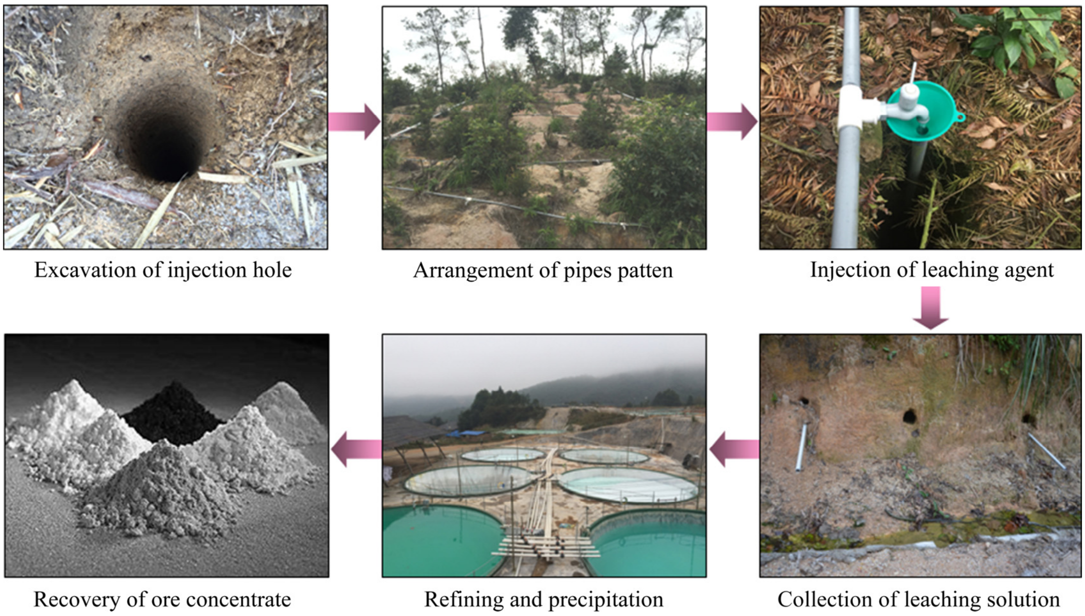

Fig. 1 Main process of in-situ leaching

elution-deposited rare earth ores is conducive to analyze permeability characteristics of ore body, and it can provide theoretical basis for the mining design of injection well pattern parameters.

The hydraulic characteristics of ore body refer primarily to the soil−water characteristic curve (SWCC). The SWCC is a graphical relation curve between matric suction and water content [6]. At present, many methods or soil property indexes have been adopted to estimate SWCC [7]. As an explanation to the basic constitutive relation of non-saturated soil phenomenon, SWCC is sensitive to many factors [8]. Some scholars have carried out a lot of meaningful studies. BLACK [9], TAO et al [10] and NIU et al [11] discussed influence of mineral components on SWCC. CHIU et al [12], RAJKAI et al [13], CHEN and NCHIMURA [14] studied the influence of particle size on SWCC. MILLER et al [15] and WANG et al [16] analyzed the influence of water content on SWCC. WEN et al [17,18], SHENG and ZHOU [19] discussed effects of dry density on SWCC. MIAO et al [20] and GONG et al [21] analyzed the influence of compaction degree on SWCC. VANAPALLI et al [22], CHARLES and PANG [23], and WANG et al [24] studied the influence of stress history and stress level on SWCC. SALAGER et al [25] and WANG et al [26] considered the influence of temperature on SWCC. Above all, influencing factors of SWCC mainly include internal factors and external factors. The internal factors consist of mineral composition, particle size, initial water content, initial dry density, compressivity and structure. The external factors consist of stress history of soil, stress state, temperature and dry−wet cycle.

According to engineering background of weathered crust elution-deposited rare earth in-situ leaching, there are few studies concerning the influence on water holding behavior of ore body. In this study, rare earth ore samples were collected from the Longnan Zudong Rare Earth in Jiangxi Province of China. After particle screening and solution leaching, soil−water characteristics of ore samples were tested by the pressure plate instrument under different conditions. The influence of different factors on soil−water characteristics of weathered crust elution-deposited rare earth ores was investigated, and the mechanisms were revealed.

2 Experimental

2.1 Experimental ore

Weathered crust elution-deposited rare earth ore samples are from the Ganzhou Longnan Rare Earth Ore in Jiangxi Province, China. The ore samples of this experiment were taken from a depth of 0.5−1 m in the ore body (6−8 m below the ground). Basic physical parameters of samples are listed in Table 1. The particle size distribution curve of rare earth ores is shown in Fig. 2. The percentages of sand, silt and clay are 51.89%, 14.32% and 1.92%, respectively. The quantitative

Table 1 Basic physical parameters of rare earth ores

Density, ρ/(g·cm^{-3})	Natural water content, θ/%	Specific gravity, G_s/(g·cm^{-3})	Void ratio, e	Liquid limit, w_L/%	Plastic limit, w_P/%	Plastic index, I_p
1.66	16.26	2.68	0.88	40.56	30.27	10.29

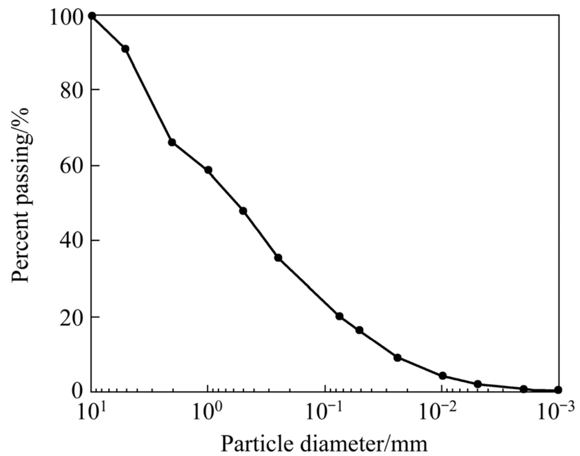

Fig. 2 Particle size distribution of rare earth ore sample

X-ray diffraction (XRD) and X-ray fluorescence (XRF) analysis of the ore samples were carried out, and the results are shown in Fig. 3 and Table 2, respectively. It can be seen that silicate minerals such as kaolinite are the main carriers of rare earth, and potassium feldspar, quartz and muscovite are in the secondary position. In this kind of rare earth ores, a large number of Al, K, Fe and other metal elements are associated.

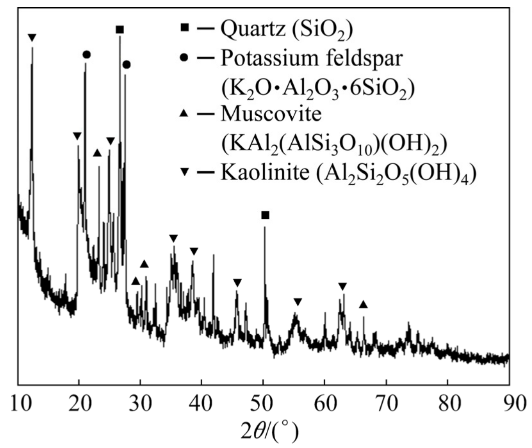

Fig. 3 XRD pattern of ore sample

Table 2 XRF chemical elements analysis results of ore sample (wt.%)

O	Si	Al	K	Fe	Cu
41.899	30.964	16.610	4.738	1.135	0.180
Mn	Rb	Pb	Th	RE	Others
0.115	0.113	0.042	0.005	0.108	4.091

2.2 Experimental apparatus, scheme and principle

In this experiment, Geo-Experts stress-related soil−water characteristic curve pressure plate apparatus was applied (Fig. 4). It is mainly composed of pressure plate apparatus, vertical loading system, pressure control system and water volume measurement system.

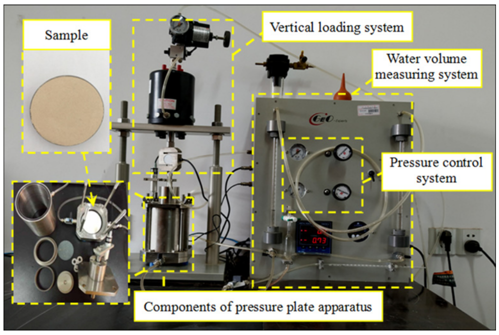

Fig. 4 Geo-Expert stress-related soil and water characteristic curve pressure plate apparatus

To study the effects of different factors on SWCC of weathered crust elution-deposited rare earth ores, different test schemes are designed as follows.

(1) Different dry densities

Samples without leaching were selected, and the initial water content was set as the optimal water content, i.e. w_{op}=15%, because different dry density can be set by different compaction standards in the optimal water content. The dry density was selected according to the void ratio e=1, e=0.9, and e=0.8, i.e. ρ_d=1.34 g/cm^3, ρ_d=1.41 g/cm^3, and ρ_d=1.49 g/cm^3. At the same time, the undisturbed soil was set for comparison. The void ratio of undisturbed soil e=0.88 and dry density ρ_d=1.43 g/cm^3.

(2) Different particle sizes

Rare earth ore samples were screened by a standard round-hole sieve, thus getting samples with different particle sizes. Four kinds of particle sizes were used: three kinds of single grain size ore samples, such as <0.075 mm, 0.075−0.25 mm, and 0.25−0.5 mm, and the undisturbed soil size distribution. In the undisturbed soil, the particles which are smaller than 0.5 mm account for 48.22%. The sample which contains particles larger than 0.5 mm has poor adhesion like sandy soil and shows significant differences with engineering properties of the collected soils. Therefore, sample with particles larger than 0.5 mm was neglected in the present study.

(3) Leaching effect

According to the rare earth industrial standard of XB/T 619—2015 [27], the rare earth ore samples in Scheme (2) were put into ammonium sulfate solution (20 g/L) for leaching. The photos for ore samples before and after leaching are shown in Fig. 5. After leaching, the samples were placed and dried, and the soil−water characteristic curve tests were carried out.

The soil−water characteristic samples were remoulded by a *d*70 mm × 19 mm cylinder. Sieved and dried rare earth ores were collected to prepare test samples according to preset dry density and water content. Later, the prepared samples were installed into a cutting ring and compacted. The prepared samples were then treated with 24 h of vacuum saturation by a vacuum saturation device before the experiment. Drying experiment was carried out under 0, 10, 20, 50, 100, 150, 200, 300, 400 and 480 kPa. The wetting experiment was conducted after finishing the drying experiment, in which matric suction was decreased level by level to 0. Water would reflow into soil gradually. Data were read after reaching the water equilibrium. Equilibrium standards of samples under single-level matric suction were referred to suggestions of PHAM [28]: When the water discharge amount in 24 h is smaller than 0.1 mL, the matric suction is considered to be stable.

In the Geo-Experts pressure plate instrument, the ceramic plate with high inlet air serves as a membrane that prevents air inlet and assures water entrance. The upper surface of ceramic plate bears the air pressure (u_a) and the lower surface bears the pore water pressure (u_w). The pressure difference between the upper and lower surfaces (u_a-u_w) is the matric suction of rare earth samples. In the experiment, it is believed that u_w=0 when water in the water volume measurement tube remains constant. Under this circumstance, u_a is equal to the matric suction. At this moment, u_a and variation of water volume in tube (Δv) were recorded.

The initial saturated mass water content of rare earth samples is

$$w_s = \frac{m_t - m_s - m_0}{m_s} \times 100\% \quad (1)$$

(a)

(b)

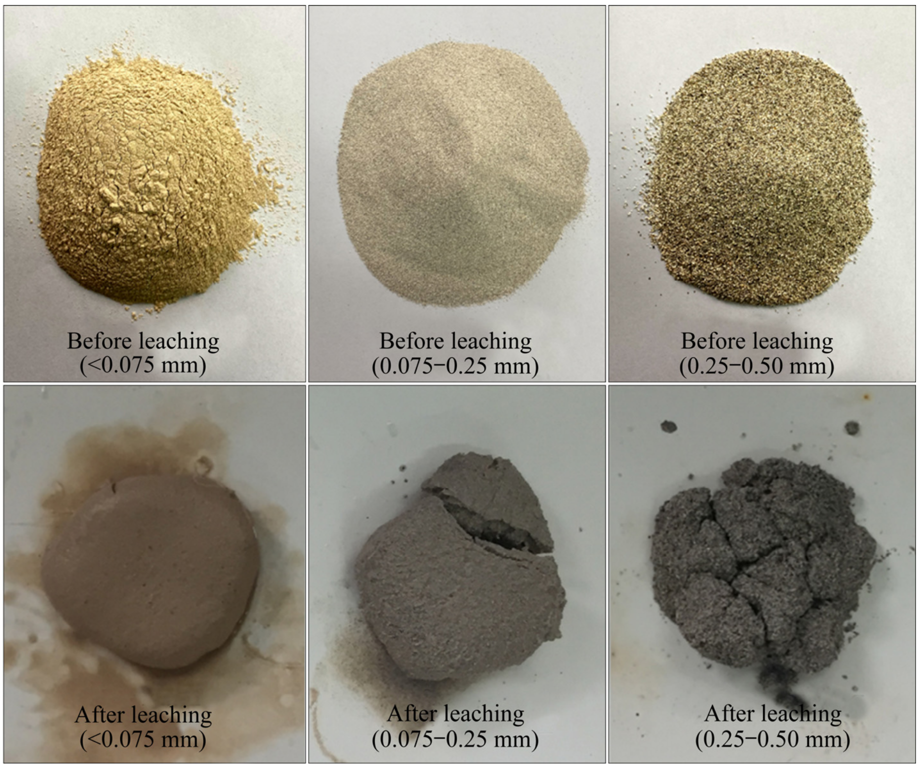

Fig. 5 Photos of ore samples with different particle sizes before (a) and after (b) leaching

where w_s is the saturated mass water content; m_t is the total mass of cutting ring and saturated samples after vacuum saturation; m_s is the mass of dried samples after the experiment; m_0 is the mass of cutting ring.

In this experiment, mass water content of samples under each level of matric suction was calculated from variations of water volume in the tube:

$$w = \frac{m_t - m_s - m_0 - \Delta v_i \rho_w}{m_s} \times 100\% \quad (2)$$

where w is the mass water content; Δv_i is the variation of water volume in the tube; ρ_w is the density of water.

The volume water content of samples under different matric suctions is

$$\theta = \frac{w\rho_d}{\rho_w} \times 100\% \quad (3)$$

where θ is the volumetric water content and ρ_d is the dry density of soils.

2.3 SWCC model

For studies of SWCC of unsaturated soils, lots of models were proposed. It is found that the Fredlund & Xing model has good accuracy for weathered crust elution-deposited rare earth ores [29]. Function of the Fredlund & Xing model [30] is

$$\frac{\theta}{\theta_s} = \left\{ \ln\left[e + \left(\frac{\psi}{a}\right)^n \right] \right\}^{-m} \quad (4)$$

where θ_s is saturated water content. ψ is the matric suction of soil mass. And a, n, and m are optimization parameters of the model. The parameter a is related with air inlet, n is a parameter related with drying rate and it controls slope of the SWCC, and m is a parameter related with residual water and it is correlated with the overall symmetry of curve. This model believes that there is a small θ_r. For the simplification of models, it is hypothesized that θ_r=0.

3 Results and discussion

3.1 Effects of dry density on soil−water characteristics

To study the effect of dry density on the soil−water characteristics of the ores, the dry density of the samples were set to be 1.34, 1.41 and 1.49 g/cm^3, and the corresponding void ratio was 1, 0.9 and 0.8, respectively. The dry density of undisturbed soil was 1.43 g/cm^3 and the void ratio was 0.88. The soil−water characteristic curves of the four samples with different dry densities are shown in Fig. 6. It can been seen that the soil−water characteristic curve not only reflects the relationship between soil matric suction and water content, but also reflects the pore state in soil. The effect of dry density on soil−water characteristic curve is shown by changing the pore condition of soil. Therefore, experimental observations indicate that with the decrease of dry density, the pore ratio of the sample increases gradually, and the inter-pore connectivity is better, so the saturated volume water content increases. At the same time, when the suction is low, the ore sample begins to lose water. On the contrary, the larger the dry density of the ores is, the closer the particles will be. The smaller the porosity is, the lower the saturated volume water content is, so the lower the penetrability will

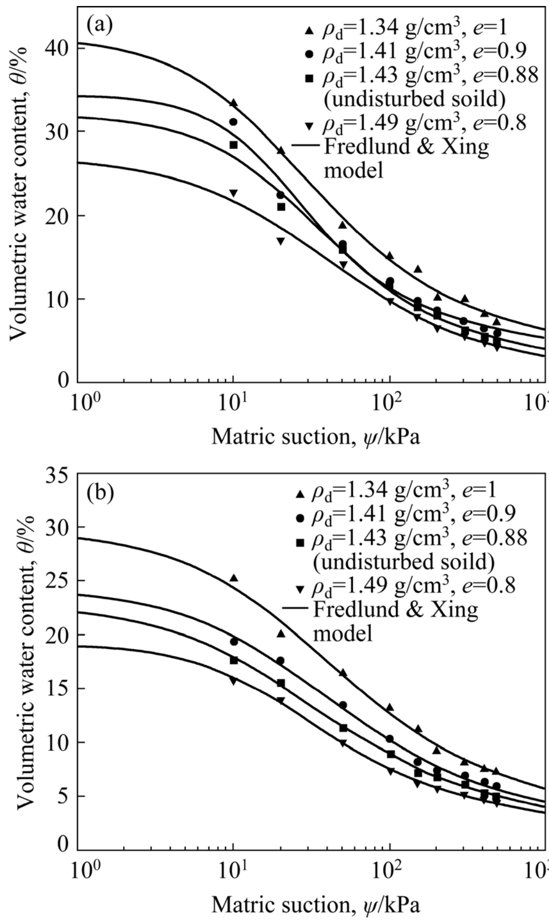

Fig. 6 Soil−water characteristic curves of ore samples with different dry densities: (a) Drying; (b) Wetting

be. In the same matric suction, the volume water content decreases gradually with the increase of dry density, thus decreasing water holding capacity of ore accordingly.

It is reasonable and conservative to consider that with the increase of dry density, the porosity of the sample decreases gradually, and it is difficult for air to enter into the ore body. It is difficult to drain water or absorb water, so the sample with a small pore ratio has higher air entrance value. The smaller the dry density is, the smaller the air entrance value is, so the sample with a small dry density is easier to drain. The dry density determines the tightness of the ore structure. The larger the dry density is, the more compact the pore structure is, and the stronger the ability to bind water is. Within the same matric suction range, the samples with a larger dry density is more difficult to lose water.

3.2 Effects of particle size on soil−water characteristics

To study the effect of particle size on soil−water characteristics of the ores, rare earth ore samples with three particle sizes (<0.075 mm, 0.075−0.25 mm and 0.25−0.5 mm) and undisturbed soil grading (particles smaller than 0.5 mm accounting for 48.22%) were tested. Drying curves of ores with different particle sizes before and after leaching are shown in Fig. 7, and wetting curves are shown in Fig. 8. Clearly, SWCC moves upward when the particle size is small. Under the same matric suction, water content of ore samples with smaller particle size is higher than ore samples with lager particle size. And thereby ore samples with smaller particle size own the larger water holding capacity. Variation laws of water content of these ore samples are consistent in the drying and wetting processes. With the increase of particle size and decrease of content of fine particles, water content declines gradually and the water holding capacity decreases accordingly. Further analysis shows that the pore diameter is increased with the increase of particle size, but the air inlet value and residual water content decline, thus resulting in reduction

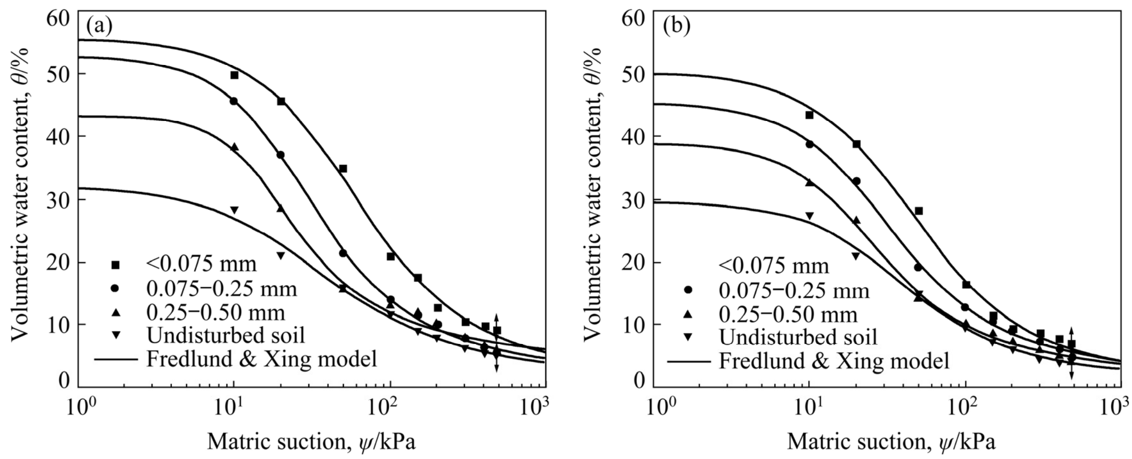

Fig. 7 Drying curves of soil samples with different particle sizes: (a) Before leaching; (b) After leaching

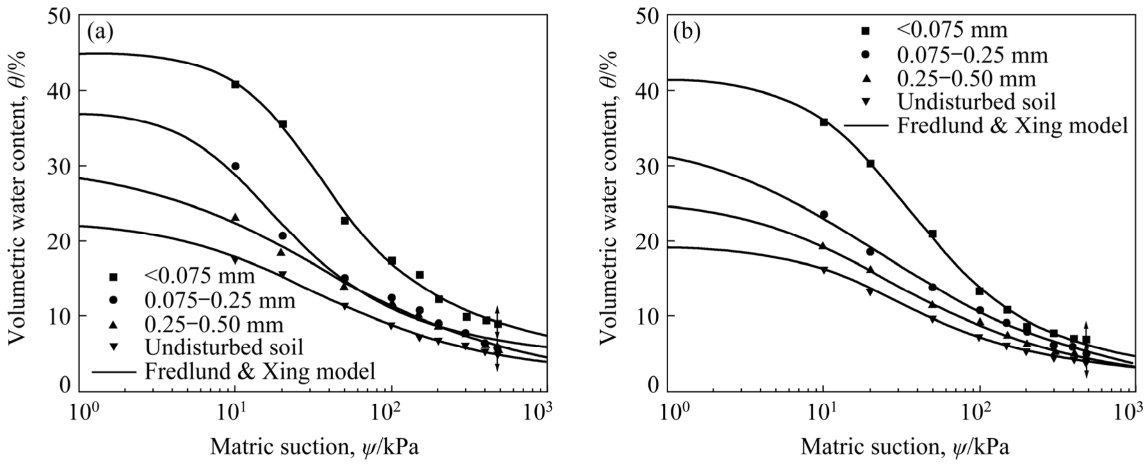

Fig. 8 Wetting curves of soil samples with different particle sizes: (a) Before leaching; (b) After leaching

of water holding capacity. It is easy to discover that water content decreases gradually when the matric suction increases from 0 to 200 kPa and the water content decreases slowly when the matric suction increases from 200 to 480 kPa. The change amplitude of water content tends to be smooth. When the volume water content is constant, there is a significant difference in matric suction among samples with different particle sizes. This difference is manifested by the inversely proportional relationship between matric suction and particle size.

When the matric suction increases from 0 to 480 kPa, the variation of water content of different samples is shown in Fig. 9. It can be seen from Fig. 9 that the content of coarse particles in rare earth ores increases with the increase of particle size, and the variation amplitude of water content decreases gradually. Before the solution leaching, the water content variation amplitudes of ores with particle size <0.075 mm on the drying curve and wetting curve reach as high as 46% and 36%, while variation amplitudes of water content of samples with particle size ranging 0.25−0.5 mm are 37% and 24%, respectively. Water content of undisturbed sample on the drying curve and wetting curve is changed slightly (only 27% and 18%), which is related with the increased content of coarse particles and extended range of particle size. After the solution leaching, variation amplitudes of water content on drying curve and wetting curve are 43% and 35% for sample with particle size <0.075 mm, as well as 35% and 22% for sample with particle size ranging 0.25−0.5 mm. Variation amplitudes

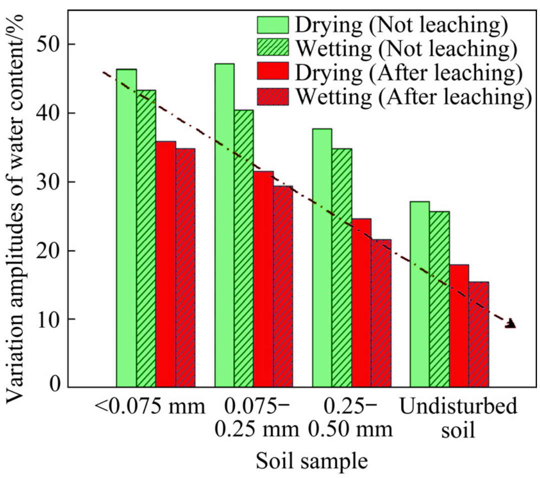

Fig. 9 Variation amplitudes of water content of different soil samples

of water content on drying curve and wetting curve of undisturbed sample are only 26% and 15% after the solution leaching, which are consistent with those before the solution leaching. To sum up, variation amplitude of water content decreases gradually with the increase of particle size and content of coarse particles.

Based on the in-situ leaching engineering background, the water content of ore body is low in the early stage of leaching. For unsaturated soil with low water content and high suction value, suction is mainly affected by relatively short-range adsorption, which is strongly controlled by the surface properties of soil particles. Therefore, in the process of wetting and drying, the water holding behavior of the soil is mainly affected by the microstructure of soil particles, such as morphology, particle size, pore characteristics and interparticle relationship. In order to study the effect of the surface properties of soil particles with different sizes on the water holding behavior of ionic rare earth, three kinds of soil particles with particle size <0.075 mm, 0.075−0.25 mm and 0.25−0.5 mm were scanned and photographed with scanning electron microscope. Because the particle size of mineral soil is small, PCAS system [31] was selected to process and analyze the typical SEM images, as shown in Fig. 10, and the quantitative parameters of microstructure information are given in Table 3.

From Fig. 10, it can be seen that ore particles and pore units are composed of mostly dense structures formed by face to face or edge to face. Ores have uneven pore size distribution, with high structural dispersion of particles and pores. The surface of soil particles with particle size less than 0.075 mm has large concave opening pores, with obvious pore development, larger pore diameter and larger specific surface area, which can be used as the channel and storage place for water infiltration. The surface of soil particles with particle size of 0.075−0.25 and 0.25−0.5 mm are complex, and the surface opening pores of soil particles with particle size of 0.075−0.25 mm are small and many, which can absorb and hold certain amount of water. The soil particles with particle size of 0.25−0.5 mm are composed of massive agglomerated structure, which are closely arranged. The pore diameter of the surface pore is small, and the pore crossing is shallow. The analysis shows that the smaller the

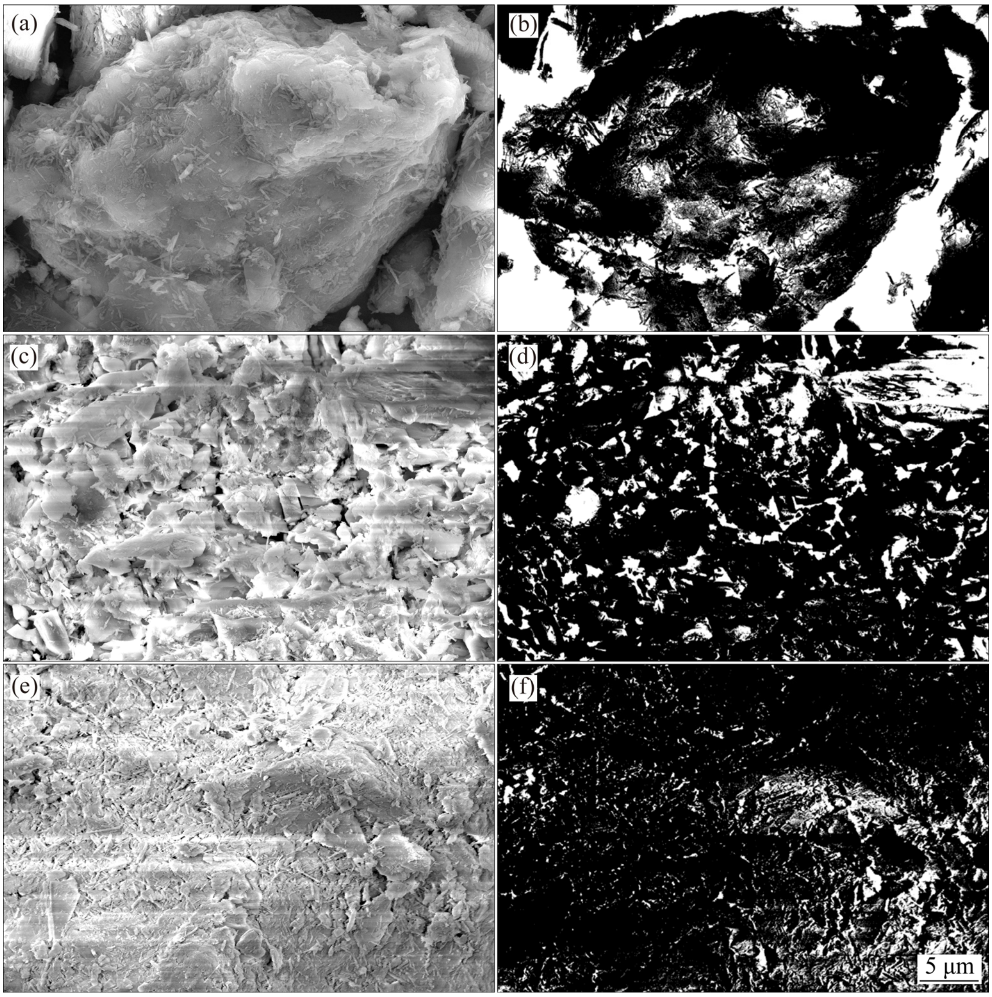

Fig. 10 Typical SEM images (a, c, e) and binary pictures (b, d, f) of different soil samples: (a, b) <0.075 mm; (c, d) 0.075−0.25 mm; (e, f) 0.25−0.5 mm

Table 3 Parameters of SEM microstructure

Particle size/mm	Porosity of particle surface/%	Probability entropy	Mean shape coefficient
<0.075	31.04	0.9879	0.3432
0.075−0.25	22.94	0.9891	0.4373
0.25−0.5	12.55	0.9716	0.3961

particle size is, the larger the opening pore in the particle is, and the wider the space for free water flow and storage is. Therefore, it can be inferred that the smaller the particle size is, the more the water can be adsorbed by the ionic rare earth particles when the soil is mainly affected by short-range interparticle reaction.

From Table 3, it can be seen that the surface porosity of soil particles is 31.04%, 22.94% and 12.55% when the particle size is <0.075, 0.075−0.25 and 0.25−0.5 mm, respectively. With the increase of particle size, the opening porosity of soil particles gradually decreases, which is also consistent with the morphology and porosity of soil particles in the SEM images. The particle and pore structure of soil is uncertain and random, and the probability entropy is an index reflecting the orderliness of soil microstructure unit. Its value is between 0 and 1. The larger the probability entropy is, the more chaotic the arrangement of particle and pore unit is, and the lower the orderliness of structure is. The change range of probability entropy of soil particles with particle size <0.075, 0.075−0.25 and 0.25−0.5 mm is very small, which is between 0.9716 and 0.9891, indicating that the pore distribution of soil samples is chaotic and the orderliness is low at these particle sizes. The mean shape coefficient is an index to describe the shape of soil particles and pore units. The mean shape coefficient represents the geometric shape of particles and pores in the soil microstructure of the whole region. The smaller the mean shape coefficient is, the more complex and narrow the shape of particles and pores is, and the larger the average shape coefficient is, the more circular the shape is. The mean shape coefficients of soil particles in different particle size ranges are not much different, ranging from 0.3432 to 0.4373, indicating that the pore shapes of ionic rare earths are mostly narrow and slender, and the shapes are very complicated. It can be seen that the porosity of particle surface is an effective parameter to analyze the short-range interparticle reactions. In brief, the saturated volume water content is negatively correlated with particle size.

3.3 Effects of solution leaching on soil−water characteristics

SWCCs of different rare earth ore samples before and after leaching are shown in Fig. 11. Both drying curves and wetting curves of ores before leaching are above those after leaching. The saturated water content of ores before leaching is 32%−55%, and the saturated water content of ores after leaching is 30%−50%. The minimum water content of ores before leaching is 5%−9%, and the minimum water content of ores after leaching is 4%−7%. Rare earth ore samples before leaching have higher water holding capacity than after leaching. Under the same matric suction, volume water content of rare earth ore sample after solution leaching is lower than that before solution leaching, indicating that solution leaching decreases water holding capacity of ores.

Variations of volume water content before and after solution leaching can be obtained from Fig. 9. Water content variation amplitudes of ores with particle size <0.075 mm are 46% (drying process) and 36% (wetting process) before solution leaching, which are decreased to 43% (drying process) and 35% (wetting process) after solution leaching. Water content variation amplitudes of ores with particle size ranging 0.075−0.25 mm are 47% (drying process) and 32% (wetting process) before

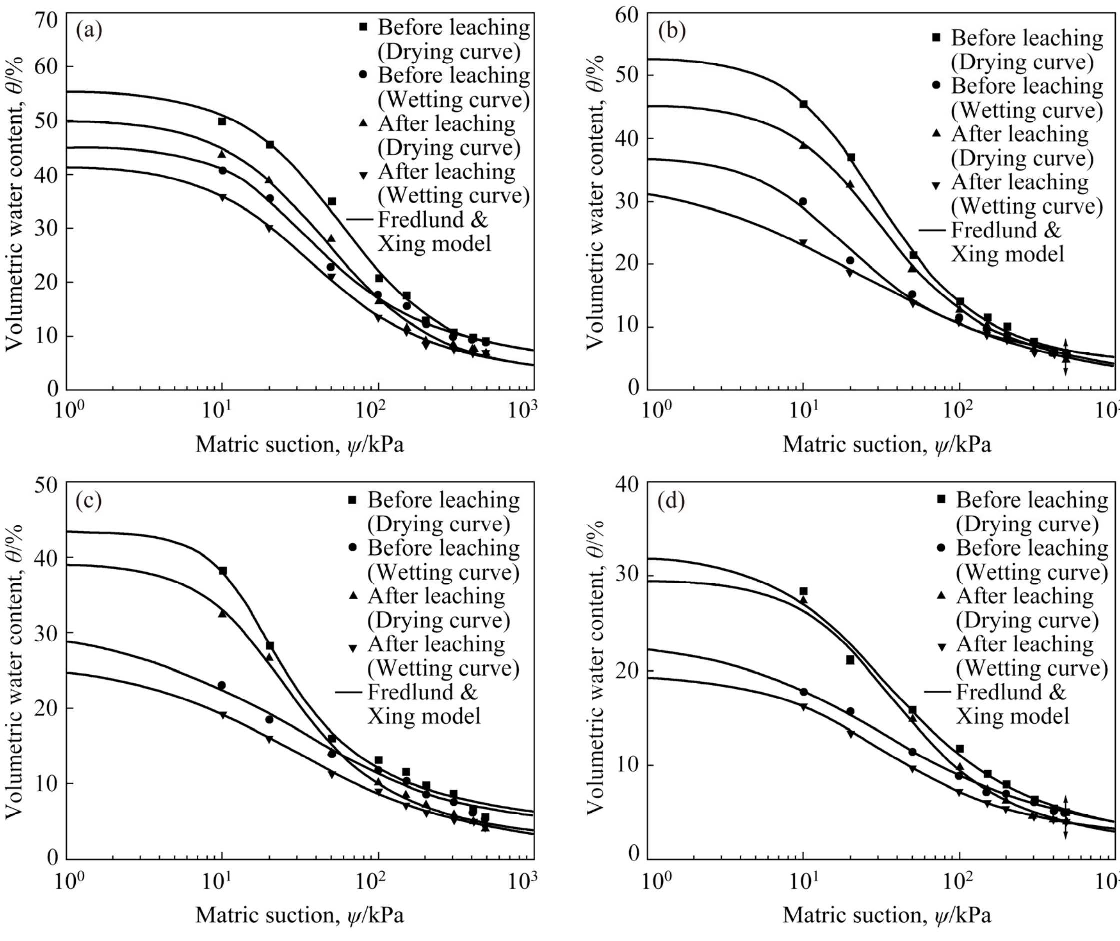

Fig. 11 Soil−water characteristic curves of samples before and after leaching: (a) <0.075 mm; (b) 0.075−0.25 mm; (c) 0.25−0.5 mm; (d) Undisturbed soil

solution leaching, which are decreased to 41% (drying process) and 29% (wetting process) after solution leaching. The water content variation amplitudes of ores with particle size ranging 0.25−0.5 mm are 38% (drying process) and 25% (wetting process) before solution leaching, which are decreased to 35% (drying process) and 22% (wetting process) after solution leaching. Water content variation amplitudes of undisturbed soil are 27% (drying process) and 18% (wetting process) before solution leaching, which are decreased to 26% (drying process) and 15% (wetting process) after solution leaching. It can be seen that water content of ores after solution leaching changes more slightly than that before solution leaching.

Rare earth ions in ore body are adhered onto clay as hydrated cations or carboxyl hydrated cations. According to available data and research results, rare earth ions are mainly adhered onto surface of fine soil particles. Interaction between rare earth ions and clay minerals do not change physical and mechanical properties of clay by changing or destroying the lattice structure of minerals. Instead, they exist in clay minerals at adhesion state and change the bonding state and bonding strength of particles by changing thickness of the double diffusion layer, thus influencing physical and mechanical properties of soil mass.

Clay particles can suspen in water rather than be dissolved in water. Clay ions have different electric properties in aqueous solution. In the structure of clay, Si^{4+} in the SiO_2 tetrahedral layer might be replaced by Al^{3+} and Al^{3+} in the alumina octahedral layer might be replaced by divalent ions like Mg^{2+} and Fe^{2+}. Due to such replacement, clay particle surface is negatively charged. Some cations, including K^+, Na^+, Ca^{2+} and RE^{3+}, are adhered onto clay surface as a response to electrostatic attraction. These cations are actually hydrated cations. Hence, a negatively charged cation layer (counter-ion layer) corresponding to the positively charged hydrated cations is formed on clay particle surface. These two layers are called as the double electric layers (Fig. 12). The thickness of the double diffuse layers is related with valence number of ions in pore water, ion concentration, temperature and pH.

In the process of solution leaching of ion rare earth ore, the type of ions and ion concentration in the counter-ion layer are changed. Some ions enter from free solution into the counter-ion layer, while some ions migrate from the counter-ion layer to free solution. Such chemical displacement is actually ion exchange. In rare earth exploitation based on in-situ leaching, ammonium ions in ammonium sulfate liquid enter into clay minerals and replace rare earth ions RE^{3+} (counter-ion layer) which are adhered on clay particle surface. The chemical equation of ion exchange reaction in ore leaching process can be expressed as [32,33]

$$[Al_2Si_2O_5(OH)_4]_m \cdot nRE^{3+}(s)+3nNH_4^+(aq) \rightleftharpoons [Al_2Si_2O_5(OH)_4]_m \cdot [NH_4^+]_{3n}(s)+nRE^{3+}(aq)$$

$$[Al(OH)_6Si_2O_5(OH)_3]_m \cdot nRE^{3+}(s)+3nNH_4^+(aq) \rightleftharpoons [Al(OH)_6Si_2O_5(OH)_3]_m \cdot [NH_4^+]_{3n}(s)+nRE^{3+}(aq)$$

$$[KAl_2(AlSi_3O_{10})(OH)_2]_m \cdot nRE^{3+}(s)+3nNH_4^+(aq) \rightleftharpoons [KAl_2(AlSi_3O_{10})(OH)_2]_m \cdot [NH_4^+]_{3n}(s)+nRE^{3+}(aq)$$

It can also be expressed as

$$[Al_4(Si_4O_{10})(OH)_8]_m \cdot nRE^{3+}(s)+3nNH_4^+(aq) \rightleftharpoons [Al_4(Si_4O_{10})(OH)_8]_m \cdot [NH_4^+]_{3n}(s)+nRE^{3+}(aq)$$

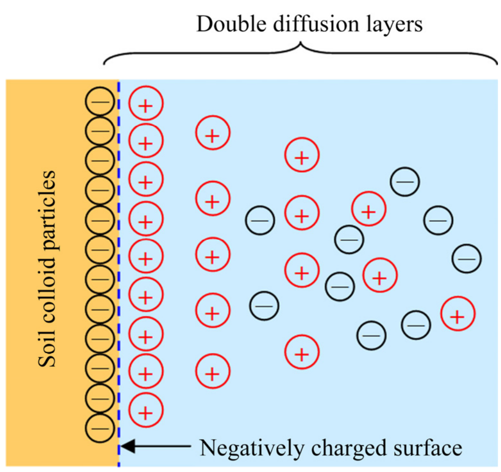

Fig. 12 Schematic diagram of double diffusion layers

According to the double diffusion layers theory of soil, the thickness of the double diffusion layers is negatively related with cation valence in pore water and ion concentration. In the process of solution leaching of ion rare earth ore, high-valence rare earth ions are replaced by low-valence ammonium ions. Therefore, rare earth and metal ions like Al^{3+} are displaced through chemical reactions, and ion concentration drops significantly, resulting in thickening of double diffusion layers. According to the theory of water film, with the increase of thickness of double diffusion layers, the pore water pressure (u_w) increases, while matric suction (u_a−u_w) decreases and water holding capacity of rare earth ores declines after solution leaching. These are consistent with macroscopic water holding behavior in this experiment. In the view of adsorbed water mechanism, hydrate wedge force from the crystal layer to particles increases continuously with the increase of thickness of the water film, resulting in volume expansion. The water film occupies the volume from pores, which decreases water holding capacity accordingly. Moreover, double diffusion layers among particles can intensify deformation of soil mass and the resistance of soil particle skeleton to the deformation is enhanced. Macroscopically, this is manifested by difficult compression of the soil particle skeleton. According to the capillary model, pore water in soils is more difficult to be adhered onto soil particle surface. Under the same matric suction, the water content of soil mass declines after leaching, indicating that water holding capacity of soil mass decreases after solution leaching.

4 Conclusions

(1) With the decrease of dry density, the pore ratio of the sample increases gradually, and the inter-pore connectivity becomes good, so the saturated volume water content increases. In the same matric suction, the volume water content decreases gradually with the increase of dry density, thus decreasing water holding capacity of ore accordingly.

(2) Under the same matric suction, rare earth ores with smaller particle size or higher content of fine particles have higher water content. The smaller the particle size is, the higher the water holding capacity is. Under the same volume water content, matric suction is inversely proportional to the particle size. Since pore size increases with the increase of ore particle size, the matric suction declines accordingly. In the processes of drying and wetting, water content variation amplitudes of ores become more and more slightly with the increase of particle size and content of coarse particles.

(3) Under the same matric suction, water content of rare earth ore samples decreases after solution leaching compared with that before solution leaching, indicating that solution leaching can decrease water holding capacity of ore. In both drying and wetting processes, water content of the ore after leaching changes less than that before leaching.

(4) In the process of solution leaching of ion rare earth ore, high-valence rare earth ions are replaced by low-valence ammonium ions. According to water film theory, the thickness of the double diffusion layers is increased. This leads to the increase of pore water pressure and reduction of matric suction. Consequently, water holding capacity of ores decreases after solution leaching.

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风化壳淋积型稀土矿的土水特性

郭钟群[1]，周尖荣[1]，周可凡[1]，金解放[1]，王晓军[2]，赵 奎[2]

1. 江西理工大学 土木与测绘工程学院，赣州 341000；
2. 江西理工大学 江西省矿业工程重点实验室，赣州 341000

摘 要：风化壳淋积型稀土矿的渗透特性直接影响原地浸矿的浸出效率。土水特征曲线是研究矿体渗透特性的重要基础，与许多因素具有关联性。为了研究不同因素对矿体土水特征曲线的影响，采用压力板仪进行土水特性试验，分析干密度、粒径和溶浸对稀土矿体土水特性的影响及其作用机理。结果表明，随着干密度的减小，孔隙率增大，矿体饱和含水量增加。采用同一基质吸力时，随着粒径的增加，矿体含水率逐渐减小，矿体持水能力降低。在相同体积含水率情况下，基质吸力与粒径大小成反比。采用同一基质吸力时，溶浸后矿体含水量比溶浸前矿体含水量降低，说明溶浸使得矿体持水能力减小。

关键词：风化壳淋积型稀土矿；干密度；粒径；溶浸；土水特征曲线

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