

Article

Experimental Study on Pore Structure and Soil-Water Characteristic Curve of Ionic Rare Earth Ore under Seepage

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Abstract: The ionic rare earth (RE) ore body undergoes particle transport and pore structure change during the leaching process, resulting in “uneven percolation, preferential channel, leaching blind area,” and other problems, leading to structural changes in the ore body, low leaching efficiency, and waste of resources. The unsaturated infiltration process is also the key stage that causes these problems. The initial pore structure evolution of the ore body plays a decisive role in the permeability coefficient of the ore body, and the direct influencing factor of the permeability coefficient is the distribution of the pore radius. We carried out research through indoor simulated leaching, the filter paper method for determining matrix suction, and nuclear magnetic resonance (NMR) testing. An ionic rare earth ore soil-water characteristic curve within a large matrix suction range was obtained by the filter paper method. With the increase in volumetric water content, the matrix suction presents a sharp downward trend. When the volumetric water content is less than 20%, this rule is particularly obvious. With the increase in matrix suction, the thickness of the adsorbed water film on the particle surface and pore radius show a decreasing power function trend. Under percolation, the porosity of an ionic rare earth ore sample tends to increase linearly with the increase in volumetric water content during the process from non-saturation to saturation; the porosity of a saturated ore sample after seepage expanded by 17.5 times compared to that of an unsaturated ore sample before seepage. The change rule of the internal microstructure of the ore sample is reflected in the gradual disappearance of micro pores and the gradual formation of small, medium, large, and mega pores, which shows a gradual increase trend. In the pore radius distribution, the more large and medium pores, the larger the permeability coefficient; the more micro and small pores, the smaller the permeability coefficient. For some ore bodies with poor permeability, the ore body is infiltrated with clear water under small water pressure before leaching with a leaching solution, which can improve the permeability of the ore body, effectively improve the efficiency of rare earth leaching, and increase the economic benefits.

Keywords: ionic rare earth ore; filter paper method; soil-water characteristic curve; nuclear magnetic resonance; pore structure



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1. Introduction

Ion adsorption-type rare earth (RE) is an important mineral resource unique to China and of world concern that is distributed in seven southern provinces of China, including Jiangxi, Guangdong, and Fujian [1,2]. The in situ leaching process is usually used for ion-type RE mining. The RE cations are recovered by the chemical substitution reaction between the leaching solution and the ionic RE ore, so as to realize the extraction of RE elements. [3–5]. Feng et al. [6,7] studied the adsorption properties and mechanism of action on mineral surfaces, thereby achieving efficient extraction of minerals. Although chemical adsorption is important in RE element extraction [8], the permeability of the ore body also plays an important role in the leaching efficiency of RE elements [9,10]. As the

liquid injection proceeds, this will lead to an increasing saturated region of ionic RE ore and a decreasing unsaturated region, which in turn will lead to the continuous loss of matrix suction of the ore body. The soil-water characteristic curve (SWCC) is an important indicator to evaluate the permeability performance of the soil in unsaturated soils [11]. In turn, the pore structure is the key to the study of matrix suction, and the morphological and structural characteristics of its pores play an important role in the percolation effect of the solution. The pores' structure evolves continuously under the action of percolation. Therefore, it is important to study the pore structure characteristics of the leaching system under percolation to optimize the leaching effect of ionic RE ore [12,13].

The respective characteristics of the solid, liquid, and gas phases in unsaturated soils and their interaction are fundamental factors affecting the physical and mechanical properties of unsaturated soils. This is due to the formation of curved liquid surfaces at the water-gas interface between soil pores, resulting in matrix suction in the pores, and the change in matrix suction reflects the strength-deformation characteristics of the soil, which leads to a change in the structural characteristics of the soil pores. [14]. The relevant research on pore structure and SWCC mainly focuses on loess and expansive soil, etc. Zhang et al. [15] analyzed the SWCC change rule of unsaturated loess when the pore structure was changed based on a capillary model. Li et al. [16] compared and analyzed the variation rules of SWCC of loess with different densities by filter paper method tests. Sun et al. [17] obtained from the analysis that there is a big difference between high and low suction intervals for swelling soils with different densities. Tan et al. [18] measured the volume change during the moisture absorption process of swelling soil, and obtained the variation law of macroscopic volume and SWCC of expansive soil. Ding et al. [19] proposed that the effect of wet swelling on the change in pore structure of swelling soil and on SWCC is much greater than that of compaction. However, there are few studies on the relationship between ionic RE ore pore structure and SWCC, and there are many methods to study matrix suction, and various testing methods have their own characteristics. The measurement of matrix suction under seepage usually uses the tensiometer method; however, the tensiometer method is mostly used for measurements within 100 kPa, which has certain limitations for the measurement of SWCC. The matrix suction measurement range is not limited by the filter paper method, but the test operation steps are relatively strict. Huang et al. [20] measured the matrix suction of unsaturated expansive soil based on the filter paper method and verified the feasibility and advantages of the filter paper method for measuring the SWCC. Wang et al., and Bai et al. [21,22] established the suction rate determination curve of domestic "double-loop" filter paper by using the NaCl salt solution method and completed the determination of SWCC. For the study of pore structure, Chen et al. [23] used CT scanning to obtain the evolution characteristics of the pore structure of RE ore under seepage, and Zhang et al. [24] used the NMR technique to study the evolution law of the pore structure of ionic RE ore under seepage. However, current studies have only analyzed the pore structure or soil water characteristics of ionic RE ore unilaterally, and few studies have linked the two.

At present, there are many studies on the pore structure change laws in the saturated stage, but there are few studies on the pore structure change laws in the unsaturated stage. We study the change in pore structure in the unsaturated stage to guide and optimize the leaching process. In response to the above issues, this paper selected a RE ore in Longnan County, Ganzhou, to carry out a simulated leaching experiment of ionic RE ore using clear water as the leaching solution, conducted SWCC tests using the filter paper method, and used NMR technology to obtain the change law of pore structure during the seepage process. The soil-water characteristics of the RE ore body are analyzed and measured from the essence of suction generation, and the law of change of SWCC caused by the change of pore structure is studied so that the research on the law of pore structure and SWCC of ionic RE ore can be derived under the effect of seepage, which provides scientific methods and theoretical support for the efficient mining of ionic RE ore and promotes the development of ionic RE ore in the direction of high efficiency, greenness, and safety.

2. Experimental Program

2.1. Experimental Materials and Their Characteristic Parameters

The RE samples selected for this study were taken from a rare earth ore in Longnan County, Ganzhou, and a number of RE ore samples were taken by the ring-knife method, then sealed with cling film. Their relevant physical parameters were measured according to the “Geotechnical Test Procedure,” and the results are shown in Table 1. In this paper, the water sieve method was used, the mineral samples were air-dried and crushed, and then 500 g of ore samples were taken out for sieving experiments by using the quarter diagonal sampling method. The particle sizes of the sieve were 5, 2, 1, 0.5, 0.2, 0.1, and 0.075 mm in order, and the sieved particles were dried and weighed, and then the mass proportion of each particle grade was calculated. The results of the particle size distribution of the ore samples are shown in Figure 1.

Table 1. Physical parameters of ionic RE ore.

Parameter	Numerical Value
Natural density (g/cm^3)	1.58
Dry density (g/cm^3)	1.37
Plasticity index	11.12
Water content (%)	14.00
Porosity ratio	0.90
Specific gravity of soil particles	2.64

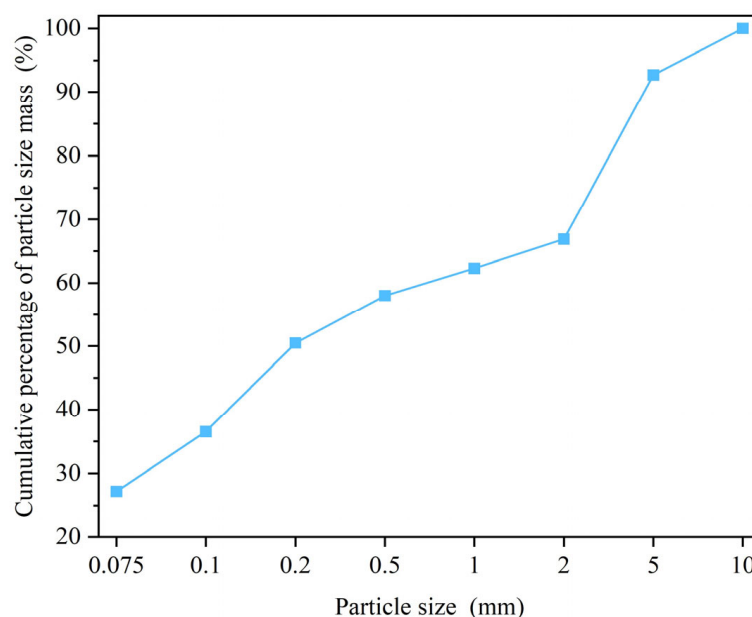


Figure 1. Cumulative curve of particle size and mass percentage.

2.2. Experimental Methods and Procedures

In-situ leaching is currently the main process for ionic RE ore mining; see Figure 2. The experimental method used in this paper is mainly the indoor simulated column leaching method of ionic RE ore and is strictly implemented with reference to the standard of remolded soil samples. The inner diameter of the acrylic tube selected for the experiment was 44 mm, and the tube wall thickness was 2 mm. The tube was processed into a length of 2 cm, 1.5 cm, 1.5 cm, and 2 cm in four sections, and then transparent tape was used to firmly bond the above four sections from top to bottom into the overall length of 7 cm. The previous stone's diameter was 44 mm, and the thickness was 5 mm. The height of the remodeled soil sample was 60 mm according to the effective area detected by the NMR (NM-60, Suzhou Niumaga Analytical Instrument Corporation, China). Then configure

a certain water content of the ore samples, and the preparation of the water content of the ore samples is transferred to the sealed bag, smothering the samples for about three days to ensure that the water content of the ore samples has a uniform distribution so as to reduce the test error. Subsequently, use the medicine spoon to evenly fill the mold with the prepared ore sample with water content, and use the compacting instrument to compaction in layers. When using the compactor, determine the height of the drop hammer to ensure that each time the compaction work is the same, thus ensuring that the quality and density of each ore sample are the same. The 14 ore samples of the same water content were prepared and divided into two groups of seven each, one of which was used as a parallel ore sample for value averaging and comparison verification. After all the parallel ore samples of the tested ore samples are completed, proceed to the next step of testing. This experiment uses clear water as the leaching solution to carry out leaching experiments while using a peristaltic pump to adjust the liquid injection flow rate. The experimental setup is shown in Figure 3. When the leaching solution reaches the position of the lowest filter paper, data are measured at short intervals, and when the previous stone is out of water and is judged to be in a saturated state, the measurement is terminated at this point. The test filter paper is placed at three bonding positions on the acrylic tube of the remodeled ore sample, and the filter paper used in this experiment is Whatman No. 42 quantitative filter paper. At present, the matrix suction rate curve of Whatman No. 42 quantitative filter paper is widely measured by ASTM, and its matrix suction rate curve is shown in Equation (1), and the transparent tape is cut when placing the filter paper. A 40-mm-diameter filter paper is used as the test filter paper, and two 42-mm-diameter filter papers are used as the protection filter paper. The test filter paper is sandwiched between the two-layer protection filter paper to prevent soil particles from entering the test filter paper and producing test errors. After placing the filter paper, the mold is glued tightly with transparent tape to ensure close contact between the two acrylic tubes and prevent gaps. Install the mold by testing the filter paper, wrapping it tightly with plastic wrap, and placing it in a sealed container. Then put it into the constant temperature and humidity box for maintenance. The constant temperature and humidity are 25 °C, and the humidity is 50% RH. After maintenance is completed for seven days, quickly remove the test filter paper with tweezers and use an electronic balance when weighing, with an accuracy of 0.0001 g. This process needs to be carried out quickly, and the entire measurement process needs to be completed within 30 s. Then put the filter paper into the oven for 10 h, and measure its drying quality. In order to minimize the error, the results of the top, middle and bottom three filter papers should be averaged for each parallel ore sample so as to calculate the weight water content of the filter paper, and then calculate the matrix suction according to the weight water content of the filter paper and the formula on the rate curve of the matrix suction, in which the weight water content of the ore sample should be measured according to the same drying method, and then convert the weight water content into the volumetric water content, and finally calculate the matrix suction and volumetric water content of the ore sample through data processing and draw the SWCC.

$$\begin{aligned} \log s &= -0.0779 + 5.327\omega, & \omega < 45.26\% \\ \log s &= 2.412 - 0.0135\omega, & \omega > 45.26\% \end{aligned} \quad (1)$$

where s is the filter paper matrix suction value and ω is the filter paper weight water content.

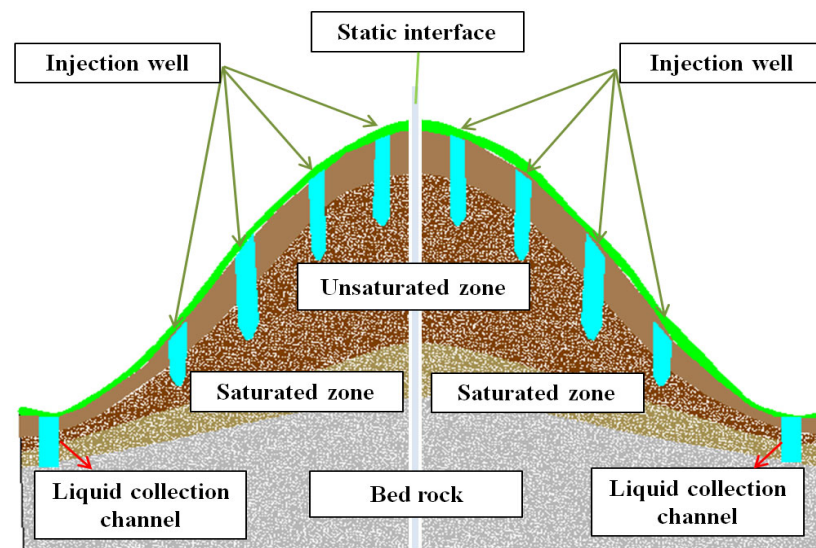


Figure 2. Schematic diagram of the in-situ leaching process.

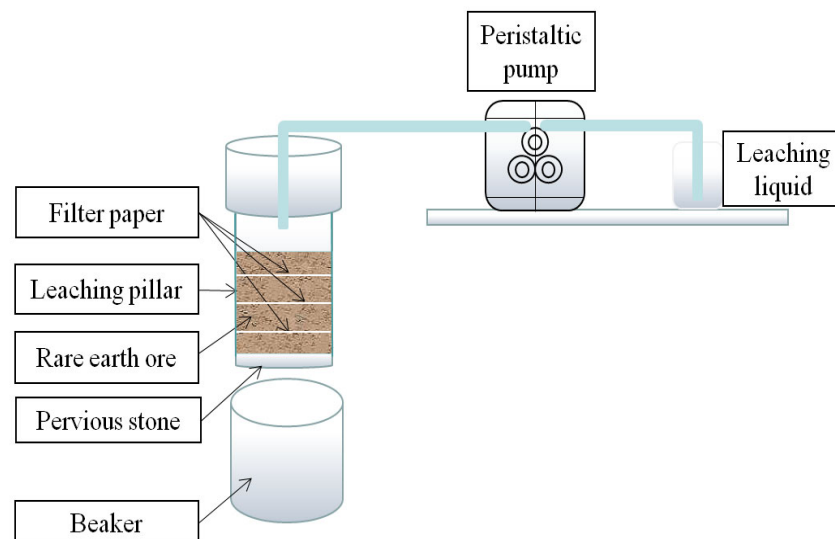


Figure 3. Indoor column immersion experimental device.

3. Result Analysis and Discussion

3.1. Fitting and Analysis of SWCC

According to the above experimental methods, the SWCC test results were obtained, as shown in Table 2. There are many theories and methods to describe the SWCC. Among the SWCC models, the representative is the Van Genuchten (VG) model, and the SWCC is described by the VG model [25] as follows:

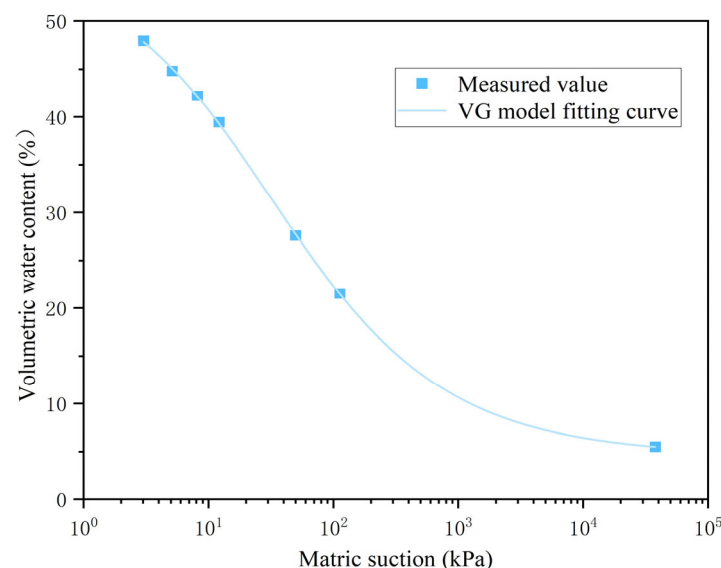
$$\theta_w = \theta_r + \frac{\theta_s - \theta_r}{\{1 + [d(\mu_a - \mu_w)]^n\}^m} \quad (2)$$

where θ_w is the volumetric water content of the soil, θ_r is the residual volumetric water content of the soil, θ_s is the saturated volumetric water content of the soil, $(\mu_a - \mu_w)$ is the matrix suction (kPa), d is the parameter related to the air intake value of the soil, n is the parameter related to the dewatering rate of the soil after the matrix suction is greater than the air intake value, and m is the parameter related to the residual volumetric water content of the soil.

Table 2. SWCC test results.

Ore Sample Number	Matrix Suction (kPa)	Volumetric Water Content (%)
1	37931.50	5.50
2	112.81	21.53
3	50.00	27.60
4	12.19	39.43
5	8.17	42.20
6	5.14	44.80
7	3.03	47.94

The curve fitting is performed according to the measured results in Table 2, and the fitting results are shown in Figure 4. From the experimental results, it can be seen that the fitting effect on the measured data is relatively good, with $R^2 = 0.98$. The analysis of the test results shows that, at the same dry density, the matrix suction is sensitive to the change in volumetric water content. With the increase in volumetric water content, the matrix suction presents a sharply decreasing trend. When the volumetric water content is less than 20%, this change in law is especially obvious. When the volumetric water content is greater than 20%, the trend of the matrix suction decreasing slows down with the increase in volumetric water content. The pore structure affects the soil-water action area and the shape of the shrinkage film, while the latter determines the magnitude of the matrix suction. When the pore size of the soil is small, the intake value is high, and the water-holding capacity is strong, the SWCC is flat. Pore structure is usually related to particle size, gradation, and soil skeleton structure, and pore structure reflects the influence of soil structure on the SWCC. For a specific soil type, the pore structure contains the pore ratio that determines the shape of the SWCC, the intake value, and the magnitude of the residual water content. Therefore, it can be said that the pore structure is a key factor affecting the SWCC. The following will conduct an in-depth study of the change law in the pore structure of ionic RE ore under seepage.

**Figure 4.** SWCC of remodeled ore body.

3.2. Changes in the Pore Structure and Permeability Coefficient of the Ore Body under Seepage Action

3.2.1. The Variation Law of Ore Body Porosity under Seepage

The evolution law of ore sample porosity under seepage was obtained through NMR technology. In this experiment, only the process from non-saturation to saturation of the ore sample was tested. Gao et al. [26] found that the porosity did not change during the saturation process when the ore was leached with clean water. Thus, the test was not

conducted after saturation. In parallel experiments, ore samples are placed into the NMR instrument to detect the pore structure of ore samples with different volumetric water contents. Through the NMR instrument, the porosity variation rules of ore samples under different water contents can be obtained; the measured data are shown in Figure 5. It can be seen from the figure, during the process of converting the ore sample from non-saturation to saturation, the porosity of the ore sample shows a linear increasing trend with the increase in volumetric water content. The porosity of saturated ore samples after seepage has increased 17.5 times compared to the porosity of unsaturated ore samples before seepage. Due to the relatively small size of the ore sample and the need to measure a certain amount of matrix suction in an unsaturated state, a column leaching method with low water pressure and a low flow rate is required. Hu et al. [27] also pointed out that for ionic RE leaching, it is necessary to use a "small water pressure" injection method as much as possible, which can prevent the occurrence of pore clogging and increase the permeability of the ore body. From the envelope area of the later T_2 spectrum curve, it can also be determined that the porosity will have such a change rule.

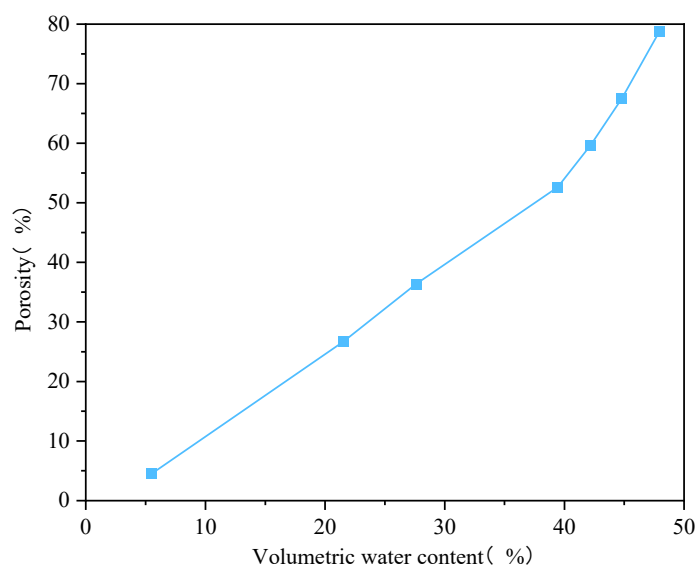


Figure 5. Variation of porosity of mineral samples at different volumetric water content.

3.2.2. The Variation Law of Ore Body Pore Size under Seepage

The evolution law of the pore structure of an ore sample was obtained through NMR technology under seepage [24]. NMR is a technique that obtains hydrogen proton information based on the interaction between external magnetic fields and hydrogen nuclei in the sample. The sample is placed in a magnetic field, and a certain frequency of pulse is applied when testing. At this time, the hydrogen nucleus in the sample will absorb a specific frequency of electromagnetic waves, jumping from the low energy state to the high energy state, and the magnetization vector will deviate from the equilibrium state. The hydrogen nucleus will release the absorbed energy when the pulse stops, and the hydrogen nucleus will recover from the unbalanced state to the equilibrium state. This process is called relaxation, and the required time is called relaxation time. The transverse relaxation time T_2 can be represented by equation (3) [24,28]:

$$\frac{1}{T_2} = \frac{1}{T_{2B}} + \rho_2 \left(\frac{S}{V} \right) + \frac{D(\gamma G T_E)^2}{12} \quad (3)$$

where T is the volume relaxation time of the fluid, ms, D is the diffusion coefficient, $\mu\text{m}^2/\text{ms}$, G is the magnetic field gradient, $10^{-4} \text{ T}/\mu\text{m}$, T_E is the echo interval, ms, V is the pore volume, μm^3 , S is the pore surface area, μm^2 , γ is the magnetic spin ratio, $(\text{T}\cdot\text{ms})^{-1}$, ρ_2 is the transverse surface magnetic strength, $\mu\text{m}/\text{ms}$, which depends on the properties of the

pore surface, mineral composition, and fluid properties. T_{2B} value is 2000~3000 ms. Since the T_{2B} value is much larger than T_2 , the first term on the right side of Equation (3) can be ignored. When T_E is small enough, the third term on the right side of Equation (3) can also be ignored. Therefore, Equation (3) can be simplified as follows:

$$\frac{1}{T_2} = \rho_2 \left(\frac{S}{V} \right) \quad (4)$$

The relationship between transverse relaxation time T_2 and pore radius r can be expressed as follows [29]:

$$\frac{1}{T_2} = \rho_2 \left(\frac{S}{V} \right)$$

where r is the pore radius, μm , and F_S is the pore size factor. Generally, the spherical pore size factor is taken as three, and the cylindrical pore form factor is taken as two.

In the indoor column leaching experiment, a clear water solution was used to leach the ore, and NMR technology was used to measure the T_2 distribution curve of the ore sample under different volumetric water contents. The envelope area formed by the T_2 distribution curve and the x-axis is an indicator of the number of internal pores in the ore sample. The larger the area of the envelope, the more pores it represents. The transverse relaxation time represents the time it takes for the hydrogen proton in the water to transition from a stable arrangement state to a stable arrangement state under the action of a magnetic field when the pores in the ore sample are filled with water. The shorter the transverse relaxation time, the less hydrogen protons are in the pores, which means a smaller pore radius. The changes in transverse relaxation time also represents a change in internal pore structure. The T_2 distribution curves of ore samples with different volumetric water content under seepage were selected for comparative analysis. It can be seen from Figure 6 that as the volumetric water content increases, the T_2 distribution curve of the ore sample gradually shifts to the right, indicating that the radius of the internal pore structure is increasing in the sample, and the T_2 distribution curve and the relaxation time envelope area also increase rapidly, indicating that the number of internal pores is also increasing.

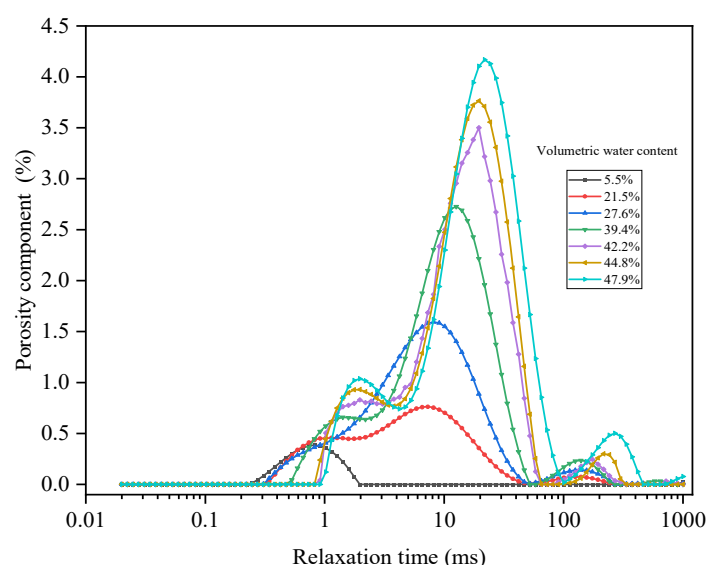


Figure 6. Variation of T_2 distribution curves for different volumetric water contents of the ore sample.

The pore radius is the maximum radius of the sphere that can pass through the pore throat; the unit is micrometer (μm). The size and proportional distribution of the pore radius are closely related to the pore structure. The larger the pore radius, the better the connectivity of the pore space. The percentage of pore radius of different sizes in total pores reflects the distribution of pore radius with different volumetric water contents. According

to the range of pore size measurement values, pore size is divided into five categories: A pore size range of 0–0.24 μm is called a micro-pore; a pore size range of 0.24–0.65 μm is called a small pore; a pore size range of 0.65–1.6 μm is called a medium pore; a pore size range of 1.6–10 μm is called a large pore; and a pore size greater than 10 μm is called a mega pore. The distribution of different pore sizes is calculated by the T_2 distribution curve, as shown in Figure 7. In this way, the dynamic changes of the pore radius in the internal structure of the pore can reflect the evolution of the pore structure of the ore sample under the action of solution percolation. During the leaching process, the pore structure of the ore sample is constantly undergoing dynamic changes due to the action of the seepage field. When clean water is used as the leaching solution, as the volumetric water content of the ore sample increases, the porosity of the ore sample gradually increases, micropores gradually disappear, and small, medium, large, and mega-large pores gradually form and show an increasing trend.

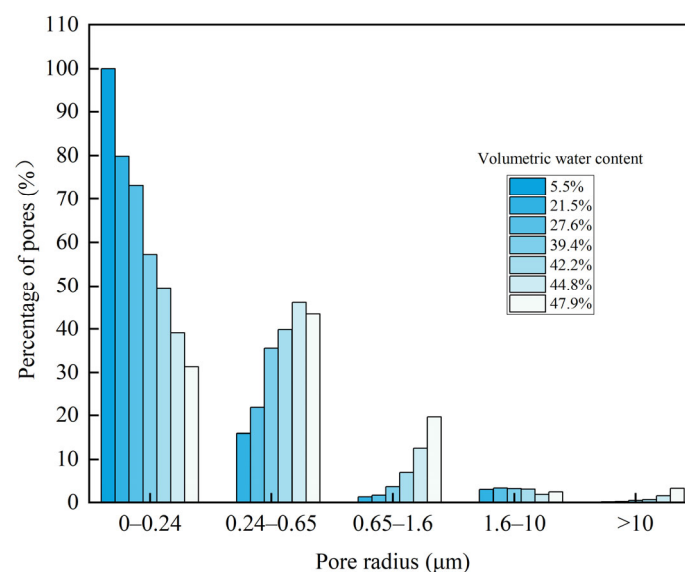


Figure 7. Pore radius ratio of ore samples under different volumetric water contents.

3.2.3. Calculation of the Permeability Coefficient under the NMR Technique

The permeability coefficients of the ore sample under seepage were obtained by the NMR technique. Due to the small geometric size of the ore sample, it is difficult to determine the permeability coefficient of the ore sample by using conventional head test methods. Therefore, the use of the T_2 spectrum to solve the permeability coefficient can subtly solve this problem. The permeability coefficient of ionic RE ore was calculated by the average T_2 (SDR) model [30]. The equation is as follows:

$$a = F_s \cdot \rho \quad (5)$$

$$K = a \cdot T_{2g}^2 \Phi^4 \quad (6)$$

where F_s is the pore shape factor, ρ is the surface relaxation rate of the soil sample, T_{2g} is the geometric mean of the T_2 distribution, and Φ is the effective porosity.

The permeability coefficient for different volumetric water contents was calculated by using the T_2 (SDR) model, as shown in Figure 8. Research has found that the distribution of pore radius is an important factor affecting the change in permeability coefficient of weathering crust leaching type RE ore [31]. During the process of the ore sample from non-saturation to saturation under seepage, the permeability coefficient increases almost very little when the volumetric water content is less than 22%. At this time, the pore structure is still dominated by micropores, and when the volumetric water content is

greater than 22%, the permeability coefficient increases. At this time, some large, medium, and small pores have already been generated, and it shows an increasing trend, which can be explained by the fact that when the proportion of small pores is high, the bound water film formed on the surface of RE ore particles occupies the effective pores and greatly hinders the permeability of the leaching solution. However, when the proportion of large, medium, and small pores is high, the bound water film effect is weakened and the seepage effect of the leaching solution in the ore body is significantly enhanced. Based on the above research analysis, in the distribution of pore radius, the more large and medium pores, the greater the permeability coefficient, and the more micro and small pores, the smaller the permeability coefficient. However, the reduced effective percolation pore size is not recoverable due to particle migration, which makes it impossible to restore the permeability of the ore sample to its original level. Zhou et al. [32] found that the ion exchange process hinders the permeation of the leaching solution. Therefore, through the analysis of the above study, in order to ensure the leaching effect, the ore body with poor initial permeability should be leached with low water pressure and clear water first and then with leaching solution, which can prevent the phenomenon of pore blockage and improve the permeability of the ore body, effectively improve the efficiency of RE leaching, and save materials, which is also very considerable in terms of economic benefits.

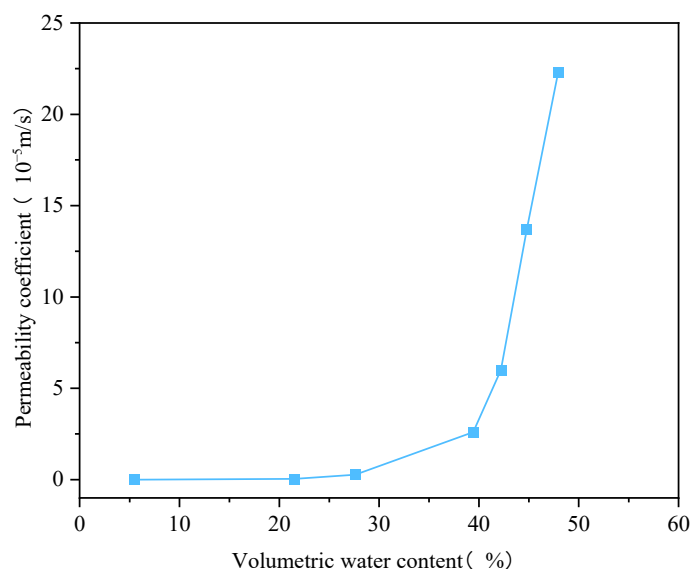


Figure 8. Permeability coefficients corresponding to different volumetric water contents of ore samples under percolation.

3.3. Relationship between Matrix Suction and Pore Structure of the Ore Body

3.3.1. Relationship between Matrix Suction and Thickness of the Adsorbed Water Film

The water film on the surface of soil particles in the mineral layer includes bound water and free water caused by capillary action and matrix suction [33]. When assuming that the pores of the soil are capillaries, the water film layer adhered to the surface of soil particles and between particles will change under the dominant effect of matrix suction, and the thickness of this adsorbed water film can be calculated by the Halsey equation [34]. The calculation results are shown in Figure 9. As can be seen from the figure, the thickness of the adsorbed water film on the surface of the rare earth particles shows a power function decreasing trend with the increase of the matrix suction. It can be interpreted as assuming that one mol of water is unfolded to a single molecular thickness and covers the entire solid surface; the smaller the volumetric water content at this time, the greater the matrix suction, and the smaller the thickness of this adsorbed water film will be.

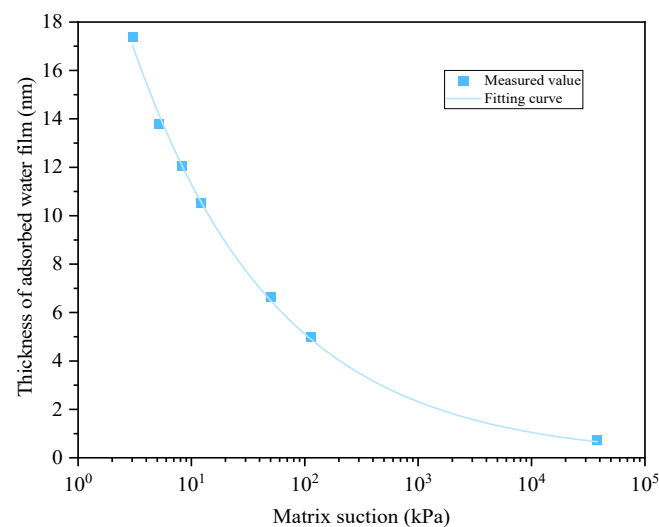


Figure 9. Relationship between matrix suction and thickness of the adsorbed water film.

3.3.2. Relationship between Matrix Suction and Pore Radius

Calculate the pore size distribution calculation steps from matrix suction, and then find the interrelationship between the two. Calculate the pore size corresponding to different matrix suction, which is the pore size of the soil pores filled with air and is the sum of the Kelvin radius and the thickness of the adsorbed water film. The calculation steps are as follows: ① convert the volumetric water content in the SWCC into mass water content; ② convert the matrix suction into relative humidity; ③ convert the mass water content into the volume of water filling pores within each unit mass of ore body; ④ calculate the Kelvin radius and water film thickness; ⑤ calculate the actual pore radius and the decrease of pore volume within each unit mass of ore body; ⑥ calculate the average Kelvin radius and the average pore radius during the reduction of pore volume. The calculation results are shown in Figure 10. It can be seen from the figure that with the increase in matrix suction, the pore radius presents a decreasing trend in the power function. From the previous analysis, it is also known that when the ore body is in the unsaturated stage, a large number of pores are in the microporous stage when the volumetric water content is very small and the matrix suction is maximum at this time, which also forms a mutual verification with the previous conclusion.

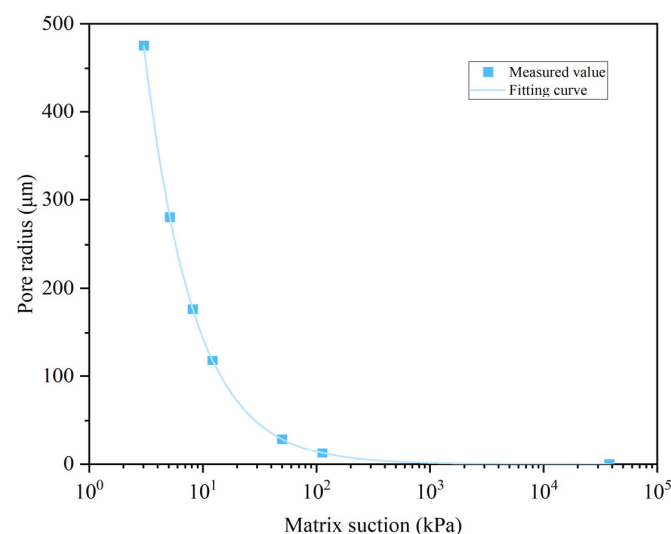


Figure 10. Relationship between matrix suction and pore radius.

4. Conclusions

(1) At the same dry density, matrix suction shows a sharp decreasing trend with the increase in volumetric water content, and this change rule is especially obvious when the volumetric water content is less than 20%.

(2) Under the effect of percolation, the porosity of the ore sample increases linearly with the increase in volumetric water content, and the porosity of the saturated ore body after percolation expands 17.5 times relative to that of the unsaturated ore body before percolation; the change rule of the internal microstructure of ionic RE ore reflects that the micropore is gradually disappearing and showing a decreasing trend, while the small, medium, large, and mega large pore is gradually forming and showing an increasing trend.

(3) In the pore radius distribution, the more large and medium pores, the larger the permeability coefficient; the more micro and small pores, the smaller the permeability coefficient. For mining the ore body with poor permeability, leaching with a leaching solution after leaching with clear water under low water pressure can improve the permeability of the ore body, effectively improve the efficiency of RE leaching, and increase the economic benefits.

(4) With the increase in matrix suction, the thickness of the adsorbed water film and the pore radius on the surface of the particles show a decreasing trend in power function.

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