Study on Fractal Characteristics of Pore Structure of Unsaturated Loess Based on NMR

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Abstract. Under the influence of water and external loads, the microstructure of loess changes, leading to a loss of strength and ultimately frequent engineering accidents. The fractal characteristics and influencing factors of the microscopic pore structure of unsaturated loess were investigated using nuclear magnetic resonance (NMR) test and fractal theories. The results show that the microscopic pore structure of the sample at different dry densities is dominated by small and medium pores, and increasing the dry density can significantly reduce the medium pores and large pores of the soil. However, the effect on the micro and small pores was small, resulting in the fractal dimension of the medium pores (D_3), and the fractal dimension of the large pores (D_4) increased with increasing dry density, whereas the fractal dimension of the small pores (D_2) did not change significantly. The moisture content significantly affected the medium pores and large pores of the soil, decreasing the fractal dimension of small pores (D_2) and large pores (D_4) with increasing moisture content and the fractal dimension of medium pores (D_3) with increasing moisture content. The medium pore structure of the soil was more sensitive to the change in moisture content when the dry density was smaller, and increasing the dry density effectively reduced the effect of moisture content on the large pore structure of the soil.

Keywords: unsaturated loess; microscopic pore structure; fractal dimension; nuclear magnetic resonance

1 INTRODUCTION

Loess is a typical porous medium. Water and steam have complex physical, chemical, and mechanical effects under the action of natural factors and load. The soil microstructure affecting the coupled water-steam-heat transport in soil primarily includes the particle arrangement and pore size distribution. It has a random size, shape, and spatial position, leading to the dispersion effect of macroscopic transport characteristics such as water-vapor-heat, which is affected by many factors.

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Previous research has indicated that the conventional Euclidean geometry theory is inadequate for describing the microstructural properties of soil. However, soil microstructures have self-similar characteristics such as pore size distribution, particle size, and pore structure, which can be characterized using fractal theory[1,2]. Kong et al.[3] used the NMR test to obtain soft soil's pore size distribution curve after freezing and thawing and described the influence law using fractal theory. The study showed that fractal dimension is an important parameter for pore features. Qiu S et al[4] introduced a novel fractal model for characterizing the microscale pore structure, which was measured on pre-dewatered sludge samples using NMR tests. It is shown that the fractal dimension is directly proportional to the porosity. Zhang et al.[5] believe that sedimentary rocks have fractal characteristics, in which the fractal dimension of macropores is more obviously affected by average pore diameters. Sun et al.[6] used bentonite of Czech Cerny vrch deposits to quantify the fractal characteristics of pores of different sizes, and found that the fractal dimension had increased slightly with the increase of suction and dry density. With the help of fractal theory, combined with the NMR test, this paper extracts the microscopic pore structure parameters of unsaturated remolded loess, and studies the fractal characteristic parameters and influencing factors, which provides theoretical support for the study of macroscopic transport processes such as water-gas-heat in unsaturated soil from the microscopic perspective.

2 TEST CONTENT AND METHOD

2.1 Test Material

The sample was Lanzhou loess, brown to yellow-brown, at a depth of 50–200 cm. It was a quaternary silty clay. Table 1 displays the fundamental physical parameters.

Table 1. Basic physical property parameters of trial loess.

Natural density (g/cm³)	Liquid limit (%)	Plastic limit (%)	Plasticity index (I_P)	Optimum moisture content (%)	Maximum dry Density (g/cm³)	Granulometric composition (%)		
						< 0.074 (mm)	0.074~0.005 (mm)	< 0.005 (mm)
1.41	26.3	16.7	9.6	15.4	1.85	24.19	71.42	4.39

2.2 NMR Test

Through scanning electron microscope test, mercury intrusion test and nuclear magnetic resonance test, the soil microstructure can be studied, among which NMR has the advantages of accurate, non-destructive and three-dimensional space test. In this study, the Numai MacroMR 12-150H-I low-field NMR instrument was used to test the full water samples of remolded loess under different dry densities and moisture contents and to analyze the influence of different dry densities and moisture contents on the microstructure of remolded loess.

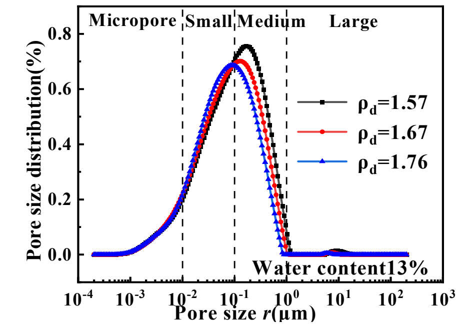
2.3 Sample Preparation and Test Design

The experiment was designed to study the effects of different dry densities and moisture content on the microstructural characteristics of unsaturated remolded loess. The experiment included three kinds of specimen moisture content, 13%, 15%, and 17%, and three kinds of soil dry density, 1.57, 1.67, and 1.76 g·cm–3, respectively. The quantitative soil samples were divided into three layers, filled into a special mold, pressed into a sample with Φ 39.1 mm × H 40 mm. Finally, the pressed and molded soil samples were placed in a saturator to evacuate for 2 h and placed in distilled water to saturate for 12 h. This resulted in soil samples with a saturation degree greater than 98%.

3 ANALYSIS OF NMR TEST RESULTS

3.1 Characterization of Pore Size Distribution

NMR tests were conducted on remolded loess specimens with three moisture contents and three dry densities. Referring to the criterion for the division of microscopic pore size r of soil by Deng et al.[7] and Horpibulsuk et al.[8], the microscopic pores of the specimen were separated into four groups: micropore ($r \leq 0.01$ μm), small pore (0.01 μm < $r \leq 0.1$ μm), medium pore (0.1 μm < $r \leq 1$ μm), and large pore ($r \geq 1$ μm). The distribution of the specimen microscopic pore sizes under different conditions is displayed in Figures 1.



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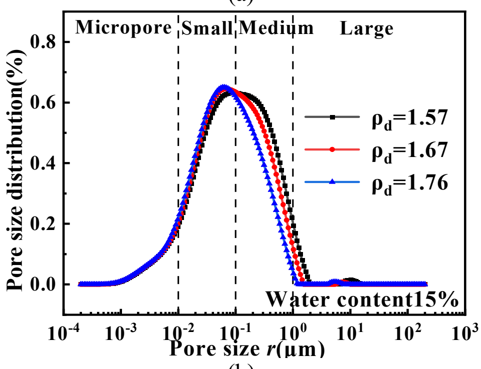

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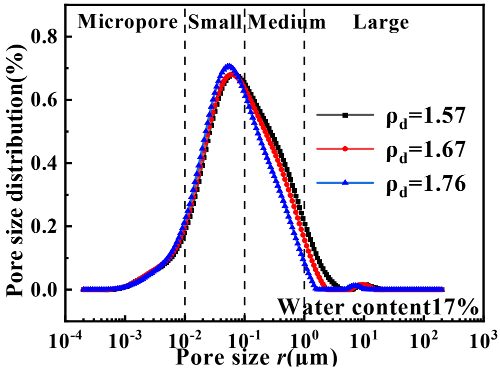

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Fig. 1. Pore size distribution curves at different dry densities.

Figure 1 illustrates how the pore size distribution curve in various dry densities has the same form when the moisture content is constant, with small and medium pores predominating. As the dry density of the soil rose, the pore size distribution curve moved to the left. The pore size of the soil sample trended downward, indicating that the increase in soil density decreased the microscopic porosity of the different pore sizes. The micropores and small pores in the soil grew as the dry density rose, whereas the medium pores and large pores decreased significantly. This suggests that the medium and large pores in the soil were predominantly affected by the dry density. In contrast, the effect on micropores and small pores was weaker. Altering the ratio of the medium to large pores, which affects the soil's strength and ability to hold water, is the primary micro-mechanism for improving the macroscopic mechanical and physical properties of the ground through dry density. When the dry density is constant. The specimen's peak value on the pore size distribution curve with varying moisture contents shows a first decrease followed by an increase in accordance with the change rule. The position of the main peak gradually shifted from the middle pore interval to the small pore interval, indicating that small pores gradually dominated when the moisture content increased. After the moisture content of the specimen exceeds the optimum moisture content, the rate of change of the pore size distribution in the medium and large pores intervals decreases gradually. The medium pores of the soil were transformed into small and large pores as the moisture content gradually increased because when the moisture content of the soil was low, the soil particles were fixed by the cementing material. At this time, the medium pores accounted for the main part. The cement material was diluted as the soil moisture content gradually increased. Water lubricates the soil particles, and the particles are rearranged by compaction. Part of the medium pores was transformed into small pores, and the other part was connected and transformed into large pores[9].

3.2 Fractal Characteristics Analysis

3.2.1. Fractal Calculation Model of Pore Volume-pore Size Distribution.

The fractal dimension of the pore volume-pore size distribution can measure the irregularity of the pore volume inside the soil, reflecting the complexity of the microscopic pore structure[10]. The pore volume-pore size distribution fractal dimension calculation model is a mathematical calculation model considering the three-dimensional space pore structure. When the fractal dimension of the soil increases, the soil pore structure becomes more complex. Conversely, when the fractal dimension of the soil decreases, the soil pore structure tends to become simpler, with a reasonable range of 2~3[11,12]. Liu et al.[2] found that the available pore size r can be used to measure the pore structure of soil. If the two have a power function correspondence, then

$$N(r)_{+} = \int^{\infty} P(r)dr \propto r^{-D} \tag{1}$$

Where *P(r)* is the pore size distribution density function; *N* is the total number of pores; $N(r)_{+}$ is the number of apertures larger than *r*.

Let *V(r)* is the pore volume with a pore size less than *r*, *V* is the total pore volume of the soil sample, and considering the pore morphology as a sphere, then we have the following[13]:

$$V(r) = \int_0^r \frac{1}{6}\pi r^3 dN_{+} \propto r^{3-D} \tag{2}$$

$$\frac{V(r)}{V} \propto r^{3-D} \tag{3}$$

Taking the natural logarithm on both sides of equation (3) yields the relationship curve between ln[*V(r)/V*] and lnr. equation (3) indicates that the pore volume-pore size distribution fractal dimension *D* can be found by the slope (3-*D*) of this relationship curve.

3.2.2. Analysis of the Pattern of Change in the Fractal Dimension of Pore Volume-Pore Size Distribution.

Test data from the remolded loess specimens with different dry densities and moisture contents were processed. Combined with the microporous pore size division method[7,8], the relationship curve was divided into four regions based on the pore size *r*. The slopes k_1, k_2, k_3, and k_4 of the four regions were obtained after fitting the ln[*V(r)/V*]- lnr relationship curves, and the pore volume-pore size fractal distribution dimensions D_1, D_2, D_3, and D_4 were calculated for micropore, small pore, medium pore, and large pore, respectively, by $D_i = 3-k_i$.

Table 2. Results of fractal dimension calculation.

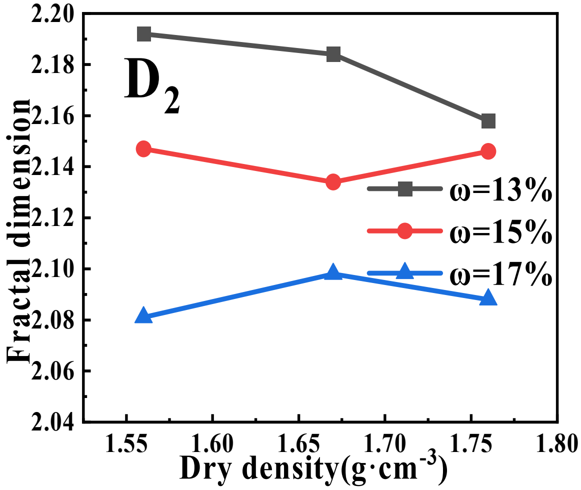
ω/%	ρ_d/g·cm^{-3}	D_1	R^2	D_2	R^2	D_3	R^2	D_4	R^2
	1.57	0.312	0.898	2.192	0.992	2.685	0.949	2.996	0.984
13	1.67	0.290	0.909	2.184	0.990	2.731	0.933	2.997	0.994
	1.76	0.302	0.900	2.158	0.988	2.771	0.915	2.998	0.995
15	1.57	0.331	0.897	2.147	0.988	2.709	0.970	2.995	0.991

	1.67	0.338	0.896	2.134	0.986	2.742	0.958	2.997	0.995
	1.76	0.326	0.897	2.146	0.984	2.788	0.935	2.997	0.994
	1.57	0.380	0.889	2.081	0.987	2.746	0.965	2.995	0.964
17	1.67	0.359	0.893	2.098	0.985	2.767	0.959	2.995	0.992
	1.76	0.316	0.908	2.088	0.982	2.805	0.944	2.996	0.980

Table 2 indicates that the fractal dimension D_1 of the micropore interval is much smaller than 2, which is not within the reasonable interval $2 \leq D_i \leq 3$. This indicates that the micropore structure in the soil does not exhibit fractal characteristics. When the pore size r is small, the pore size r and pore structure no longer have a power-function relationship.

To analyze the impact of soil dry density and moisture content on the fractal dimension of the remolded loess microstructure, the variation curves of the small pore fractal dimension (D_2), medium pore fractal dimension (D_3), and large pore fractal dimension (D_4) were plotted for various dry densities and moisture content conditions (Figures 2 and 3).

Figure 2 indicates that when the moisture content was unchanged, the fractal dimension of the D_3 and D_4 increased as the dry density increased. However, the fractal dimension of the D_2 did not exhibit a clear pattern of change. The range of change was small, indicating that the change in dry density can directly affect the fractal dimension of medium and large pores, and the effect on the fractal dimension of small pores is smaller. This is because, with the increased dry density, the medium and large pore structures in the soil were significantly reduced and redistributed by extrusion under the action of compaction and became more complex, while the effect on the small pore structure was smaller. From the perspective of the microscopic, an increased degree of compaction can improve the microscopic pore structure of the soil and its physical and mechanical properties.



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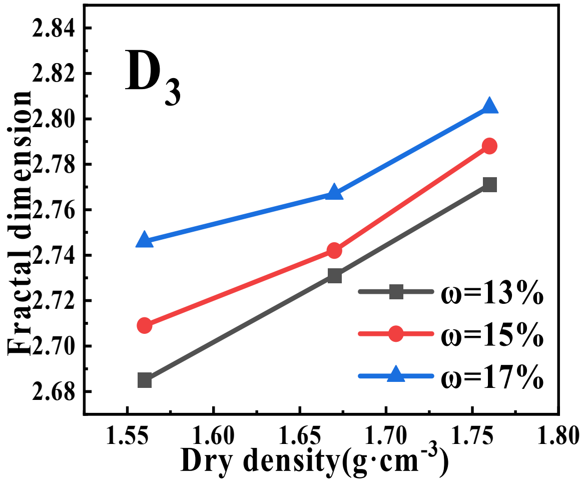

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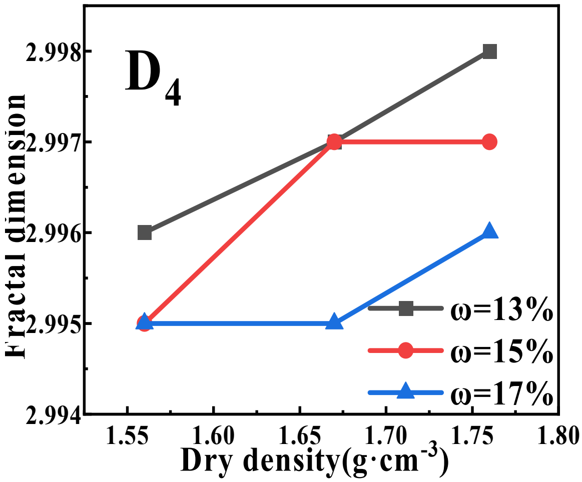

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Fig. 2. Dry density-fractal dimension relationship.

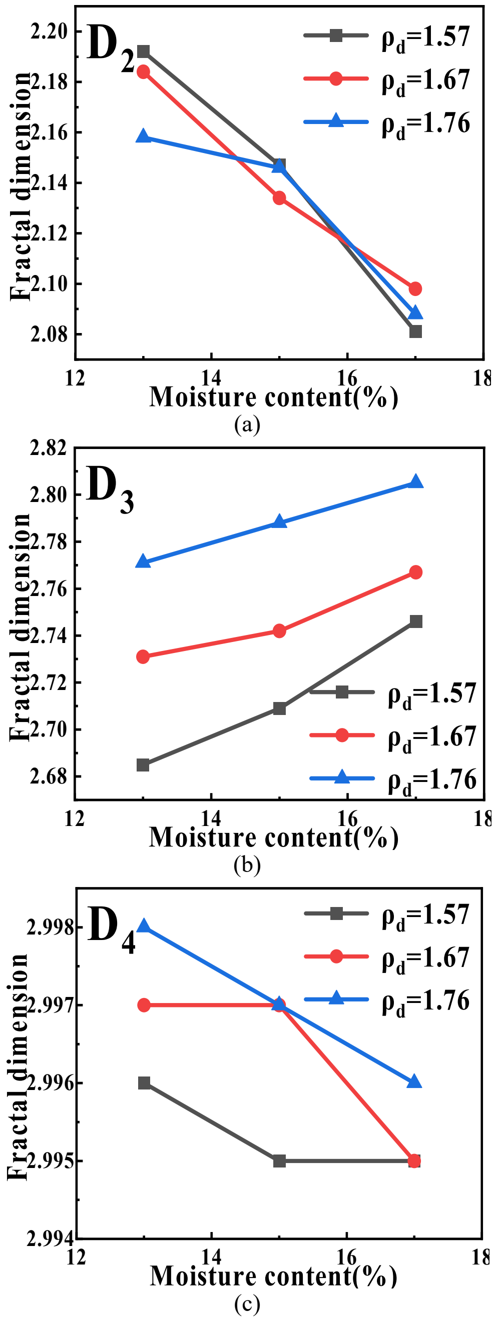

Fig. 3. Moisture content-fractal dimension relationship.

Figure 3 illustrates that when the dry density was unchanged, the moisture content rose from 13% to 17%, and the D_2 of the soil with a larger dry density decreased nearly linearly, indicating that the increased moisture content promoted compaction of soil particles and simplify the small pore structure, decreasing the D_2 with increasing moisture content. The D_3 increased with increasing moisture content, indicating that the medium pore structure became more complex as the moisture content rose. The slope of the curve is larger when the dry density is smaller, indicating that the medium pore structure is more susceptible to variations in the moisture content at a smaller dry density. The D_4 decreased with increasing moisture content, indicating that the large pore structure in the soil was more simplified when the moisture content was higher. The decreasing trend slows as the dry density rises, indicating that increasing the dry density can successfully lessen the effect of moisture content on the large pore structure of the soil. As the moisture content rose, the thickness of the water hull on the surface of the soil particles rose, and the frictional resistance between the particles and resistance during misalignment decreased. The small and large pores in the soil, as a result of the action of compacting work, were reduced with increasing dry density. Some of the large pores were transformed into medium pores, resulting in a simplified microscopic pore structure of the soil and a stable layered stacking structure with greater compactness.

4 CONCLUSIONS

1) The distribution curve for pore size moved to the left as a whole as the dry density increased, indicating that the effect of dry density on the pore space of the soil is primarily manifested in the drastic reduction of medium and large pores, with a weaker effect on micropores and small pores. As the moisture content increased, the micropores and medium pore spaces in the soil decreased. The small and large pore spaces increased, significantly affecting the medium and large pore spaces, respectively.

2) Changes in dry density at constant moisture content can directly affect the fractal dimension of medium and large pores while having less of an effect on the fractal dimension of small pores. The D_2 and D_4 decreased with increasing moisture content when the dry density was constant. The D_3 increased with the moisture content. The medium pore structure was more sensitive to the change in moisture content when the dry density was small. An increase in the dry density can effectively reduce the effect of moisture content on the large pore structure of the soil.

3) The influence of moisture content and dry density on the microscopic pore structure of unsaturated remodeling loess is analyzed by fractal theory, which provides theoretical support for the study of macroscopic transport processes such as water-gas-heat in unsaturated soil from the microscopic perspective. The insufficient point in this paper is that the quantity of samples is small, and the quantity of samples will be increased in the subsequent study to ensure the authority of the test results.

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