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Research Article

Study on the Changing Rules of Silty Clay's Pore Structure under Freeze-Thaw Cycles

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For engineering construction in seasonally frozen regions, when the soil below the frost depth without freeze-thaw effect was exposed or reclaimed after excavation, long-term freeze-thaw will change soil skeleton and porous characteristics, thereby leading to the deterioration of soil engineering properties. This study focused on seasonally frozen silty clay from Changchun, China, and conducted different freeze-thaw cyclic tests on remoulded soil samples, during which both freezing temperature and the number of freeze-thaw cycles were varied. The related data of pore structures under different test conditions were acquired through mercury injection porosimetry (MIP) tests, and the effects of the number of freeze-thaw cycles and freezing temperature on the change of the soil's pore structure were investigated in detail in combination with fractal theory. The variation rules of pores in the soil after freeze-thaw cycles were investigated from a microperspective so as to essentially analyze the mechanism of the deteriorating effect of freeze-thaw on a soil's engineering properties.

1. Introduction

Freezing and thawing of soil is an important research object in frozen soil mechanics and engineering. Seasonally frozen soil is extensively distributed on the Earth. In particular, seasonally frozen soil in the northern hemisphere covers an area of approximately $48.12 \times 10^6\ km^2$, which occupies approximately 50.5% of the total land area [1]. Frost heave and thaw collapse have always been primary causes of engineering disasters in frozen areas [2]. To civil engineering, the freeze-thaw cycles can cause two disadvantages: one causes the destruction of engineering structures, such as the foundations of buildings, bridges, culverts, and roads, and makes other structures incline, crack, suffer uneven settlement, or even collapse. The other damages the soil structure and its physicomechanical properties, thus increasing the operation and maintenance costs and reducing the service life of buildings thereon [3]. Scholars have conducted a great deal of research on the effects of extensive freeze-thaw action on the engineering properties of soil from many aspects including soil physical properties, water-physical properties, and mechanical properties [4–8].

It has become common understanding that soil engineering properties depend greatly on microstructure and related structural changes. Many macromechanical phenomena can be essentially explained by microstructural properties. To study soil structure is of significance to the change of soil engineering properties being determined accurately for the purposes of engineering construction. Freeze-thaw cycle can change the engineering properties of a soil in many ways, all of which are realized by changing the structure of the soil [9]. It was found that freeze-thaw cycle increased the vertical permeability of soil by changing its structure [10]. Freeze-thaw cycle changes the mechanical properties of soil by breaking the binding force between soil particles and rearranging them [11]. Porosity is an important parameter that describes a soil's microstructure, whose change can directly reflect a soil's structural change. Therefore, investigating the variation rules of pores in the soil after freeze-thaw cycles from a microperspective can essentially analyze the mechanism of deteriorating effect of freeze-thaw on a soil's engineering properties. Currently, scholars have investigated soil microporous structure by means of mercury injection porosimetry (MIP), the adsorption method, magnetic resonance imaging (MRI), X-ray diffraction (XRD), optical microscopy, scanning electronic microscopy (SEM), the CT scanning method, and the isothermal adsorption method [12, 13]. Scholars have extensively examined the variation rules of microstructures of different types of soil including silty clay, soft clay, grassy soil, yellow soil, and various kinds of improved soil. Skvortsova et al. employed three-dimensional (3D) X-ray computer scanning system for analyzing changes in microstructures and pore-diameter changes in grassy soil after freeze-thaw cycles [4]. Based on static and dynamic triaxial test results, Cui et al. investigated the mechanical properties of silty clay and qualitatively analyzed SEM images of silty clay before and after freeze-thaw cycles; moreover, they extracted the mechanical properties of silty clay and examined the effects of freeze-thaw on silty clay [5]. Özgan et al. investigated the change of fundamental properties of low plastic clay before and after freezing and thawing and analyzed the soil's microstructure using SEM [6]. Tang and Yan focused on grey-black mucky soil from Shanghai, China, and conducted a series of freeze-thaw tests, hydrostatic tests, MIP, and SEM tests to explore the effects of freeze-thaw action on hydraulic conductivity and microstructure of the soil [7]. Jamshidi et al. employed transmission optical microscopy to investigate the change of properties and structure of cement-treated soil and evaluate the destroying mechanism of water-cement substrate after freeze-thaw cycles [8]. In spite of a lot of investigations on the structural characteristics of various types of soil under freeze-thaw action, the effect of freezing on soil properties has been poorly investigated thus far. In fact, freezing temperature is a key factor in a soil's freezing process. Temperature acts as the driving source of water phase change and migration, which determines the content of unfrozen water and water migration in the freezing process and significantly affects a soil's freezing degree and physical and mechanical properties after thawing.

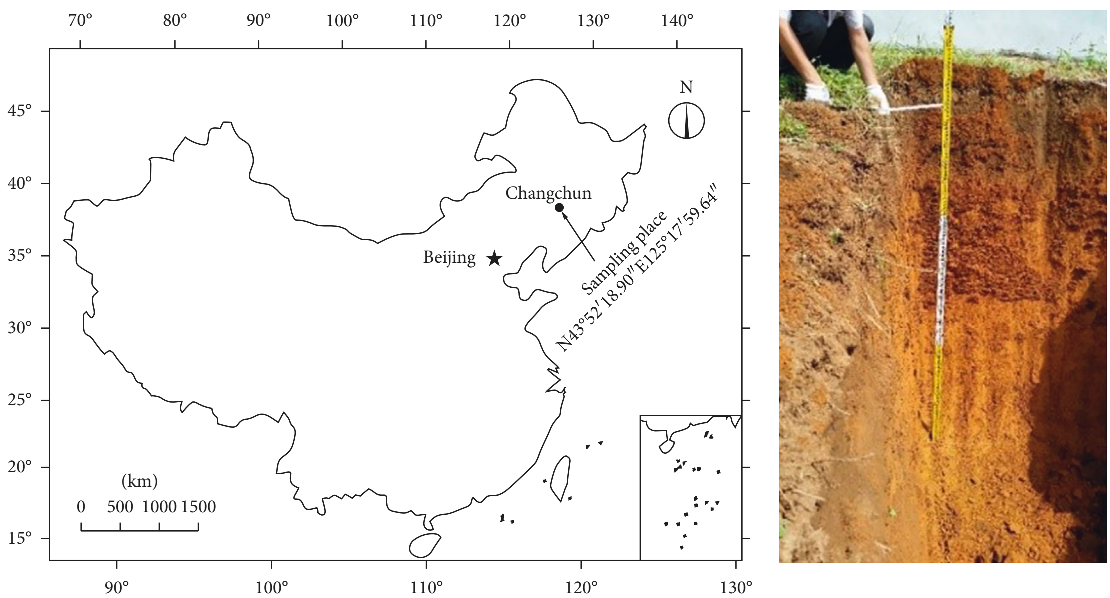
For engineering construction in regions with seasonally frozen soil, when constructing deep foundation pits and other underground works, the soil below the frost depth without freeze-thaw effects was exposed or reclaimed after excavation. Under freeze-thaw conditions, the structure of the soil changes, thus changing its skeleton and pore characteristics; therefore, the soil quality deteriorates, which has an impact on engineering safety. In this study, by combining MIP and fractal dimension theory, the variation rules of soil pores after freeze-thaw cycles at different freezing temperatures and freeze-thaw phases were analyzed in detail so as to further determine the mechanism of changes in soil engineering properties after freeze-thaw cycles.

2. Sample Properties and Test Method

2.1. Soil Properties and Sample Preparation. As shown in Figure 1, the soil samples that were collected from Chaoyang Park, Changchun City, Jilin Province, China, were used in this study. As shown in Figure 1, the longitude and latitude are N43°52′18.90″ and E125°17′59.64″, respectively. The sampling points were located in seasonally frozen soil regions, with a standard frost depth of 1.60 m [14]. The sampling depth was 2.5 m under the ground, and soil samples underwent no freeze-thaw cycles under natural state. Tables 1–3 list basic physical properties, particle size analysis results, and mineral compositions of the soil samples. The natural density and plasticity index of undisturbed soil samples were 1.95 g/cm^3 and 16.9, respectively, i.e., the soil samples exhibited a compact structure and can be classified as low liquid limit clay. The content of silt component that is beneficial to frost heaving is above 70% [15]. In terms of mineral components, the primary mineral occupies the greatest proportion while secondary mineral mainly consists of clay.

In this study, samples were prepared according to Standard for Soil Test Method [16]. Before sample preparation, soil samples were first dried in the air and ground using a wood roller. After the soil was completely destroyed, the soil sample was sieved by a sifter with a diameter of 2 mm; then, the soil sample after sieving was uniformly mixed, and the air-dried moisture content of the sample was measured. According to compaction test results, the maximum dry density and optimal moisture content of the soil sample were 1.79 g/cm^3 and 20.9%, respectively. In subgrade engineering and earthwork backfilling projects, a compaction degree of 90% is the lowest requirement for the backfilled soil. The soil samples in the present tests were prepared using the compaction method controlled by dry density. The sample was compacted hierarchically in the sample striker ($\varphi = 10$ cm) so as to ensure the sample's uniformity, during which the dry density was set as the maximum value (90%), i.e., the compaction degree was 90%. Finally, the sample was cut by the cutting ring.

2.2. Freeze-Thaw Cyclic Tests. The present freeze-thaw cyclic tests were conducted using the developed freeze-thaw tester, as shown in Figure 2. The tester can achieve constant temperature through automatic control and includes three temperature controllers from top to bottom. Each temperature controller can independently realize temperature adjustment within a temperature range from −30°C to ambient temperature, with a temperature regulation precision of below 1°C. Since the sampling point in this study was approximately 7 m at depth, capillary water cannot supply water for the frozen zone and soil samples were placed in a closed system and supplied with no water in the present freeze-thaw cyclic tests. In order to prevent the evaporation of water from soil samples after multiple freeze-thaw cycles, each sample was covered by a plastic bag and tightly sealed using tape. Next, the sample was placed in the temperature controller and underwent triaxial freeze-thaw, specifically, a 24-hour freeze-thaw cycle with 12 hours of freezing and 12 hours of thawing. According to the statistical data from the meteorological station, the lowest temperature in Changchun generally occurs in January in winter, and the mean temperature occurs in January and can reach up to −15.1°C, with a lowest surface temperature of approximately −10°C [17]. In the process of seasonal change, freeze-thaw



(a) (b)

Figure 1: Illustration of the location of the sampling point.

Table 1: Basic physical properties of the soil sample.

Moisture content (%)	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)
20.9	39.3	22.4	16.9

Table 2: Components in the soil sample based on particle size.

Proportion of the component with different particle sizes in the soil		
Sand grains (mm)	Silty grains (mm)	Clay grains (mm)
2~0.075	0.075~0.005	<0.005
2.79	74.37	22.84

Table 3: Contents of different mineral components in the soil sample.

Relative content of the mineral component ω (B)/10^{-2}						
Q	fs	Pl	I/S	I	K	Ch
48	17	18	8	5	3	1

Note. Q denotes quartz, fs denotes alkali feldspar, PI denotes plagioclase, I/S denotes illite/smectite formation, K denotes kaolinite, I denotes illite, and Ch denotes chlorite.

Figure 2: Picture of the developed freeze-thaw tester.

cycle will occur yearly in a seasonally frozen soil. In spring and autumn, when the diurnal temperature range is larger, the temperature does not reach the minimum meteorological temperature, but a freeze-thaw cycle may occur in artificial fill that may freeze at night and melt during the day. To simulate the freeze-thaw process of earth backfill and subgrade under different temperatures, the minimum meteorological temperature was selected as the low temperature limit in these tests. Accordingly, using the same temperature gradient, the freezing temperature was set as −15°C, −10°C, and −5°C, respectively, while the thawing temperature was set as the ambient temperature. Generally speaking, the number of times that soil resists freeze-thaw cycle is limited. Take fine-grained soil as an example: through freeze-thaw cyclic testing, Wang et al. found that mechanical indices of fine soil tended to be stable after seven freeze-thaw cycles [18]. As for the silty clay in the Changchun area, previous test results demonstrate that after 20 freeze-thaw cycles, soil properties tend to be stable and remain unchanged with freeze-thaw cycles [19]. Therefore, the data after 20 freeze-thaw cycles were selected to represent the pore characteristics of the soil after long-term freeze-thaw action. At each freezing temperature, the number of freeze-thaw cycles was set as 3 and 20, respectively. The freeze-thaw processes for backfilled soil and the subgrade at different temperatures in different phases (at the beginning of construction and long-term stability phase) were simulated. Different schemes in the freeze-thaw cyclic test are listed in Table 4. After multiple freeze-thaw cycles, MIP tests were performed on the soil samples.

2.3. MIP Test. MIP is an important way of measuring soil microporous characteristics. In this study, the mercury injection apparatus (Auto pore 9500, Micromeritics Instrument Corporation, USA) was used. The sample used for MIP testing was collected from the upper center of the soil sample after freeze-thaw, and the sampling positions in various sets of tests remained unchanged. The soil sample was small in volume and underwent triaxial freeze-thaw; however, it cannot be completely frozen quickly during the freezing process, and water can migrate from the sample center towards the edges. The upper part of the sample was selected for MIP testing, which can favorably reflect the migration characteristics of pore water. In order to retain the sample's original microstructure, the samples under MIP testing were prepared and dried using liquid nitrogen refrigeration vacuum sublimation rather than high-temperature drying that can lead to shrinkage of samples. Soil samples after freeze-thaw cycles were cut into soil blocks with a size of approximately 1.0 cm^3 and then placed under liquid nitrogen at a boiling temperature of −196°C for rapid freezing. Next, after vacuum pumping at low temperature for 24 hours, ice in the soil sample was sublimated into water vapor and pumped out. Accordingly, the soil sample can be dried without deformation and retain the original microstructure. The prepared soil sample was placed in the mercury injection apparatus (as shown in Figure 3) for MIP testing.

3. Test Results and Analysis

3.1. Analysis of MIP Test Results. MIP testing was conducted on soil samples after different numbers of freeze-thaw cycles (3 and 20) at different freezing temperatures (−15°C, −10°C, and −5°C), and the pore-diameter distribution patterns of the above-processed remoulded soil samples were acquired, as shown in Figures 4 and 5, respectively.

As shown in Figures 4 and 5, pore-diameter distribution curves of different soil samples all exhibit three peaks. The local minimum at a pore diameter of approximately 4000 nm can be regarded as the experimental illusion caused by the transition from a low-pressure to high-pressure system during the MIP testing process [20]. Scholars always believed that it does not affect the readings of injection volume at higher or lower pressures, which cannot bring about significant errors in the data analysis. Therefore, by neglecting local minima, pore-diameter distribution curves are actually two-peak curves, which represent two types of pores in remoulded unsaturated silty clay. Specifically, the first peak with greater pore diameter corresponds to the inter-aggregate pores while the second peak with a smaller pore diameter corresponds to the pores within soil particle aggregates [21, 22].

It can also be observed from Figures 4 and 5 that the peak corresponding to the inter-aggregate pores overall exhibited an obvious shift towards the right with the increase in both the freezing temperature and the number of freeze-thaw cycles, i.e., the proportion of the pores with small diameter dropped while the proportion of the pores with great diameter increased. Accordingly, it can be concluded that soil structure became looser after freeze-thaw cycles. This is due to the fact that water in the soil froze and increased in volume, thereby leading to the increase of pore volume. In addition, some pores were formed in the soil after freeze-thaw cycles, which can connect small pores and form some large pores. Conclusively, the increasing number of freeze-thaw cycles and the rise of freezing temperature aggravated the deterioration of soil properties.

Table 4: Different schemes in the freeze-thaw cyclic test.

Properties of soil sample	Soil sample ID	Number of freeze-thaw cycles	Freezing temperature (°C)
With a compaction degree of 90%, a moisture content of 20.9% and a dry density of 1. 61 g/cm^3	a3	3	−15
	a20	20	−15
	b3	3	−10
	b20	20	−10
	c3	3	−5
	c20	20	−5

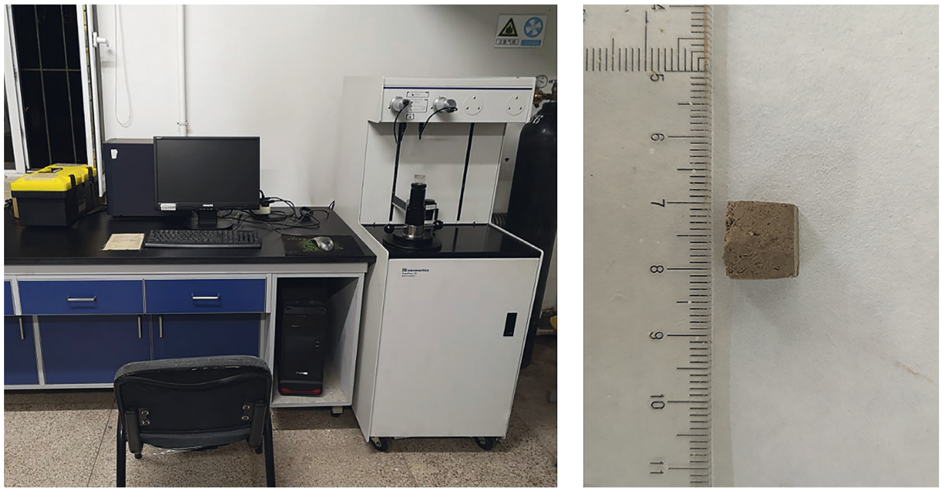
At a freezing temperature of −15°C and −10°C, the peak corresponding to the pores in soil particle aggregates overall rose and narrowed from the beginning to long-term freeze-thaw cycles, but the peak exhibited no obvious shift. At a freezing temperature of −5°C, the peak corresponding to the intra-aggregate pores increased drastically at the beginning of freeze-thaw and then dropped off after long-term freeze-thaw. After the same freeze-thaw cycles, the peak corresponding to the intra-aggregate pores gradually moved to the right and rose with the increase of freezing temperature, accompanied by a narrowing of peak width. Accordingly, freeze-thaw can make the intra-aggregate pores concentrate on a certain diameter, and the diameter increases at higher freezing temperatures.

The total volume of the pores among and in soil particle aggregates after freeze-thaw can be calculated by the increased mercury volume under the first and the second peaks. Pore data for soil samples are listed in Table 5 and Figure 6.

By comparing above sets of data as listed in Table 5, the effects of freezing temperature and the number of freeze-thaw cycles on soil pore diameter can be concluded below.

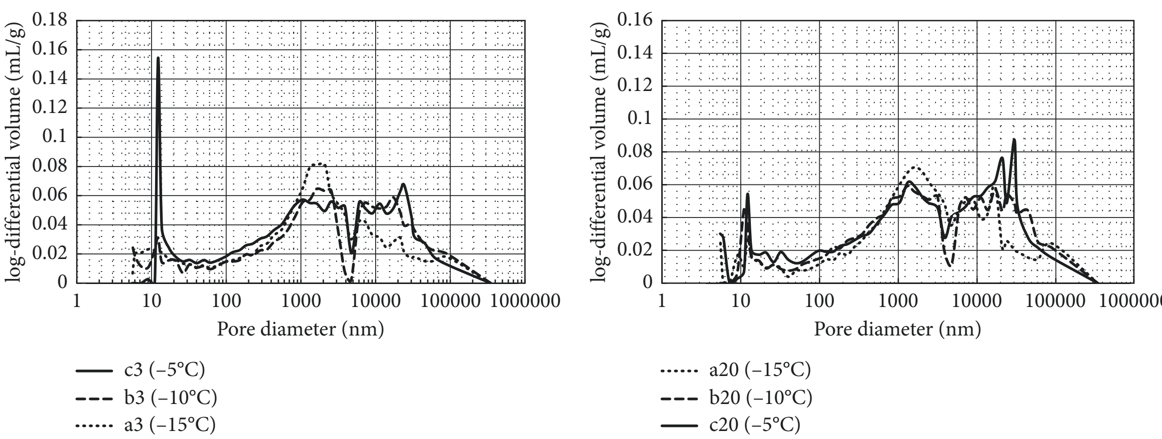
At a same freezing temperature, with increasing number of freeze-thaw cycles, the volume of the inter-aggregate pores increased and the volume of the intra-aggregate pores decreased, while the porosity of soil sample increased. After several freeze-thaw cycles, as the freezing temperature rose, the volumes of the inter-aggregate pores and the intra-aggregate pores as well as the porosity of the sample increased.

The above phenomena can be attributed to the following reasons. The bound water in the clay soil is less sensitive to changes in freezing temperature much lower than the freezing temperature of free water. As the temperature gradually dropped to a negative value, ice crystals first appeared in the large pores of the soil and grew steadily;



(a) (b)

Figure 3: Picture of the mercury injection apparatus and a prepared soil sample for MIP test.



(a) (b)

Figure 4: Distribution curves of logarithmic differentiation of soil pore diameters after 3 (a) and 20 (b) freeze-thaw cycles.

meanwhile, free water was gradually absorbed at the beginning, and then water in the bound water layer was gradually absorbed by the ice crystals. With the growth of ice crystals, the bound water film between soil aggregates in the frozen zone getting thinner rapidly, thereby increasing the electrostatic attraction of water by the surface of soil aggregates. Under electrostatic attraction, the film water in the nonfreezing zone migrated towards the freezing boundary, and ice crystals expanded gradually, which formed ice lens or ice layers. The increase in ice volume imposed wedging effect on the space among particles and then separated the aggregates, and therefore, both the distance among soil aggregates and the volume of the inter-aggregate pores increased. According to calculation results based on electric double layer theory, the thickness of the bound water film of the sampled silty clay was approximately 200~300 nm [23], and the diameter of most intra-aggregate pores was smaller than 40 nm, which was lower than the twice of the thickness of the bound water film, suggesting that the intra-aggregate pores were filled with bound water. As the number of freeze-thaw cycles rose, the bound water film became thinner and the internal spacing between structural units decreased. Therefore, after long-term freeze-thaw, the volume of the intra-aggregate pores decreased and some aggregates were fractured, which can also lead to the decrease in the intra-aggregate pores.

With an increasing number of freeze-thaw cycles, the change of pore volume accumulated gradually; as the freezing temperature rose, the bound water froze at a decreasing velocity and migrated more significantly, resulting in thinning of the bound water film and a decrease in freezing point [24]. Therefore, at a freezing temperature of −5°C, the soil sample after 20 freeze-thaw cycles exhibited the most obvious changes in pore volume, soil aggregates, and porosity.

After the same freeze-thaw cycles, total pore volume in the soil sample increased with the increase of freezing temperature. At freezing temperatures of −15°C and

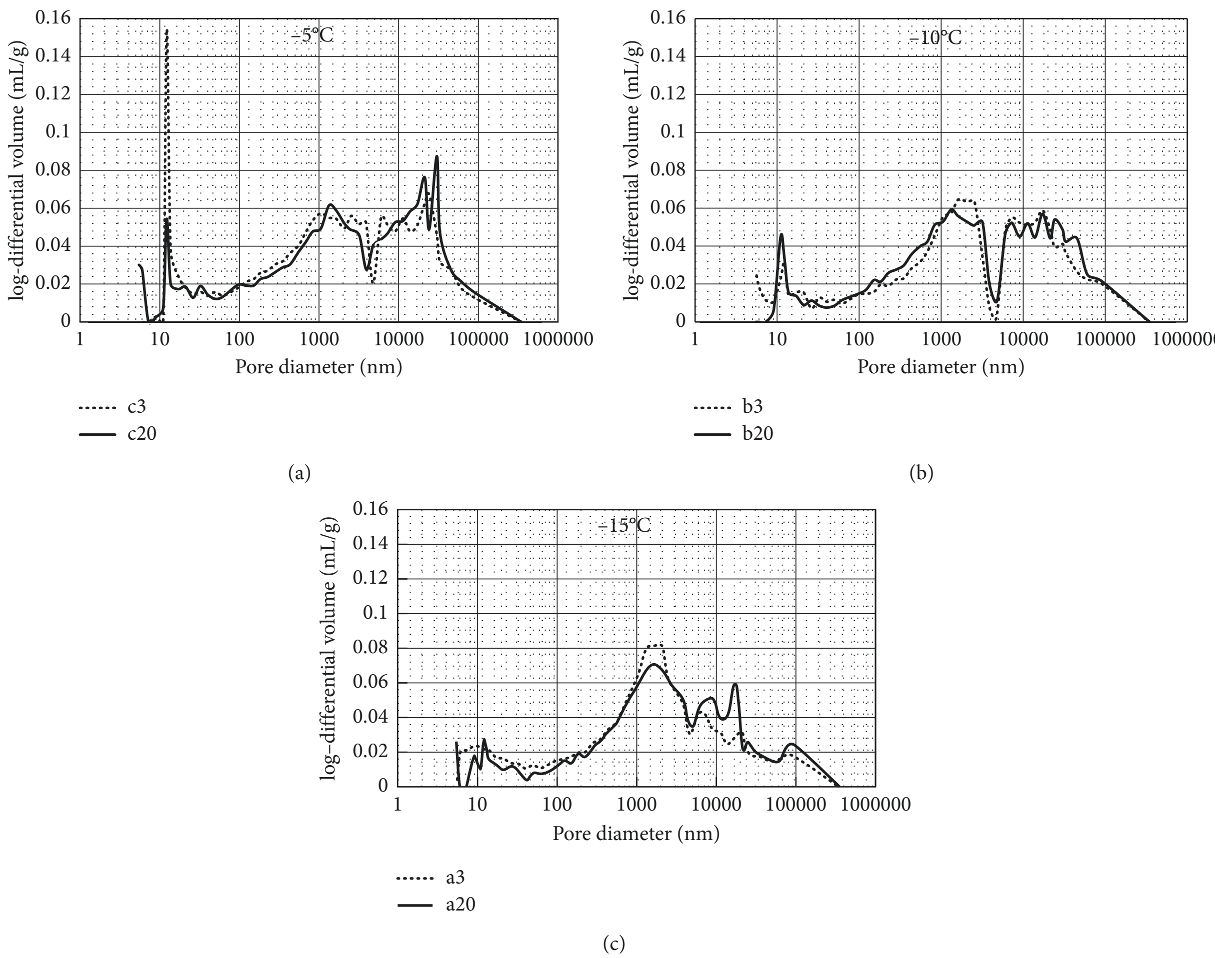


Figure 5: Distribution curves of logarithmic differentiation of soil pore diameters after freeze-thaw cycles at different freezing temperatures: (a) −5°C, (b) −10°C, and (c) −15°C

Table 5: Statistics of pore data of soil samples.

Soil sample ID	Porosity (%)	Mean pore diameter (4 V/A) (nm)	Total pore volume (ml/g)	Inter-aggregate pore volume (ml/g) > 40 nm	Intra-aggregate pore volume (ml/g) ≤ 40 nm
a3	22.72	96.3	0.1359	0.1206	0.0153
a20	23.71	153.5	0.1363	0.1263	0.0100
b3	24.65	105.8	0.1404	0.1241	0.0163
b20	26.36	166.9	0.1439	0.1333	0.0106
c3	26.41	113.9	0.1529	0.1346	0.0183
c20	27.95	108.8	0.1505	0.1356	0.0149

−10°C, mean pore diameter and total pore volume increased with the increasing number of freeze-thaw cycles. At a freezing temperature of −5°C, mean pore diameter and total pore volume at the beginning of freeze-thaw cycles were slightly lower than those after long-term freeze-thaw. At a high freezing temperature, the volume of the inter-aggregate pores increased slightly after long-term freeze-thaw compared with the beginning of freeze-thaw cycles, while the volume of the intra-aggregate pores dropped gradually after long-term freeze-thaw cyclic effect as the bound water film became thinner, thereby leading to an increase in soil porosity.

The above test results reveal that the change in soil porosity after freeze-thaw cycles is connected with freezing temperature and the number of freeze-thaw cycles. After the same number freeze-thaw cycles, soil porosity changed more significantly at a higher temperature. At low freezing temperatures (−15°C and −10°C), soil porosity changed more significantly after more freeze-thaw cycles; by contrast, at a relatively higher freezing temperature (−5°C), the soil microstructure changed more at the beginning of the freeze-thaw cycles (less than 3 freeze-thaw cycles).

As stated above, the present freeze-thaw cyclic test was conducted in a closed system without water supply from

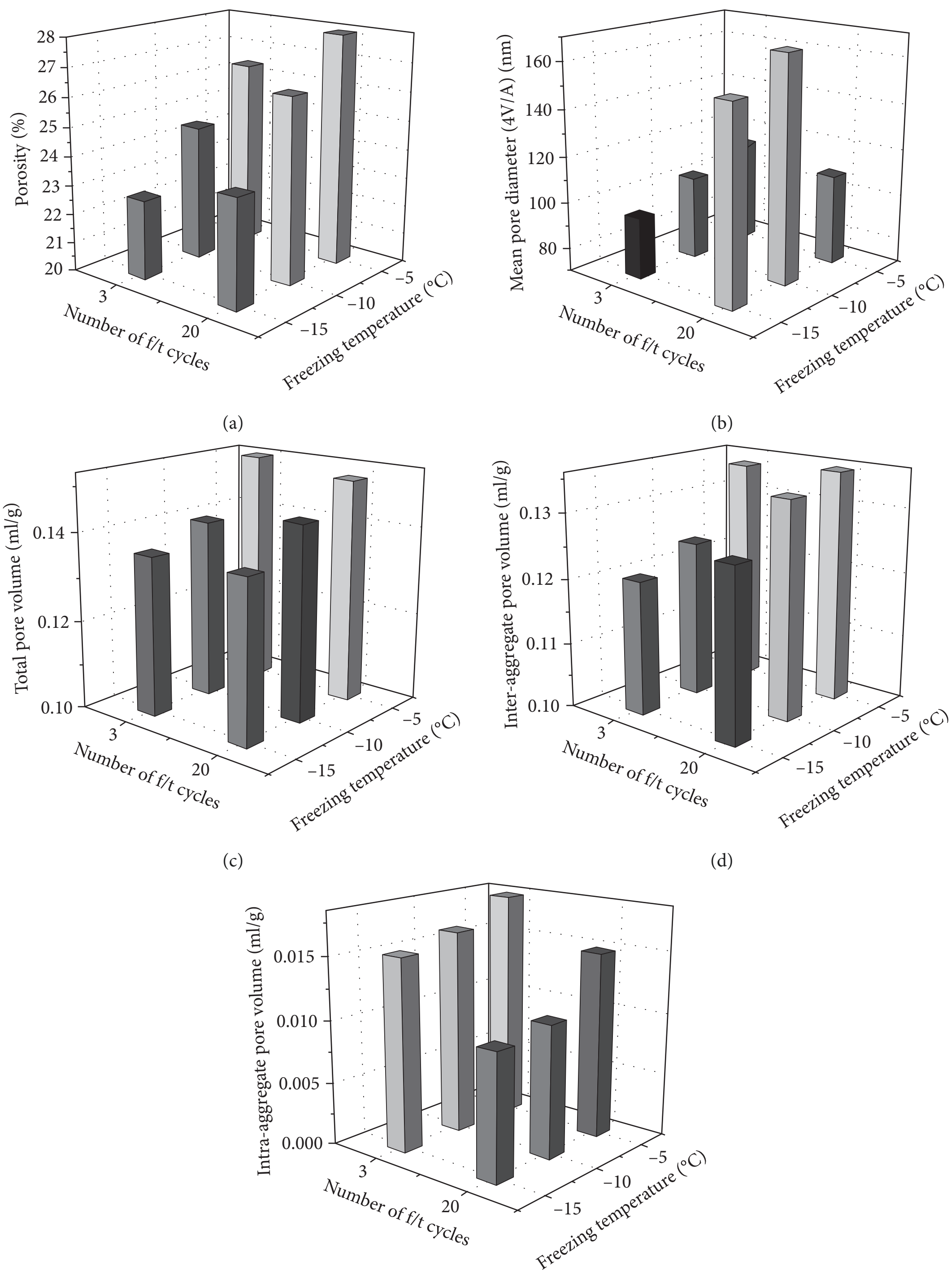


Figure 6: Histograms of pore data of soil samples. (a) Porosity. (b) Mean pore diameter. (c) Total pore volume. (d) Inter-aggregate pore volume. (e) Intra-aggregate pore volume.

the outside, and therefore, the moisture content of soil sample remained constant. The freeze-thaw process refers to freezing, thawing, and migration of water in the soil sample. At a high freezing temperature, freezing rate dropped, more water migrated in the soil sample and underwent fewer freeze-thaw cycles, and pore volume in the soil was almost equivalent to ice volume in the soil. The microstructure reached a stable state at the beginning of the freeze-thaw cycles, and pores in the soil were only redistributed with an increasing number of freeze-thaw cycles. Accordingly, the soil microstructure exhibited great changes at the beginning of freeze-thaw cycles at a high freezing temperature. By contrast, at a low freezing temperature, the soil microstructure changed steadily with the accumulation of freeze-thaw cycles until it reached a balance.

At different freezing temperatures, water in the soil underwent repeated phase transitions and migrations during freeze-thaw cyclic tests, and soil particles and pores also changed constantly with the change in water state in the soil, finally leading to changes in the soil's microstructure and engineering properties.

3.2. Fractal Calculation of Pores in the Soil Sample. The existence of pores in the soil and the transition between various types of pores are the main factors that lead to macro frost heaving and thawing collapse as well as changes in engineering properties. The pores exhibit fractal characteristics, whose fractal dimension change can reflect the variation characteristics of pores in the soil after freeze-thaw cycles. A great deal of research has demonstrated that a soil sample including a large number of pores and fractures can be regarded as a fractal [25–28]. In 3D Euclidean space, pores have extremely complex pore structures and surface structures that cannot be measured and described; however, pore structure has certain scaling property, self-similarity, and statistically follows fractal rules. Therefore, based on geometry-fractal theory for investigating these irregular states, fractal dimension was introduced for qualitatively describing complex pore structures. Fractal dimension is an important parameter for characterizing porous structure, which can reflect the disorder degree of pore structures and the surface morphology. The spatial distribution of pore structure is generally described by the fractal dimension of pore volume, which can be calculated using a combination of the volume fractal dimension model and MIP test.

If a geometrical object with a measured volume of V is filled by many small balls with a radius of r, the required number of small balls can be calculated as

$$N(r) = \frac{V}{1.33\pi r^3} \propto \frac{1}{r^3}. \tag{1}$$

If the small balls with a radius of r_0 are used for the measurement of soil's pore volume V_m, V_m can be written as $V_m = N \times 1.33\pi r_0^3$. According to the definition of a fractal, the relationship radius of the small balls (r_0) and the required number of small balls for filling all pores in the soil (N) can be written as $N = cr_0^{-D}$. Therefore, the following expression can be derived:

$$V_m = 1.33\pi c r_0^{3-D}, \tag{2}$$

where $N = cr_0^{-D}$ denotes the soil's minimum pore scale, c denotes the proportional constant, and D denotes the fractal dimension.

The relationship between pore volume (V_m) and pore radius (r) can be written as $V_m \propto r_0^{3-D}$. In differential form, $(dV_m/dr_0) \propto r_0^{2-D}$, and this expression can be derived as [29, 30]

$$\log\frac{dV_m}{dr_0} \propto (2-D)\log r_0. \tag{3}$$

In combination with Washburn equation [31], the following expression can be derived:

$$\log\frac{dV_m}{dP} \propto (D-4)\log P. \tag{4}$$

It means that the fractal dimension of pore volume can be determined by the bilogarithimic relation between dV_m/dP and P. As long as $\log(dV_m/dP)$ and $\log P$ follows a linear relationship, the distribution of pores exhibits fractal characteristics. Therefore, the fractal dimension of pore volume can be calculated by the slope of the linear segment, i.e., $D = 4 + K$, where K denotes the slope of the linear segment.

Figure 7 shows the $\log(dV_m/dP) - \log P$ regression curves of soil samples. By combining Figure 7 and equation (4), the fractal dimensions of the soil samples were calculated, as listed in Table 6 and Figure 8. Some local special points can be observed in the regression curves, which can be caused by the conversion from low-pressure to high-pressure systems in MIP tests. These points do not bring about significant errors in overall data analysis.

It can be observed the correlation coefficients of the regression curves can exceed 0.95. Therefore, the test results show a favorable correlation, suggesting that soil's pore structure has fractal characteristics. In other words, the soil's pore structure can be characterized by fractal dimension.

The fractal dimension D is a characteristic parameter for characterizing a solid's surface roughness [32]. In 3D Euclidean space, the fractal dimension of a fractal structure is a fraction within a range of 2 (for a plane) to 3 (for an extremely rough surface). According to the theory of fractal geometry, a greater fractal dimension of the fractal structure in 3D Euclidean space suggests a more complex and nonuniform structure. In other words, the greater the calculated fractal dimension, the poorer the nonuniformity of the pore structure, i.e., the pore diameters have greater difference, the surface is rougher, and the structure is more complex.

After freeze-thaw cycles, the proportion of large pores in the soil sample increased, accompanied by the increase of porosity. With the increase of porosity, fractal dimension decreased significantly. At the same freezing temperature, the fractal dimension of soil pore volume dropped as freeze-thaw cycles continued, suggesting that soil's pore structure became smoother, less complex, and more regular while pore diameters were more uniformly distributed. After 20 freeze-thaw cycles, the calculated fractal dimensions of soil pore structure dropped as the freezing temperature decreased from −15°C to −5°C. After long-term freeze-thaw, pore surfaces became smoother and more uniform while the difference in pore diameter decreased with the increase of freezing temperature. After 3 freeze-thaw cycles, the fractal dimension of pore structure of the soil sample at a freezing temperature of −5°C was significantly greater than that at a freezing temperature of −15°C and −10°C, respectively. It can thus be concluded that at a high freezing temperature, the pore structure changes significantly at the beginning of freeze-thaw cycles, i.e., the pore structure became less uniform

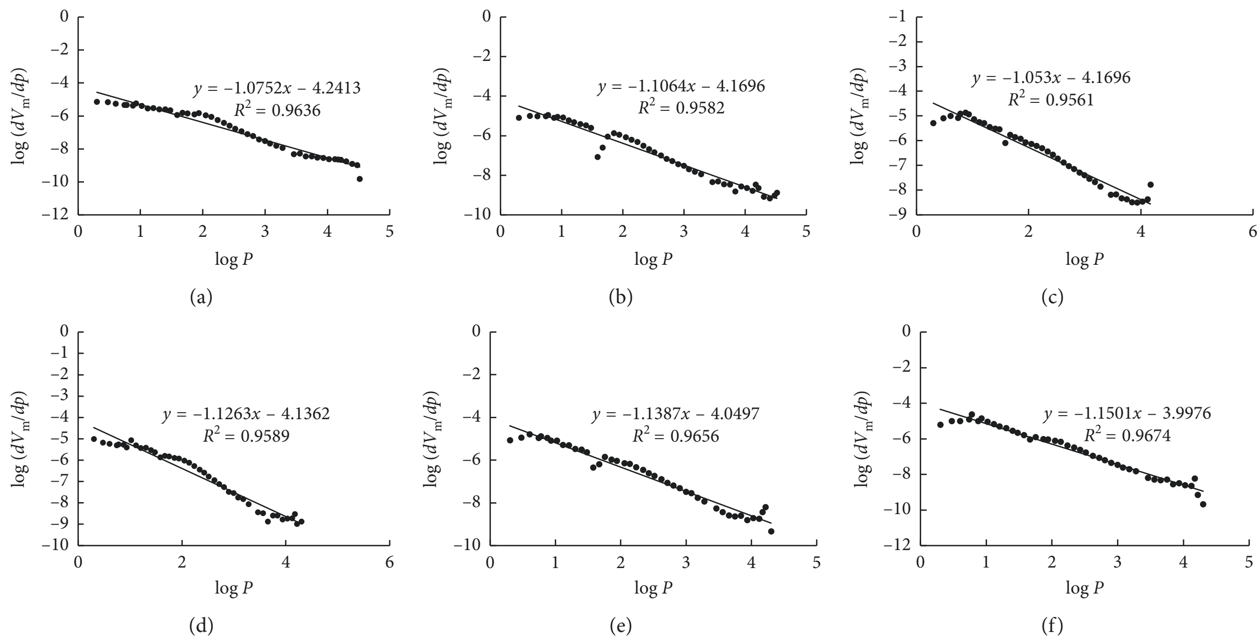


FIGURE 7: The $\log(dV_m/dP) - \log P$ regression curves of the remounted soil samples. (a) a3; (b) b3; (c) c3; (d) a20; (e) b20; (f) c20.

TABLE 6: Calculated fractal dimensions and regression coefficients of different soil samples.

Soil sample ID	Fractal dimension D	Regression coefficient R^2
a3	2.9248	0.9636
a20	2.8737	0.9589
b3	2.8936	0.9582
b20	2.8613	0.9656
c3	2.9470	0.9561
c20	2.8499	0.9674

and more complex and pore diameters exhibit a greater difference while the pore surface was rougher.

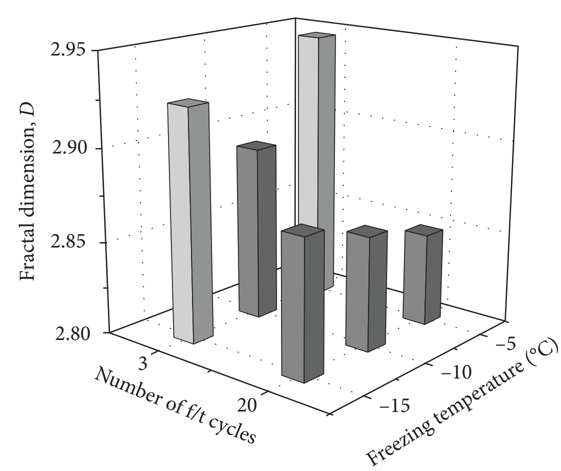


FIGURE 8: Histogram of the calculated fractal dimension of different soil samples.

4. Conclusions

(1) Overall, the pore-diameter distribution curves of the remoulded soil samples exhibited two peaks; specifically, the peak corresponding to larger pore diameters representing the inter-aggregate pores, while the peak corresponding to smaller pore diameters representing the intra-aggregate pores.

(2) At the same freezing temperature, the volume of the inter-aggregate pores increased while the volume of the intra-aggregate pores dropped with the increase of freeze-thaw cycles. After the same number of freeze-thaw cycles, both pore volumes among/in soil aggregate increased with the increase of freezing temperature.

(3) When the number of freeze-thaw cycles is constant, total pore volume in the soil sample increased as the freezing temperature rose. At a low freezing temperature (such as −15°C and −10°C), soil pore structure changed more significantly with the increase of freeze-thaw cycles. By contrast, at a high freezing temperature (−5°C), freeze-thaw imposed a more distinct weathering action on soil samples at the beginning of the freeze-thaw cycles (with a number of freeze-thaw cycles of less than 3).

(4) The inter-aggregate pores increased with the rising temperature and increasing number of freeze-thaw cycles, i.e., the diameter of this type of pore increased. Under freeze-thaw effect, the diameters of the intra-aggregate pores gradually approached a certain value; moreover, the higher the freezing temperature, the greater the concentrated diameter.

(5) At a freezing temperature, the fractal dimension of soil pore structure dropped with the increasing number of freeze-thaw cycles, i.e., the soil pore

structure became simpler. After 20 freeze-thaw cycles, the fractal dimension of soil pore structure decreased significantly as the freezing temperature rose, suggesting that the pore structure became more complex. After 3 freeze-thaw cycles, the fractal dimension of the soil pore structure at a freezing temperature of −5°C was significantly higher than those at a freezing temperature of −10°C and −15°C. It can thus be concluded that at a high freezing temperature (−5°C), pore structure was significantly affected and became more complex at the beginning of the freeze-thaw cycles.

Data Availability

The analytical data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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