

Research Article

Soil-Water Characteristics of the Low Liquid Limit Silt considering Compaction and Freeze-Thaw Action

Yongsheng Yao,^{1,2} Shenping Luo,¹ Junfeng Qian ,^{1,3} Jue Li,⁴ and Hongbin Xiao¹

¹School of Civil Engineering, Central South University of Forestry and Technology, Changsha 410004, China

²Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong SAR, China

³Technology R&D Center, Hubei Provincial Road & Bridge Group Co., Ltd., Wuhan 430056, China

⁴National Engineering Laboratory of Highway Maintenance Technology, Changsha University of Science & Technology, Changsha 410114, China

Correspondence should be addressed to Junfeng Qian; qianjunfeng@csuft.edu.cn

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The soil-water characteristic curve of silty soil in seasonal frozen area during freezing-thawing process was studied in this study. By means of a laboratory test, specimens with different compaction degrees and different initial moisture content were prepared and put into the temperature change testing machine for freeze-thaw action. The influence of different degrees of compaction and different times of freeze-thaw action on SWCC of low liquid limit silt was analyzed, a V-G model was used to fit the test data, and a set of fitting parameters with a reference value was obtained. At the same time, the change of microstructure between soil particles during the freezing-thawing cycle is illustrated. The results showed that with the same water content and the same compactness, the matric suction of the test soil decreased with the increase of freeze-thaw cycles. For the same number of freeze-thaw cycles, the greater the compactness, the greater the matric suction of the soil. The V-G model can well represent the SWCC of low liquid limit silt during the freeze-thaw cycle.

1. Introduction

China's seasonal frozen soil area takes up 53.5% of its land area and is widely distributed throughout North China, Northwest China, and Northeast China [1]. The building foundation, road subgrade, and hydraulic structure's properties of seasonal frozen soil areas are affected by the freezing-thawing process [2]. When the temperature is lower than zero, the volume of soil expands, thus resulting in frost heaving. When the climate is warming, the overall moisture content of soil increases, resulting in a melting and sinking effect. This kind of repeated freezing-thawing action in the superstructure of the damage is inevitable and lasts a long time. Such damage can be serious and can lead to building or structural damage. Meanwhile, Wang et al. [3] explored the dynamic characteristics and thawing-

settlement characteristics of roadbed fillers in a place on the Qinghai-Tibet Plateau. The test results showed that the soil samples with higher and lower compaction showed frost heave deformation. In order to thaw and deform, the dynamic characteristics of the soil sample after six freeze-thaw cycles were stable. Ishikawa and Kawabata studied the effect of freezing-thawing action and water content on the mechanical properties of subgrade through the CBR test and model test of subgrade soil, and the results showed that the bearing capacity of subgrade increased in the freezing season and decreased in the melting season [4]. Solanki et al. compared the durability of subgrade soil with additives under the freezing-thawing cycle through laboratory tests [5]. The test results showed that the unconfined compressive strength and elastic modulus of all test groups decreased with the number of freezing-thawing cycles and the

maximum reduction was achieved when the number of freezing-thawing cycles was 1. Ruan et al. analyzed the influences of various environmental factors on the durability of subgrade, especially the huge effects of the freeze-thaw cycle and dry-wet cycle on the durability of subgrade [6]. Lin et al. [7] used a dynamic triaxial test to explore the law of accumulated plastic strain of soil samples under freezing and thawing. The greater the number of cycles, the greater the accumulated strain. In view of the effect of frost heave and thawing-settlement problem, Hansson and Lundin [8], Shoop et al. [9], and Klinova et al. [10] have carried out a series of experiments, and the results showed that the internal structure of unsaturated soil subjected to freeze-thaw action, temperature, water, and the solute changes, physical and mechanical properties and chemical properties gets more complex in the internal structure of soil, and irreversible damage is produced in the buildings and structures located in the area after the freeze-thaw action, respectively. Compared with the complex stress state experienced by engineering soils, the freeze-thaw action often lasts for a long time and causes great damage to the superstructure. In particular, the freeze-thaw action in engineering often occurs underground and has concealment. Therefore, it is necessary to discuss and analyze the effect and law of the effect of freezing and thawing on soil water-holding capacity.

Actually, the evaluation of soil water-holding capacity needs to be explained with the help of unsaturated soil theory. Since the 1920s, with the large-scale construction of water conservancy and transportation projects, a large range of unsaturated soil mechanics problems have appeared in the project, which has also prompted people to start research on unsaturated soil [11]. Unsaturated soil is composed of the solid phase, gas phase, liquid phase, and the interface between the liquid phase and the gas phase (shrink film). The biggest difference between it and saturated soil is the existence of shrink film, which makes the physical and mechanical properties of unsaturated soil than the saturated soil complex. The fundamental reason is that the forces on both sides of the shrink film are different. This makes the unsaturated soils to have suction. The suction in the soil is an important factor affecting the physical and mechanical properties of the soil. From the middle of the 20th century, many scholars began to study the engineering problems of unsaturated soils and committed to establishing a complete and independent theoretical system, including Croney [12], Aitchison [13], and Fredlund and Rahardjo [14]. The soil-water characteristic curve (SWCC) describes the nonlinear relationship between soil matric suction and water content, in which matric suction is the difference between pore water pressure and pore air pressure inside soil. In addition, according to the soil-water characteristic curve, the physical and mechanical parameters of the unsaturated soil shear strength [15], volumetric strain [14], and permeability coefficient [16] can be deduced.

The shape of the soil-water characteristic curve is influenced by many factors, such as compaction, mineral composition, initial moisture content, and particle size. Many studies on SWCC focus on the pore structure and mineral composition of unsaturated soil. Vatsala and

Murthy [17] proved the influence relationship between the degree of compactness and the suction of soil media through experiments, and the two were positively correlated. Meanwhile, it was found that the influence degree mainly depended on the initial pore structure. Assouline et al. [18] have analyzed and compared the results from Brazil's Palotina and Cascavel's soils and have found that under the same soil pore structure, the water-holding properties of the two soils are also affected by the mineral composition, such as iron oxide and free aluminium hydroxide. Wang et al. [3] studied the influence of salinity on the soil-water characteristic curve of the Yili loess by using the centrifugal method and filter paper method in view of the high salinity state inside the loess in Yili, China, but the test results showed that salinity had little influence on the soil-water characteristic curve. The results in Zhou et al.'s research [19] showed that the dry density, particle size, and hydrophilic mineral content of the soil had a great impact on the soil-water characteristic curve. The residual water content of the soil with high dry density was higher, while the soil-water characteristic curve of the soil with strong mineral hydrophilicity was relatively gentle. Gao et al. [20] carried out a series of experiments on sand, and the test results showed that the soil moisture transfer was positively correlated with the heat source temperature and sand with higher initial water content also had a higher thermal conductivity. Jiang et al. [21] studied the influence of different fine grain contents on the soil-water characteristic curve by using a pressure plate instrument. The test results showed that when fine grain content was between 10 and 60%, soil water-holding capacity gradually decreased with the increase of fine grain content.

In addition to the above influencing factors, in unsaturated soil in construction projects, especially subgrade filling soil in the process of road construction, its water-holding performance cannot be separated from the influence of stress state [22]. In general, the stress state is divided into two parts: the weight of the overlying structure and the cyclic load [23]. Considering the stress state as a nonnegligible factor, some engineering researchers devote themselves to studying the influence of stress state on soil internal microstructure and the soil-water characteristic curve. Pereira and Fredlund [24] used a triaxial apparatus to obtain soil-water characteristic curves under different net average stresses and explored the change process of matrix suction during soil collapse. Ng and Pang [25] developed a new type of a pressure plate instrument with controllable stress and conducted an experimental study on the influence of vertical stress on the soil-water characteristic curve of pyroclastic soil. The test results showed that under the same volume moisture content, vertical stress was positively correlated with matric suction. However, the vertical stress used in this test was relatively low, with a maximum of only 80 kPa. Limited by the existing technology and test conditions, the current test cannot simulate the complex coupling effect of humidity and stress. The study of the impact of this dynamic stress is only a qualitative analysis and cannot be directly used in engineering design.

Considering the action process of freezing-thawing cycle, the purpose of this study is to accurately describe the change rule of water-holding performance of low liquid limit silt soil under the combined action of freezing-thawing cycle and initial physical conditions (compaction and moisture content). At the same time, based on the V-G model, a set of model parameters with high precision is proposed to provide reference for road construction and design in cold region. The structure of this paper is as follows: in Section 2, the basic theory of matrix suction is discussed and a typical soil-water characteristic curve is shown to describe the soil dehumidification process. Then several typical soil-water characteristic curve models are discussed. In Section 3, it introduces material properties, freeze-thaw cycle testing methods, and matrix suction measurement methods. Then, the experiment results are presented in Section 4, and the effects of two important factors, compaction and freeze-thaw cycles on SWCC were analyzed. At the same time, a set of predictive model parameters with a reference value is provided through statistical analysis. Finally, some findings are summarized in the last section.

2. Methodology

Soil suction has two components: matrix suction and osmotic suction. The matrix suction is defined as the capillary part of free energy of water in soil; that is, the vapor pressure of water in unsaturated soil is in equilibrium with the groundwater containing minerals. This is expressed as the difference between pore air pressure and pore water pressure, as shown in equation (1). The osmotic suction is the solute part of the free energy of water in the soil; that is, the vapor pressure of groundwater containing minerals at equilibrium with respect to distilled water. The total suction is the total free energy of the water in the soil; i.e., the vapor pressure of the mineral-containing water in the unsaturated soil relative to the distilled water. Finally, the total suction is the sum of matrix suction and osmotic suction, as shown in equation (2). Research related to suction has continued in recent years. For example, Sreedeeep and Singh [26], Arifin and Schanz [27], and Thyagaraj and Rao [28] have studied the relationships between total suction, matrix suction, and osmotic suction through laboratory tests, respectively. Their results show that, in addition to the large influence of the suction in the soil in some high-salt areas on the properties of the soil, the main factor affecting the properties of the soil is the matrix suction. As the difference between the total suction and the matrix suction, the impact on the mechanical properties of the soil has been confronted with a complex situation so far. Leong and Abuel-Naga [29] studied the influence of the unsaturated soil penetration suction on the shear strength separately. With the increase of seepage suction, the shear strength of the soil does not change, and the test results of Mokni et al. [30] show that with the increase of seepage suction, the shear strength of the soil decreases slightly. In addition, a large number of studies have

shown that the reduction of osmotic pressure can cause soil volume expansion [31–33]. When the mineral concentration in the unsaturated soil has little effect on the suction (i.e., when the osmotic suction is negligible), the matrix suction in the soil is the total suction. In this paper, the effect of osmotic suction can be neglected, and matrix suction is then used to describe the index of the soil's water-holding capacity:

$$\psi = U_a - U_w, \quad (1)$$

$$\psi_m = \psi + \psi_0, \quad (2)$$

where ψ is the matrix suction; U_a is the pore air pressure; U_w is the pore water pressure; ψ_m is the total suction; and ψ_0 the osmotic suction.

The SWCC can be used to analyze the water absorption and retention ability of unsaturated soil. The SWCC represents the relationship between the suction (matrix suction) of unsaturated soil and the weight or volume water cut or saturation. The SWCC can be described as a measure of soil water-holding capacity when water content changes with suction. Therefore, the SWCC model is the basis for determining the matrix suction under various humidity conditions of subgrade soil.

Figure 1 shows a typical SWCC. As can be seen, the matrix suction rises with the decrease of water content and is roughly “S” shaped. The curve is divided into three areas by two characteristic points: namely, boundary effect zone, transition zone, and residual zone. The abscissa of the first characteristic point C1 is the intake pressure value. This point describes that the air begins to enter the pores in the soil, and the soil enters the unsaturated state. The ordinate of the second characteristic point C2 is the residual water content. This point characterizes the state of the pore water in the soil as suspended water. At this time, the drainage of the soil pore water must be premised on a large change in the matrix suction.

The whole freezing and thawing process of soil from saturated state to dry state undergoes three phases. First, the pores of the soil in the boundary effect zone are filled with water; the matrix suction cannot be changed at this point. At this time, the mechanical properties of the soil can be described by the effective stress theory of saturated soil. Then, when the pore water of the soil begins to drain, the matrix suction increases with the curve, and the curve enters the transition area. The matrix suction increases with the decrease of the water content. This area is the most significant influence of the soil-water content on the strength and deformation properties of the soil area. Eventually, when the pore water content of the soil decreases to a certain degree, the curve enters the residual area, the pore gas and the atmosphere circulate, the pore water remains in some pores, and the matrix suction rises rapidly as the water content decreases.

In the past few decades, a considerable number of scholars proposed various SWCC models. At present, two models are widely accepted by researchers and engineers: the van Genuchten model and the Fredlund and Xing

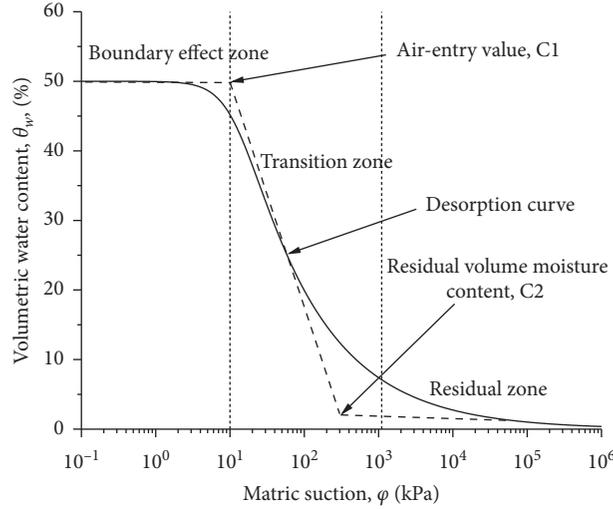


FIGURE 1: A typical soil-water characteristic curve.

TABLE 1: Common soil-water characteristic curve model.

Model	Expression
Van Genuchten [34]	$\theta_w = \theta_r + (\theta_s - \theta_r) / [1 + (a\psi)^n]^m$
Mckee and Bumb [35]	$(\theta_w - \theta_r / \theta_s - \theta_r) = \theta_r + (\theta_s - \theta_r) / (1 + e^{(1 - a)\psi/b})$
Fredlund and Xing [36]	$\theta_w = C(\psi) [\theta_s / \ln[e + (\psi/a)^n]]^m, C(\psi) = [1 - \ln(1 + (\psi/\psi_r))] / \ln(1 + (10^6/\psi_r))$

ψ is the soil suction; θ_w is the volume water content; θ_r is the saturated water content; a , b , n , and m are the fitting parameters.

(F&X) model. Several kinds of the concrete forms of the model are shown in Table 1 along with the parameters, their definitions, and the applicable conditions.

3. Materials and Methods

3.1. Materials. The soil samples used in the tests were taken from Daxing airport in Beijing. The average minimum temperature in this region is -16°C for many years, and the average maximum temperature with a hottest temperature of 7 days is 34°C , which is typical of regions with seasonal frozen soil. The performance-related soil property tests, including the sieve analysis, Atterberg limits, and the Proctor test were performed on the selected materials. The sieve analysis and the Atterberg limit tests were carried out and the result displayed that the soil is defined as the low liquid silt according to Universal Soil Classification System (USCS). Physical properties and grain-size distribution curves of soil samples are shown in Table 2 and Figure 2, respectively.

3.2. Sample Preparation. The selected soil sample was screened using a 2 mm standard sieve, after which the screened soil was baked in an oven at 105°C for 24 h to ensure that the samples were sufficiently dried. In order to obtain a more complete SWCC, based on the optimal water content (13%), 4%, 7%, 10%, 13%, 16%, 19%, and 22% were selected as the test water contents. Simultaneously, in order to reflect the influence of relative compactness on the soil matrix suction, sufficient samples of compactness range

should be set for the test. Therefore, the test samples were prepared in five compactions of 80%, 85%, 90%, 95%, and 100%, respectively. The soil samples were configured according to the designed moisture content. Once the water content in the soil sample reached the balance state, the samples with different relative compactness conditions were prepared by static pressure formation. According to the requirements of ASTM D5298-10 for filter paper type, container volume, and test details, the sample size of 61.8 mm in diameter and 20 mm in height was selected for the soil-water characteristic curve test.

3.3. Testing Methods. The saturated moisture content of the soil can be determined through three steps. In the first step, the soil is made into samples under different compaction conditions. In the second part, the sample is placed inside a vacuum saturation machine for saturation. The third part is to determine the saturated moisture content of the sample after conducting the saturation and moisture content test. In order to ensure that the data obtained by the test are sufficiently accurate, two sets of parallel samples were tested simultaneously, and the obtained data are averaged. The saturated water content of the soil is shown in Table 3 for reference.

According to the climatic data of this region, the annual lowest temperature in Beijing has been $-16.4^\circ\text{C} \sim -18.7^\circ\text{C}$ in the past ten years. Normally, the freezing temperature of the specimen should be lower than the local minimum temperature. Therefore, in this study, the freezing temperature of the specimen was set at -20.0°C to cover the possible

TABLE 2: Physical properties of soil samples in Daxing airport.

Liquid limit (%)	Plastic index (%)	Less than 0.075 mm (%)	Soil particle density (g/cm^3)	Maximum dry density (g/cm^3)	Optimal moisture content (%)	Classification
25.2	17.1	58.39	2.7	1.84	13.0	ML

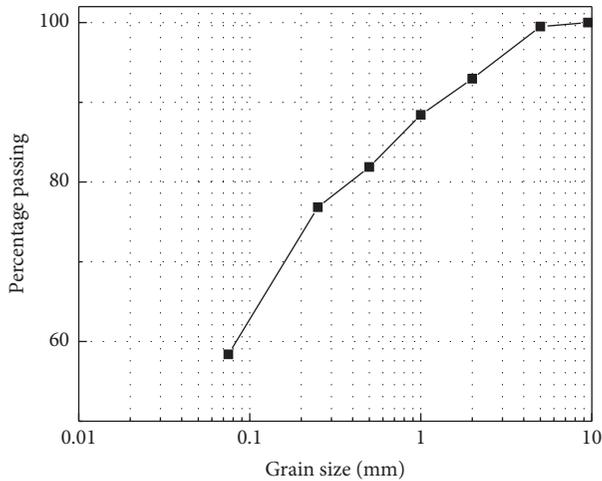


FIGURE 2: Grain-size distribution curves of samples.

TABLE 3: Saturated water content under different degrees of compaction.

Degree of compaction (%)	Saturated water content (%)
100	23.04
95	24.50
90	26.97
85	29.46
80	30.92

range of low temperature changes. The freezing time of each freeze-thaw was set at 12h. In order to ensure that the frozen specimen can completely melt in each freeze-thaw cycle, according to the principle of energy conservation, the positive temperature when the specimen is melted is set to 20°C, and the melting time is set to 12h. After comprehensive consideration of the three factors, the complete test plan is shown in Table 4.

The temperature alternating test machine provides temperature environment for the freeze-thaw cycle test. The device is composed by the ambient temperature bin and the intelligent control panel, in which the temperature range of the ambient temperature bin can be set to $-65^{\circ}\text{C}\sim 150^{\circ}\text{C}$, which means it covers all the temperature range of frozen region. Meanwhile, the panel can set the number of freeze-thaw cycles, freezing duration, and melting duration. This machine can execute the setting procedure by itself and can set the maximum freeze-thaw cycle to 100 times. The machine is shown in Figure 3(a).

For samples that need to be frozen, these were separately sealed after the formation of the static pressure and then placed inside the aluminium box. The outside part of the aluminium box was sealed to ensure that the water in the cutting ring sample does not drain during the freeze-

thaw cycle. When the sample was placed in the temperature alternating test machine, the total length of a freeze-thaw cycle was 24 h (12 h freezing time and 12 h melting time). The automatic control program can control the number of freeze-thaw cycles. Whenever the specimen reached the set number, we took out this part of the specimen and continued the test on the remaining specimens. The specimen after the freeze-thaw cycles is shown in Figure 3(b).

At present, the methods of SWCC mainly include the pressure plate, the filter paper, and the saturated solution methods. From the measurement range of the matrix suction, the SWCCs measured by the pressure plate, filter paper, and saturated salt solution methods had suctions ranging from 0 to 0.4 MPa, 0 to 40 MPa, and 3 to 367 MPa, respectively. In terms of test time, the pressure plate, filter paper, and saturated salt solution methods took about 10–15 days, 10–15 days, and 2–3 months to obtain SWCCs, respectively. The pressure plate apparatus may not be suitable for the test, which required processing a large number of test samples. Considering the large range of matrix suction that can be measured by the filter paper method, such a method is appropriate for this kind of testing, which evaluates a considerable number of samples. Moreover, it is low-cost and highly accurate. Thus, the filter paper method is chosen as the test method of the research content in this research.

The type of filter paper is determined as the common Whatman's No. 42. The finished specimens were divided into two groups for testing: the control group and the test group. The numbers of freeze-thaw cycles in the test group were determined as 1, 3, 6, 9, and 10, respectively. In contrast, the control group was the sample with 0 freeze-thaw cycles. The samples of the control group were sealed after adding the filter paper and then placed at 25°C for 14 days to ensure that the moisture of the soil samples reached a balanced state. After the freeze-thaw cycle is completed, we placed three layers of the filter paper in the middle of the two prepared soil samples and allowed them to make full contact with the soil samples. Next, we measured the matrix suction of the soil samples through the middle filter paper. The outer two pieces were used to protect the middle filter paper from being absorbed and polluted by the soil samples and to ensure the accuracy of the measurement. The test pieces to be tested were placed inside the moisture cylinder for 7 days, and the moisture content of the filter paper was tested after 7 days. Then, the matrix suction was calculated, as shown in the following equation:

$$\begin{cases} \lg \psi = 4.945 - 0.0673w, & (w < 47\%), \\ \lg \psi = 2.909 - 0.0229w, & (w \geq 47\%). \end{cases} \quad (3)$$

TABLE 4: Freeze-thaw cycle test plan.

Total sample	Factor A, number of freeze-thaw cycles	Factor B, degree of compaction (%)	Factor C, moisture (%)
175	0, 1, 3, 6, 10	80, 85, 90, 95, 100	4, 7, 10, 13, 16, 19, 22



FIGURE 3: Temperature alternating test system: (a) testing machine; (b) specimens that suffered freeze-thaw cycles.

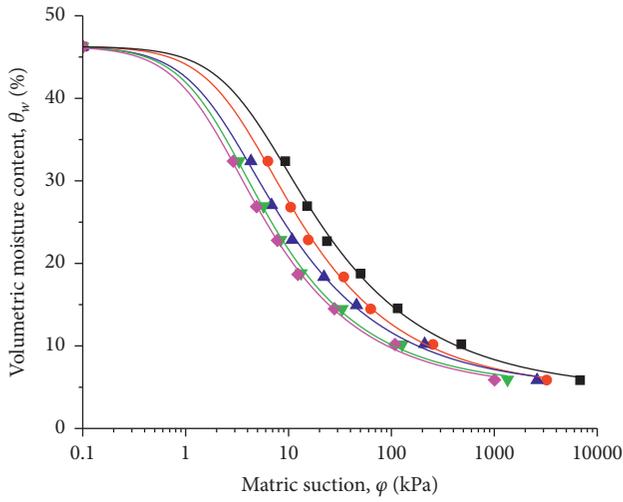
4. Results and Discussion

4.1. Effect of Freeze-Thaw Action on SWCC. Many previous researches have been proved that the freeze-thaw cycle has a great impact on the mechanical properties of subgrade, and this process is also an unfavorable factor that must be considered in the design of subgrade and pavement in cold regions. In order to explore the effect of freeze-thaw cycles on the SWCC of soil samples, five samples with compaction conditions were analyzed. Among them, SWCCs under 0, 1, 3, 6, and 10 freeze-thaw cycles under each compaction condition were used for comparison.

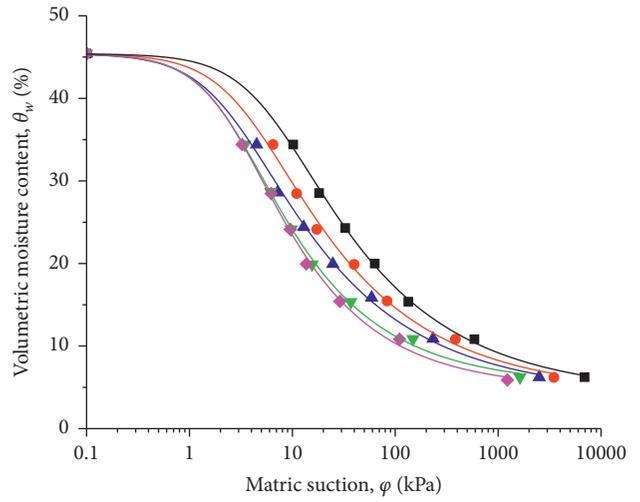
The result is shown in Figure 4 that under different compaction conditions and freezing times, the water-holding capacity of the soil has a significant effect. With the same volume of water content, the greater the number of freeze-thaw cycles, the smaller the matrix suction of the soil. This reflects a phenomenon that the freeze-thaw cycle improves the water-holding capacity of the soil. With the same water content, the matric suction of the test soil decreases with the increase of the number of freezing-thawing cycles, and the variation range of matric suction decreases with the increase of the number of freezing-thawing cycles and finally tends to be stable. In particular, the value of matric suction decreases by about 50% during the initial freezing-thawing cycle. At the same time, after repeated freezing-thawing, the boundary effect area and transition area of the soil-water characteristic curve

became smaller, while the scope of the residual area became larger, and the numerical starting point of matric suction decreased from about 1000 kPa to several hundred kPa. In addition, under repeated freezing and thawing, the intake pressure value and residual moisture content of the soil samples with the same compaction degree continue to decrease, and the air intake value of the high-pressure compaction sample even drops from several hundred kPa to tens of kPa, which is an order of magnitude. And the drop in residual moisture content is within 10%.

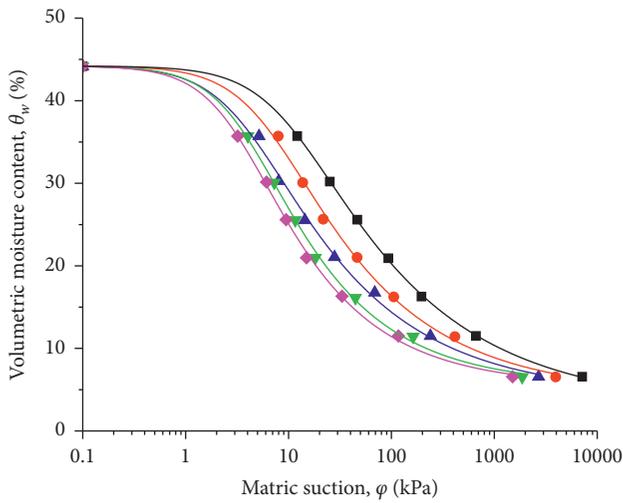
4.2. Effect of Compaction on SWCC. The degree of compaction is a key indicator for controlling the quality of subgrade filling and characterizes the compaction state and physical and mechanical properties of the filler after compaction. It may sometimes deviate from the design standard due to various factors during construction and post-operations. Therefore, the degree of compaction is a common variable in the process of freezing and thawing subgrades, and its impact on the freezing and thawing cycle effects of soil is also a matter of concern. The degree of compaction and the number of freeze-thaw cycles should be regarded as two independent variables. The four compaction degrees of 80%, 85%, 90%, 95%, and 100% were used as variables to analyze the effects of different degrees of compaction on SWCC under different freeze-thaw cycles. The relevant results are shown in Figure 5.



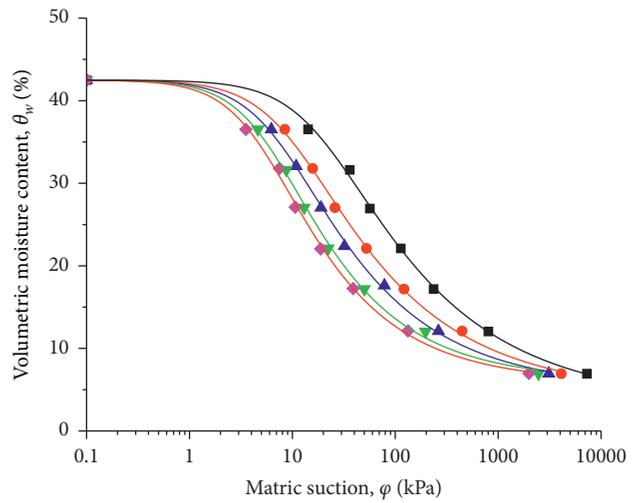
(a)



(b)



(c)



(d)

FIGURE 4: Continued.

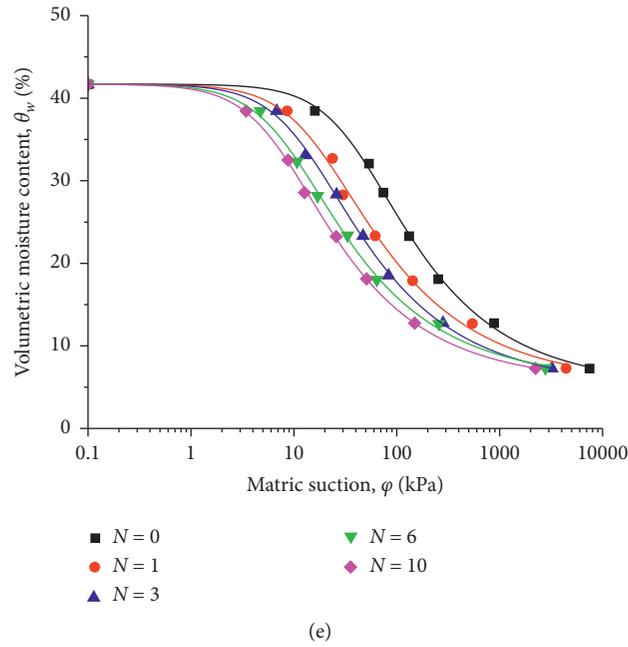


FIGURE 4: The relationship between ψ and θ_w under different compaction degrees: (a) 80%; (b) 85%; (c) 90%; (d) 95%; (e) 100%.

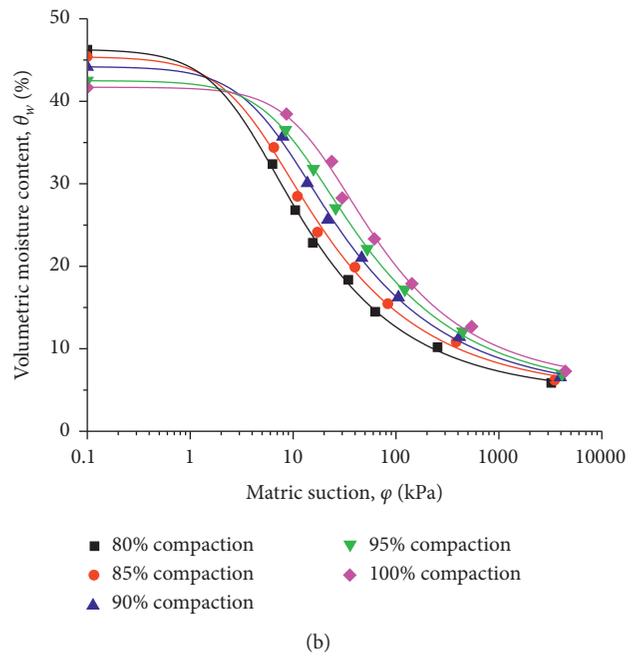
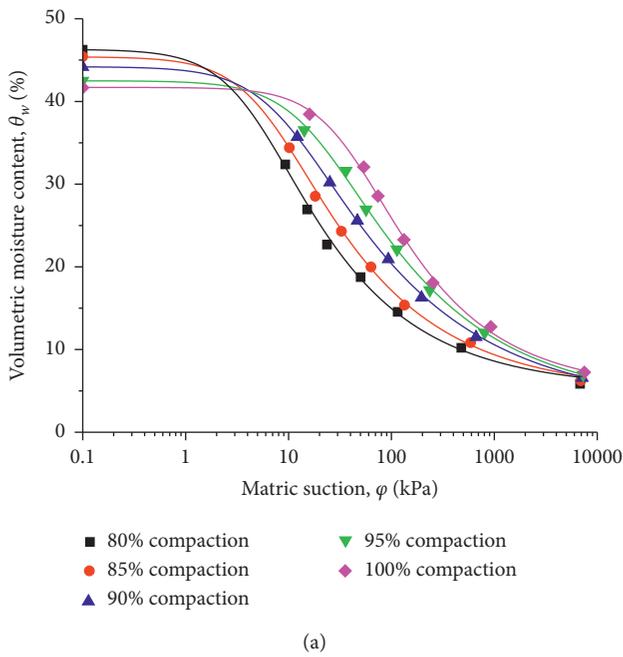


FIGURE 5: Continued.

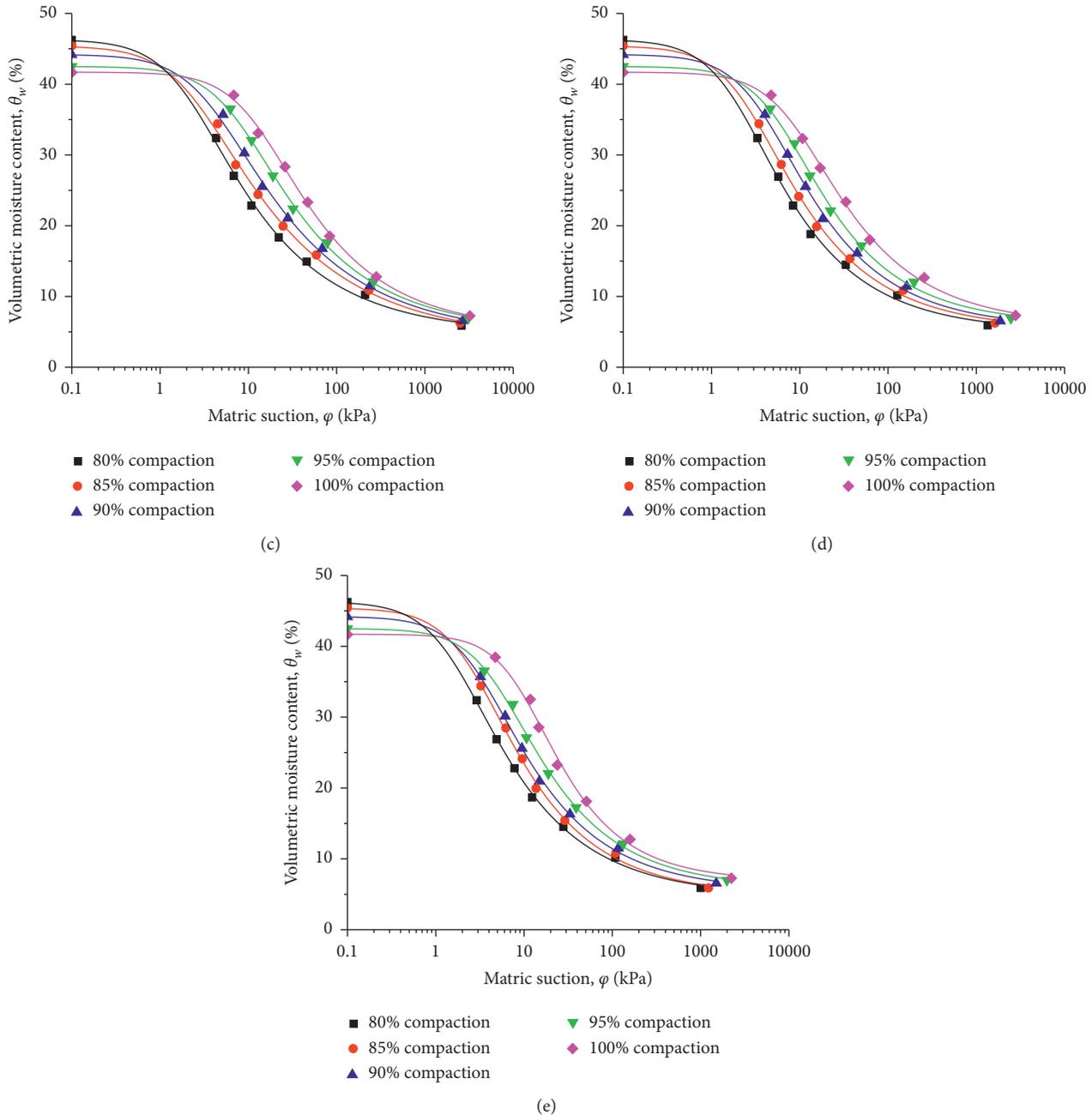


FIGURE 5: The relationship between ψ and θ_w under different freezing and thawing cycles: (a) 0 cycles; (b) 1 cycles; (c) 3 cycles; (d) 6 cycles; (e) 10 cycles.

Notably, the low degree of compaction SWCC is located under the high degree of compaction SWCC. Simultaneously, this phenomenon is reflected in every freeze-thaw cycle condition, indicating that the degree of compaction changes the density of the soil and that such a change can become an independent variable to change the matrix suction of the soil. At the same time, it is also noticed that the inlet pressure of soil samples with the same number of freeze-thaw cycles decreases with the decrease of compaction, and the decrease range is within 10 kPa. For the same volume of water content, the higher the degree of compaction, the greater the matrix suction,

thereby indicating that the degree of compaction can improve the hydrophilic capacity of the soil. In other words, the greater the degree of compaction, the denser the soil, the smaller the pores between the particles, and the greater the water absorption capacity of the soil.

4.3. *Predicting Models and Discussion.* In general, the choice of the model to describe the SWCC depends on multiple factors, the basic properties of the material, the physical state, the complexity of the model expression, and so on. Obviously, the expression of the V-G model is much

TABLE 5: Results of soil-water characteristic curve models for the experimental data.

Compaction (%)	Cycles	Fitting parameters			R^2
		a	m	n	
80	0	4.5712	4.20142	1.43921	0.99827
	1	4.582	3.18942	1.47668	0.99881
	3	4.78188	2.06556	1.46411	0.99852
	6	5.08542	1.87439	1.52775	0.99875
	10	4.72054	1.61743	1.51167	0.99926
85	0	4.1733	6.18363	1.41428	0.99934
	1	4.302	3.71573	1.41838	0.99723
	3	4.12408	2.54878	1.41191	0.99806
	6	5.28803	2.50454	1.51857	0.99885
	10	4.83545	2.5964	1.54692	0.99853
90	0	2.8785	9.92239	1.37029	0.99987
	1	4.46301	6.18273	1.43168	0.99824
	3	4.29728	3.78323	1.41879	0.99741
	6	5.53637	3.75511	1.53103	0.99869
	10	5.46588	3.14734	1.54047	0.99909
95	0	3.26176	19.04207	1.4008	0.99878
	1	4.38445	9.52057	1.42939	0.99922
	3	5.03771	7.34694	1.47461	0.99904
	6	6.10299	5.86249	1.55485	0.99837
	10	5.88419	4.93641	1.55873	0.9984
100	0	5.14721	39.64917	1.53008	0.99873
	1	5.36124	16.46128	1.48824	0.99599
	3	5.10752	12.55566	1.50705	0.99869
	6	5.74374	8.58724	1.51118	0.99861
	10	5.56827	7.03759	1.52734	0.99955

simpler than the F&X model. If a simple model processes the data and obtains ideal results, then this model with a simpler expression is easier to be accepted by the majority of practitioners in the design and construction process. This is an important consideration in the model selection process.

There is no doubt that all the data must be characterized by a model, i.e., the SWCC model described in the second chapter. Simply, the V-G model and the F&X model have their own advantages, but the V-G model expression is relatively simpler and its use is relatively wider; it can also be applied to the SWCC expression of various soils. Therefore, the V-G model was used to fit the above experimental data. The fitting curves are shown in Figures 4 and 5. Meanwhile, the parameters obtained by using the V-G model are presented in Table 5 for reference.

Basically, the effect of the freeze-thaw process on the SWCC should be explained from the basic theory of matric suction. For the unsaturated subgrade fillers, the Young-Laplace equation of their internal capillaries can be expressed as equations (4) and (5), respectively.

$$U_a - U_w = \frac{2T_s}{R_s}, \quad (4)$$

$$\psi = \frac{2T_s}{R_s}, \quad (5)$$

where T_s is the surface tension of the water-air interface, which is generally considered unchanged, and R_s is the effective radius of the intergranular pores.

As can be seen, when the value of T_s is unchanged, the matrix suction of the soil mainly depends on the effective radius of the intergranular pores. This means that, regardless of the change in compaction or the effect of freezing and thawing on the soil, the main indicator of change in the soil is R_s . In other words, the increase in the degree of compaction tightens the bond between the particles inside the specimen. In turn, this reduces the effective radius of the pores between the particles; thus, the matrix suction under the same state increases as the degree of compaction increases.

Meanwhile, the water in the pores between the particles will freeze into ice when the temperature reaches below 0°C . This process will cause the volume of ice to be greater than the volume of the original water, with an increase of about 9%. The growth of pore ice is constrained by the surrounding particles and produces frost heave force. When such a force exceeds a certain limit, it will destroy the coupling effect between the particles, push the particles, and change the pore shape. When the pore ice is at a positive temperature, when melted, the pushed particles cannot be completely reset. Therefore, a complete freeze-thaw process consisting of freezing and thawing will broaden the effective radius of the pores between the particles, lead to the decay in the matrix suction, and decrease the material's water-holding capacity. Furthermore, as the number of repeated freeze-thaw cycles increases, this can lead to the following phenomena: the pores between the particles are gradually expanded, the effect of the development of

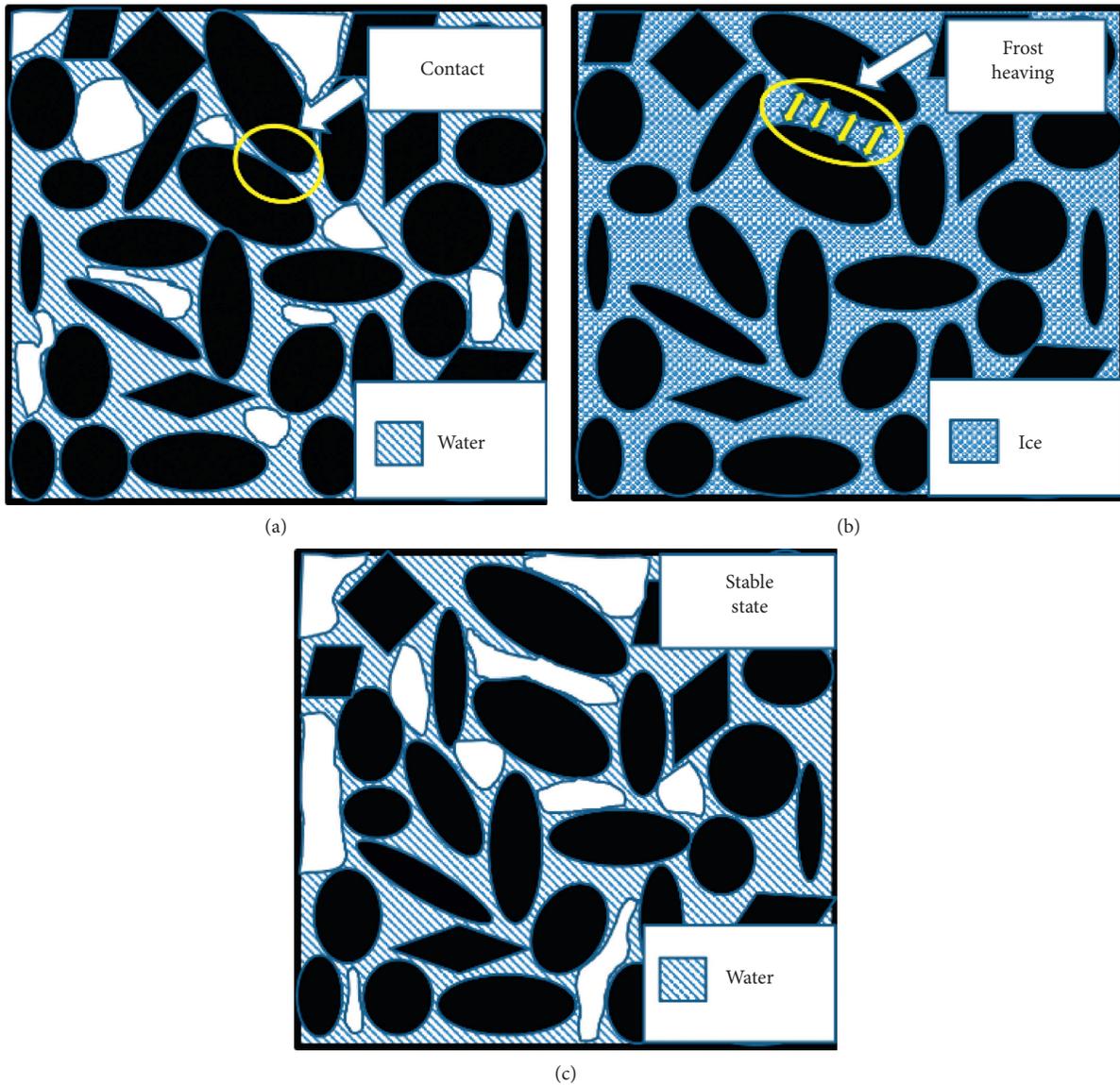


FIGURE 6: Microstructure of soil particles under freezing-thawing cycles.

pore ice on the particles gradually weakens until the pores between the particles are increased to sufficiently accommodate the volume expansion of water due to phase change, the effective radius of the pores will no longer expand, and, finally, the attenuation of the matrix suction stops.

Graphically, the entire freeze-thaw cycle can be roughly divided into three processes: a, b, and c. In the process a, the whole soil sample has not been frozen, which is equivalent to the state of $N=0$. At this time, the particles are in close contact, as shown in Figure 6(a).

When the freezing starts, the frost heaving effect occurs. As the water changes to ice, the contact between particles gradually decreases and is replaced by ice. At this time, the contact between many soil particles changes from “soil-soil” to “soil-ice,” and many soil particles are lifted, as shown in Figure 6(b).

After being subjected to multiple freeze-thaw cycles, the pores in the soil approach a stable state. Compared with the $N=0$ state, the pores in the soil are larger in this state. In fact, at this time, no matter how many times the freezing and thawing process occurs, the pores in the soil will no longer increase. This state is close to the case of $N > 6$ in the test, which is shown in Figure 6(c).

5. Conclusion

In this paper, the freezing-thawing cycle of low liquid limit silty soil in the seasonal frozen area is studied. The purpose is to reveal the change rule of water-holding performance of low liquid limit silty soil under freezing-thawing cycle and describe the change rule by SWCC. At the same time, after discussing several typical SWCC models, the V-G model is adopted to obtain a set of high-precision parameters for the design and construction of cold areas:

- (1) SWCC plays an important role in unsaturated soils. This curve is affected by factors such as the type of soil and the physical state of the soil, and the SWCC forms of unsaturated soils vary. For the soil in seasonally frozen areas subject to freeze-thaw effects, the freeze-thaw effects will also have a significant impact on SWCC. This study has some guiding significance for the design, construction, and maintenance of roads in the regions with widely distributed seasonal permafrost.
- (2) Both freezing-thawing cycle and compacting degree affect SWCC of soil in seasonal frozen area. With the same volume water content and the same compactness, the matric suction of the test soil decreases with the increase of freeze-thaw cycles. For the same number of freeze-thaw cycles, the greater the compactness, the greater the matric suction. Meanwhile, the V-G model can very appropriately describe the SWCC of the low liquid limit silt in the process of the freezing and thawing cycles. At the same time, the V-G model can be applied for the matrix suction of the soil on the seasonal frozen area and then can provide reference for the seasonal frozen area road design.
- (3) Effective radius between particles is a key index to determine soil matric suction. The freezing-thawing cycle essentially changes the effective radius between the particles in the soil particles through the freezing-thawing effect of the water in the soil, resulting in the change of matric suction. When the freezing-thawing cycle is repeated enough, the effective radius between the particles will not change, and the state between the particles tends to be stable.

Data Availability

The testing data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

Yongsheng Yao conceptualized the study, prepared the methodology, administered the project, and was responsible for funding acquisition; Junfeng Qian and Shenping Luo were involved in data curation and wrote the original manuscript; Junfeng Qian performed formal analysis; Shenping Luo investigated and validated the study; Hongbin Xiao collected the resources; Jue Li visualized the study and arranged the software; Yongsheng Yao and Hongbin Xiao supervised the study; Junfeng Qian and Yongsheng Yao reviewed and edited the draft.

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