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Abstract

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Keywords

expansive soil, water retention capacity, temperature effect, microscopic mechanism, filter paper method

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Temperature effect on water retention capacity of Nanning expansive soil and its microscopic mechanism

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Abstract: To explore the variation of water retention capacity of expansive soil at different temperatures, the calibration curves of Whatman No.42 filter paper were measured by vapor equilibrium method at 5, 25, 40 ℃ and 60 ℃, and the bilinear calibration equation considering temperature effect was established. The results show that the water retention capacity of the filter paper decreases with the increase of temperature, and the effect on the high suction section of calibration curve is weaker than the low suction section. On this basis, Nanning expansive soil is taken as the research object, and the soil-water characteristic curves of Nanning expansive soil at different temperatures are measured by filter paper method. It is found that the water retention capacity of Nanning expansive soil decreases with the increase of temperature, but the influence of temperature depends on matric suction, especially when it is above 40 MPa, the water-retention capacity of Nanning expansive soil remains unchanged with temperatures. To probe into the microscopic mechanism of the change of water retention capacity of Nanning expansive soil under temperature, some samples were selected for mercury intrusion porosimetry test and bound water adsorption test. Based on the test results, the microscopic mechanism of water retention capacity change of Nanning expansive soil was analyzed from the physical mechanism of the interaction between each phase and each phase interface.

Keywords: expansive soil; water retention capacity; temperature effect; microscopic mechanism; filter paper method

1 Introduction

Expansive soil, a typical dilative-contractile soil, is widely distributed in more than 20 provinces in China[1]. The poor engineering properties brought by its “three characteristics” (swelling-shrinking, fissure, and overconsolidation) have caused serious harm to the infrastructure construction. Therefore, its engineering property has always been one of the important topics in geotechnical engineering.

The nature expansive soil usually exists in an unsaturated state. For unsaturated soil, the properties between the surfaces of soil particles are extremely complex due to the presence of soil suction, the interaction of particle–particle, particle–water transforms into that of particle–particle, particle–water, particle–gas and water–gas, which make it difficult to comprehensively grasp the mechanical property, permeability, and particle surface characteristic of unsaturated soil. Therefore, some scholars conducted many experiments related to suction. For instance, Wu et al.[2] conducted undrained shear tests on unsaturated expansive soil after dry-wet cycles, and measured the matric suction on the fixed shear plane of the sample after shear test using the filter paper method. They found that the shear strength of the soil increased nonlinearly with the matric suction, and the growth rate decreased gradually. Zhan et al.[3] conducted unsaturated direct shear test on Zaoyang expansive soil, and the results showed that suction contributed significantly to the increase of shear strength of expansive soil, which is mainly because shear expansion potential and effective stress between soil particles increase with suction. Miao et al.[4] conducted triaxial shear tests on Guangxi expansive soil by controlling suction, and found that the shear strength of unsaturated remolded expansive soil increased with suction, and the shear strength had a clear hyperbola relationship with suction. Cui et al.[5] found that the permeability coefficient of unsaturated expansive soil increased with saturation degree, and attributed this result to the influence of matric suction. The above research reveals that the suction has an undeniable impact on the mechanical and permeability properties of the expansive soil, and the suction reflects the water retention capacity of soil macroscopically.

Recent years have witnessed a rapid development of engineering construction in China, the emergence of emerging fields, such as underground nuclear waste disposal, ground source heat pump, utility tunnel, and natural gas exploitation, has changed the soil temperature field near engineering sites significantly[6], which inevitably affects the evolution of the geological environment greatly. The original water migration mode changes under the temperature effect, the water content varies and the suction is affected, resulting in the change of the soil engineering properties, and

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triggering off engineering geological disasters[7]. Expansive soil is characterized by high clay content and large specific surface area, in addition, its mineral compositions include clay minerals with strong hydrophilicity, such as montmorillonite and illite, therefore it is more sensitive to water compared with other clayed soils, and the soil suction caused by temperature changes more significantly. As expansive soil is mainly distributed in Southwest China, it often induces engineering disasters in the environment with frequent alternation of moisture and heat, such as building deformation, slope instability, road cracking and uplift. Statistics data in terms of Guangxi region China show that expansive soil has damaged millions of square meters of buildings, resulting in direct economic losses of hundreds of millions of RMB for the constructed roads, railways, and other transportation facilities. Then it becomes one of the main geological disasters in Guangxi, and has affected the construction of many infrastructures and the improvement of the ecological environment. In addition, most scholars attributed the micro mechanism of water retention capacity to the bubbles[8], which has certain limitations, resulting in a lack of consistent and systematic understanding of the temperature effect on the water retention capacity of expansive soil. Therefore, it is necessary to investigate the temperature effect on the water retention capacity of expansive soil and its micro mechanism. This is an important part for analyzing the engineering properties of expansive soil caused by temperature changes, and has very an important engineering and theoretical value for preventing the geological disasters caused by "heat" in expansive soil regions.

The calibration curves of Whatman No.42 filter paper were measured by the vapor equilibrium method at four different temperatures (5, 25, 40, and 60 ℃), the calibration equations of the filter paper were obtained at different temperatures, and the soil water characteristic curves of Nanning expansive soil were measured at different temperatures, then the variation of water retention capacity of Nanning expansive soil was explored under the temperature effect. On this basis, the temperature effect and micro mechanism of the water retention capacity of Nanning expansive soil were explained from the physical mechanism of the interaction between each phase and each phase interface using mercury intrusion porosimetry test and bound water adsorption test.

Table 1 Physical parameters and mineral compositions of Nanning expansive soil

Water content ω /%	Density ρ /(g • cm^{-3})	Specific gravity G_s	Plastic limit ω_p /%	Liquid limit ω_L /%	Free swelling ratio δ_{ef} /%	Optimum water content ω_{opt} /%	Mineral compositions and contents /%			
							Montmorillonite	Illite	Kaolinite	Chlorite
32.2	1.93	2.76	31.4	66.0	68.9	28.1	27.5	41.5	17.5	13.5

2 Materials and methods

2.1 Materials

The used soil was collected from a site near Shuiniusuo, Nanning city, Guangxi Province, at a depth of about 2.5 m, where the medium thick mudstone layer with the colour of gray-white, gray-brown and the interbedded mudstone with siltstone are distributed. The soil has high liquid limit and strong viscosity, whose main minerals are montmorillonite and illite, and the associated minerals are kaolinite and chlorite. It is classified as a typical medium expansive soil. Table 1 presents its basic physical properties and mineral compositions.

The used filter paper is Whatman No.42, with a diameter of 55 mm, a pore size of 2.5 μm, and ash content ≤0.007%.

2.2 Methods

2.2.1 Filter paper calibration test

The filter paper method is an indirect method for measuring soil suction, and it is characterized by low cost, simple operation, short equilibrium time, and large suction measurement range. Therefore, this method is used for determining the matric suction of expansive soil. The prerequisite for this method is to obtain the calibration curve of Whatman No.42 filter paper at the corresponding temperature. Consequently, the vapour equilibrium method was first used to determine the calibration curves of Whatman No.42 filter paper at different temperatures (5, 25, 40, 60 ℃), The used suction values of the salt solution[9–11] are listed in Table 2, and the specific experimental steps can be found in Reference[12].

Table 2 The suction of salt solutions at different temperatures

Saline solution	Suction /kPa			
	5 ℃	25 ℃	40 ℃	60 ℃
0.002 mol/L NaCl	9.08	9.76	10.24	10.89
0.01 mol/L NaCl	44.81	47.99	50.37	53.52
0.05 mol/L NaCl	218.35	233.90	245.38	260.49
0.10 mol/L NaCl	431.22	462.32	485.06	514.79
0.20 mol/L NaCl	852.74	916.08	961.72	1 020.78
0.30 mol/L NaCl	1 272.82	1 370.19	1 439.53	1 528.53
0.40 mol/L NaCl	1 693.36	1 826.58	1 920.50	2 040.19
0.50 mol/L NaCl	2 115.34	2 286.15	2 405.52	2 556.66
0.06 mol/L NaCl	2 539.38	2 749.42	2 895.09	3 078.50
1.00 mol/L NaCl	4 265.64	4 646.92	4 905.55	5 225.28
1.50 mol/L NaCl	6 517.03	7 137.79	7 551.88	8 053.47
2.00 mol/L NaCl	8 903.06	9 782.49	10 363.49	11 063.26
2.50 mol/L NaCl	11 447.74	12 597.60	13 352.71	14 254.96
3.00 mol/L NaCl	14 168.69	15 594.55	16 527.53	17 635.11
Saturated KCl	16 862.69	23 684.00	28 176.92	33 762.28
Saturated NaCl	35 767.62	39 069.08	42 191.83	45 505.75
Saturated KI	39 906.91	51 301.69	59 883.68	70 855.89
Saturated NaBr	58 346.36	75 971.52	91 287.84	107 590.49
Saturated $MgCl_2 \cdot 6H_2O$	140 125.24	153 519.41	166 634.17	188 905.58
Saturated $LiCl \cdot H_2O$	262 126.22	300 274.70	316 667.34	339 664.75
Saturated LiBr	334 520.39	378 567.73	411 852.54	452 029.22

2.2.2 Water retention capacity test of expansive soil

In order to explore the temperature effect on the water retention capacity of Nanning expansive soil, four temperatures (5, 25, 40, and 60 ℃) and ten initial

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water contents (3%, 6%, 9%, 12%, 15%, 18%, 21%, 24%, 27%, and 30%) were set to match the different matric suction values of expansive soil samples. The samples preparation process is as follows:

(1) The soil was dried, grinded, and sieved with a 2mm sieve, then it was dried in an oven at 105 ℃ for 24 hours.

(2) The dried soil was cooled to room temperature, and mixed with water to the target water content, then it was sealed for 72 h to ensure the water to distribute uniformly.

(3) A certain mass of soil was weighed according to the target dry density $\rho_d = 1.5$ g/cm^3 (reference natural dry density $\rho_d = 1.46$ g/cm^3), and then it was loaded in the mold to obtain the soil samples ($d = 61.8$ mm, $h = 20$ mm) by the static pressure method.

(4) Three filter papers was placed between the two samples (with test filter paper in the middle and protective filter paper in the top and bottom), and PVC electrical tape was used to seal between the cutting ring to ensure full contact between the filter paper and the soil sample for suction balance. Meanwhile, the above samples were sealed and placed in the buckle box with plastic film for preventing the water evaporation in the soil sample, as shown in Fig. 1.

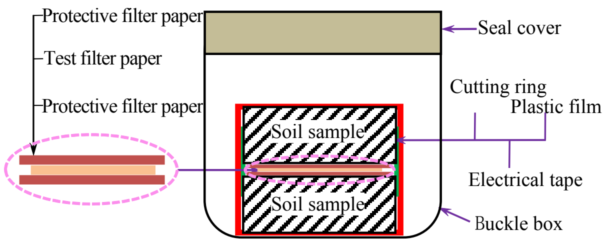

Fig. 1 Sketch of filter paper method

(5) The above prepared samples (at the same temperature) were placed in the constant temperature and humidity box, then they were cured at the corresponding temperature for 10 days.

(6) The buckle boxes were taken out after the sample curing, and the water contents of the test filter paper and soil sample were measured quickly. The matric suction was calculated by the known filter paper calibration equation, then soil water characteristic curve of Nanning expansive soil was attained at different temperatures.

It is worth noting that the volume and water content of the soil sample do not change significantly in the constant temperature curing process due to the lateral constraint of the cutting ring and the sealing effect of the plastic film. Then this process can be regarded as constant volume and water content state. It can be confirmed by comparing the measured size and water content of some samples ($\omega_0 = 24\%$) before and after curing (see Table 3).

Table 3 Measured data of some expansive soil samples before and after curing

Temperature T /℃	Before curing			After curing		
	Diameter d /cm	Height h /cm	Water content ω /%	Diameter d /cm	Height h /cm	Water content ω /%
5	6.180	2.000	24.00	6.180	1.998	23.94
25	6.180	2.000	24.00	6.180	1.999	23.98
40	6.180	2.000	24.00	6.180	2.001	23.96
60	6.180	2.000	24.00	6.180	1.999	23.96

2.2.3 Mercury intrusion porosimetry test

Research reported that the water retention capacity of soil is closely related to its pore structure characteristics[13–14], the pore structure characteristics can explain the temperature effect of the water retention capacity of compacted expansive soil. Therefore, four representative cutting ring samples were selected (with an initial dry density $\rho_d = 1.5$ g/cm^3 and an initial water content $\omega_0 = 27\%$, referring the optimal water content $\omega_{opt} = 28.1\%$) to conduct mercury intrusion porosimetry tests at different temperatures, and the variation of water retention capacity was analyzed from the perspective of soil microstructure.

The employed setup was AutoPore 9600/9510 high-performance mercury intrusion porosimeter, produced by Micromeritics in United States. The maximum pressure is 400 MPa, and the measurement range of pore size is from 0.003 to 950 μm. The measurement process is as follows:

(1) A soil cube with the size of 1.5 cm×1.5 cm×1.5 cm was cut from the cutting ring sample after the water retention capacity test, and it was frozen for 15 minutes by liquid nitrogen (boiling point –196 ℃), then the liquid water in soil became the non-expansive amorphous ice.

(2) The soil cube was evacuated by freeze dryer at –50 ℃ for more than 24 hours, then the amorphous ice sublimated to ensure the same pore structure.

(3) Mercury was injected into the soil pores under different pressures by mercury intrusion porosimeter at room temperature, and the amount of injected mercury at each pressure increment was recorded. The pressure was converted into the pore radius using the Washburn[15] equation to obtain the pore distribution of the soil.

2.2.4 Bound water adsorption test

The bound water has a significant impact on the bonding characteristics and engineering properties of cohesive soil, and the bound water content direct reflects the soil water retention capacity. Therefore, volumetric flask method was used to measure the water adsorption amount of expansive soil at different temperatures, and the microscopic mechanism of the temperature effect of water retention capacity was explained from this perspective.

This method principle is that the clay particles are highly dispersed and can adsorb water adequately after the dried soil was soaked in water, the liquid free water changes into semi solid bound water, its density increases while its volume decreases, resulting in a change in water volume. Considering that the volumetric flask method has a low precision and a large error, our research team proposed a method to correct the volumetric flask method[16]. And the bound water content of Nanning expansive was determined at different temperatures (5, 25, 40, 60 oC) according to the steps in Reference [16].

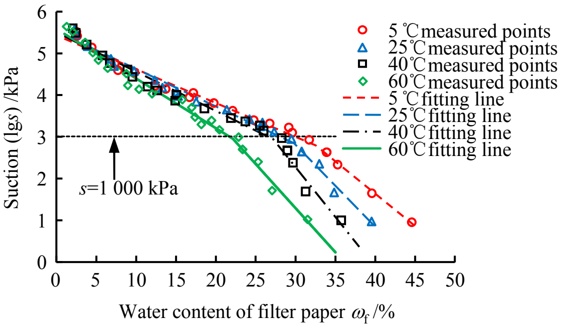

Fig. 2 Calibration curves of Whatman No. 42 filter paper at different temperatures

3 Results and analysis

3.1 Filter paper calibration curve and equation

Figure 2 presents the calibration curves of Whatman No.42 filter paper at four different temperatures. Since the suction of the filter paper has a large range (0–10^6 kPa), it was denoted by logarithmic form ($\lg s$) for convenience.

Figure 2 indicates that the suction $\lg s$ of filter paper decreases with the increase of its water content ω_f at different temperatures, that is, the suction of filter paper has negative correlation with its water content. While its change rate varies with the decrease of suction. The slopes of the filter paper calibration curve show that the inflection point is near $s = 1\ 000$ kPa (i.e. $\lg s = 3$): The slope of upper section of curve ($s \geqslant 1\ 000$ kPa) is greater than that of lower section ($s < 1\ 000$ kPa). The main reason is that the water retention mechanism of filter paper varies with water content, the lower section represents the higher water content, and the water retention mainly relies on the capillary force. While the upper section represents the low water content, and the water retention mainly relies on the bound water film in the filter paper[17–19]. Therefore, the inflection point ($s = 1\ 000$ kPa) is induced by the change of water retention mechanism of the filter paper. In order to better reflect this characteristic of filter paper, the inflection point ($s = 1\ 000$ kPa) was taken as the threshold value, and the curves in Fig. 2 were divided into upper and lower sections for linear fitting. The fitted equations of the filter paper's calibration curves at different temperatures are listed in Table 4.

Table 4 indicates that the calibration curve equation of Whatman No.42 filter paper well fits the experiment linearly (all R^2 are above 0.93), In addition, the calibration curves selected by scholars[20–23] come from Leong et al.[24], and their inflection values are also around 1 000 kPa, which verifies the correctness of this results.

Table 4 Fitted equations of filter paper's calibration curve

Temperature T /℃	Fitted equations of the filter paper's calibration curves	Water content of the filter paper ω_f /%	R^2
5	$\lg s = 5.432 - 0.0810\ \omega_f$	<32.54	0.974 5
	$\lg s = 7.843 - 0.1551\ \omega_f$	⩾32.54	0.995 8
25	$\lg s = 5.524 - 0.0898\ \omega_f$	<29.82	0.980 7
	$\lg s = 8.724 - 0.1971\ \omega_f$	⩾29.82	0.967 8
40	$\lg s = 5.501 - 0.0941\ \omega_f$	<27.19	0.969 0
	$\lg s = 9.427 - 0.2385\ \omega_f$	⩾27.19	0.933 8
60	$\lg s = 5.584 - 0.1189\ \omega_f$	<22.13	0.970 7
	$\lg s = 7.633 - 0.2115\ \omega_f$	⩾22.13	0.967 1

Figure 2 also shows that the water content of the filter paper decreases with the increases of temperature in constant suction condition, indicating that the water retention capacity of the filter paper reduces with the increase of temperature. Additionally, the difference between the calibration curves of the filter paper gradually increases with the decrease of suction, that is, the temperature effect on water retention capacity of the filter paper gradually increases, indicating that its degree mainly depends on the suction. One can see from Fig.2 that the difference between the lower sections of the curves is greater than that in upper sections, which is due to the fact that the capillary force is reduced by heating, and the bound water film becomes thinner, while the capillary force is more sensitive to temperature than the bound water film. Therefore, the difference between the lower sections of the curves is greater than that between the upper sections, and the water retention capacity of the filter paper is weakened more at this time.

3.2 Temperature effect on water retention capacity of expansive soil

The soil water characteristic curves of Nanning expansive soil at four different temperatures are shown in Fig.3. It can be seen that the volumetric water content θ decreases with the increase of matric suction s at the same temperature condition. For example, the soil sample with a matric suction of 14 kPa has a volumetric water content of 49.83% at 25 ℃. The water is drained continuously and the slope of the curve decreases with the increase of matric suction. When the matric suction reaches 101 989 kPa, the corresponding volumetric water content is only 6.04%.

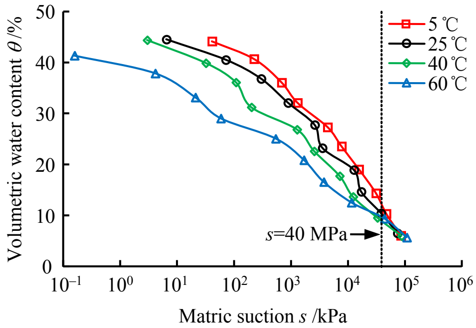

Fig. 3 SWCCs of Nanning expansive soil at different temperatures (ρ_d = 1.5 g/cm³)

Additionally, the volumetric water content of the sample decreases with the increase of temperature at constant matric suction condition, that is, the soil water characteristic curve shifts to the lower left.

In order to deeply analyze the temperature effect on the water retention capacity of Nanning expansive soil, 6 matric suction values were selected, and their volumetric water contents with temperature are showed in Fig. 4. It can be found that the volumetric water content decreases linearly with the increase of temperature at the same matric suction condition, indicating that the water retention capacity of expansive soil decreases linearly with the increase of temperature. Further analysis reveals that the decreasing trend of the volumetric water content slows down slightly when the temperature exceeds a certain value (40 ℃), and this phenomenon is only obvious in high suction section (7.71, 15.65, 31.05 MPa), while is inapparent in the low suction section (0.23, 0.69, 1.30 MPa). Similar conclusions can be found in the results of Chen et al.[25], Villar et al.[26], Tang et al.[27].

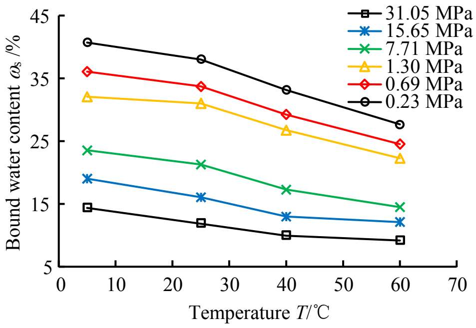

Fig. 4 Variation curves of volumetric water content with temperature under the same matric suction

Figure 4 illustrates that, the reduction rate of volumetric water content θ increases as the matric suction s decreases, indicating that the temperature effect on the water retention capacity of compacted expansive soil depends on the suction. The smaller matric suction leads to the greater impact, indicating that water retention capacity decreases more significantly. For example, when the temperature rises from 5 ℃ to 60 ℃, the volumetric water content of a sample with a matric suction of 31.05 MPa decreases from 14.37% to 9.17%, only reducing by 5.2% ($\Delta\theta_1$). However, when the matric suction is 0.23 MPa, the volumetric water content decreases from 40.69% at 5 ℃ to 27.67% at 60 ℃, reducing by 13.02% ($\Delta\theta_2$), which is 2.51 times that $\Delta\theta_1$ with a matric suction of 31.05 MPa. The above conclusions can also be validated in Fig. 3: The difference between the curves gradually decreases as the matric suction increases. When the suction reaches 40 MPa, the volumetric water content of the sample at different temperatures does not change significantly, indicating that temperature has almost no effect on the water retention capacity of the expansive soil.

3.3 Mercury intrusion porosimetry test

Figure 5 illustrates that the pore size distribution curves of compacted expansive soil at different temperatures. One can see that two obvious peaks exist in the pore size distribution curves of compacted expansive soil at different temperatures, namely a bimodal structure. According to Lloret et al.[28], 0.15 μm is selected as threshold value of pores in and between aggregates, then the compacted expansive soil contains pores in aggregates ($d < 0.15$ μm) and pores between aggregates ($d > 0.15$ μm).

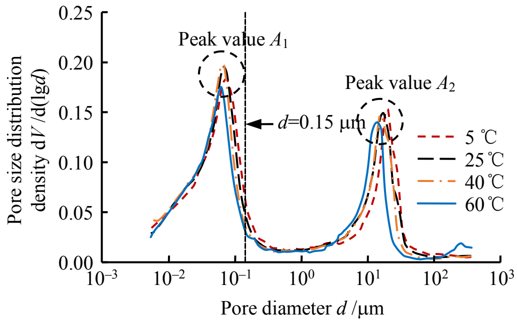

Fig. 5 Curves of pore size distributions under different temperatures

For convenience, the peak values corresponding to small pores and large pores are defined as peak value A_1 and peak value A_2, and their distribution characteristic parameters are listed in Table 5. By combining with Fig. 5, it can be seen that the pore size corresponding to peak value A_1 remains basically unchanged as the temperature increases, and only the number of pores increases slightly. While the pore size corresponding to peak value A_2 changes more markedly, and it gradually shifts to the lower left as the temperature increases. For example, when the temperature rises from 5 ℃ to 25 ºC, the pore size of peak value A_2 decreases from 20.275 8 μm to 17.276 1 μm, with a decrease of 14.8%; while the pore size of peak value A_2 decreases from 15.4437 μm to 14.292 0 μm as the temperature continues rising to 60 ℃, with a decrease of only 7.4%, indicating that the original pore size between aggregates becomes smaller, and its number decreases, but the changing range decreases in general, which can be explained in combination with the hydration mechanism of montmorillonite proposed by Ye et al.[29]: Due to the high content of hydrophilic clay minerals such as illite and montmorillonite in expansive soil, they gradually hydrate in the constant temperature curing process. As the hydration process continues, the thick layer gradually disperse and crack to form thin and small layers, resulting in an increase of the small pores in aggregate; at the same time, the layer will continue expanding after hydration, causing the large pores between aggregates to be compressed, then the pores between aggregates reduce. In addition, Liu et al.[30] also found that rising temperature will accelerate the hydration of montmorillonite. The higher temperature makes the more thorough hydration, then the above temperature influence on the pore distribution of expansive soil can be explained well.

Table 5 The pore statistical parameters of Nanning expansive soil at different temperatures

Temperature	Peak value A_1 (Peak value of pores in aggregates)		Peak value A_2 (Peak value of pores between aggregates)	
/℃	Pore diameter /μm	Distribution density /(mL • g^{-1})	Pore diameter /μm	Distribution density /(mL • g^{-1})
5	0.063 9	0.171 2	20.275 8	0.153 1
25	0.063 2	0.195 6	17.276 1	0.149 3
40	0.062 6	0.196 4	15.443 7	0.147 4
60	0.062 7	0.175 2	14.292 0	0.139 7

3.4 Bound water adosorption test

Figure 6 shows the relationship between the water content of Nanning expansive soil and temperature. It can be seen that the bound water content shows a decreasing trend as the temperature T increases, that is, they exhibit negative linear relationship approximately. When the temperature rises from 5 ℃ to 60 ℃, the bound water content of expansive soil decreases from 16.45% to 4.86%, with a decrease of 70.3%.

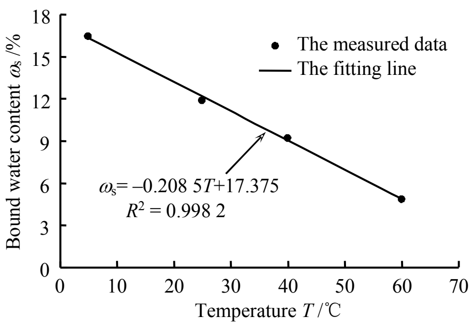

Fig. 6 Variation curves of bound water content with temperature

The reason for the above phenomenon is that the surface of clay particles is negatively charged, forming an electric field around the particles, the polar water molecules and positively charged hydration ions will be adsorbed on the particle surface, forming a strongly bound water layer. With the increase of distance, the attraction of water molecules will weaken, and transform to the weakly bound water layer gradually(Fig. 7). Since the temperature of experiment is low (5–60 ℃), strongly bound water hardly changes within the temperature range, but weakly bound water is much more sensitive to temperature than strongly bound water. The movement of water molecules intensifies as the temperature increases, and the electric attraction carried by soil particles makes it difficult to constrain the movement of water molecules. Some weakly bound water dissociates from the diffusion layer and convert to free water, reducing the bound water content and thinning the bound water film.

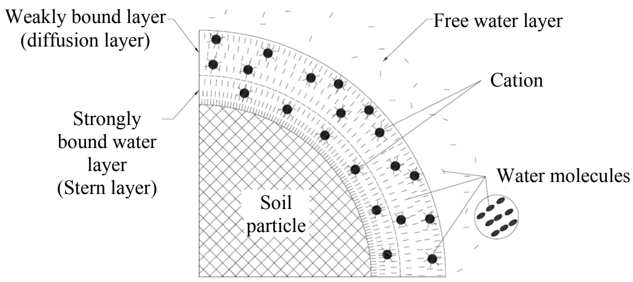

Fig. 7 Oriented arrangement diagram of bound water molecules

4 Discussion on the variation of water retention capacity with temperature

The above result indicate that the water retention capacity of expansive soil has a significant temperature effect, but most scholars attribute the decrease of water retention capacity with temperature to the decrease of surface tension and the thermal expansion of enclosed bubbles[8]. For unsaturated soil, it is a three-phase mixture composed of particles, pore water, and gas. The main reason for the decrease of water retention capacity with increasing temperature is the change in the physical mechanism of the interaction between each phase and each phase interface[25]. Therefore, limitations exist in explaining the decrease of water retention capacity from the perspective of surface tension and enclosed bubbles. In order to further explore the temperature effect on the water retention capacity of Nanning expansive soil, the mercury intrusion porosimetry test is combined with bound water adsorption test to explore the micro mechanisms of water retention capacity of expansive soil from two aspects: three phases change in soil and heat transfer mechanism.

4.1 Three phases change in soil

Solid phase: On the one hand, the mercury intrusion porosimetry test indicates that the large pores between aggregates shrink significantly in the heating process (see Fig. 5 and Table 5). Since the volume of free water is difficult to be compressed, a large amount of free water is squeezed out due to the pore shrinkage; On the other hand, the bound water adsorption test shows that some weakly bound water releases from the electric field formed by clay particles, dissociates from the diffusion layer, and converts to free water, which makes it difficult to hold so much free water in the shrinking pore, so it can only be drained from the soil, which ultimately reduces the water content and weakens its water retention capacity.

Liquid phase: the bound water adsorption test indicates that 11.59% of the bound water in expansive soil transforms into free water with the increase of temperature (see Fig.6), which means its water retention capacity is weakened. In addition, the rising temperature also weakens the viscosity of free water. When the temperature rises from 5 ℃ to 60℃, the dynamic viscosity coefficient of water decreases from 1.518×10^{-3} Pa • s to 0.466×10^{-3} Pa • s, with a decrease of 69.3%[31], its conductivity and flow ability have been greatly improved. In other words, the viscosity of liquid water is negatively proportional to temperature, and rising temperature reduces its resistance when the water flows in soil pores, making it easier to be drained from the soil, then the water content and the water retention capacity decrease.

Gas phase: gas dissolves in water at normal temperature and pressure, forming closed bubbles. As the temperature increases, the closed bubbles expand and their volume gradually increases, causing the original space of free water to be gradually occupied by bubbles. Consequently, some pore free water is squeezed out, and the water retention capacity decreases.

4.2 Heat transfer mechanism

The heat transfer mechanism in unsaturated soil mainly includes three modes: heat transfer of free water, heat transfer between soil particles, and heat transfer between soil and water interface (liquid bridge). However, the water-vapor latent heat effect becomes a new dominate heat transfer mode when the temperature continues rising[32]. The so-called water-vapor latent heat effect refers to the alternating evaporation and condensation of water at both ends of the “liquid island” under the temperature gradient effect. The emergence of the water-vapor latent heat effect greatly reduces the constraint of soil particles on water, causing the continuous transformation of free water between liquid and gas states, then the water is drained from the soil ultimately and its water retention capacity decreases.

In addition, the reasons for the rising temperature affecting the water retention capacity of the soil when the matric suction is greater than 40 MPa are as follows. (1) When the matric suction reaches a certain value (40 MPa), the water in the pores between aggregates has been drained, and only little water exists in the pores within aggregates. As the rising temperature does not have an impact on the pores in aggregates, then the water content cannot be further reduced at this time, that is, the water retention capacity remains unchanged. (2) Although rising temperature can convert weakly bound water into free water, the converted amount of weakly bound water depends on the water content. The water content is high, and the weakly bound water layer is thick at low matric suction condition, then the electrostatic attraction of the outermost weakly bound water is small. Rising temperature causes more weakly bound water to convert into free water, while the water content continues decreasing with the increase of suction; at this time, the thickness of the weakly bound water layer decreases, and the electrostatic attraction of the outermost weakly bound water is great. The rising temperature (5–60 ℃) is not enough to make the weakly bound water release from the electrostatic attraction of soil particles and convert to free water, that is, the water retention capacity is not affected by temperature. (3) Although the enclosed bubbles expand due to rising temperature, and the free water is drained from the pores, the enclosed bubbles are also drained along with the free water[8]. When the matric suction reaches a certain value (40 MPa), the number of enclosed bubbles is very small, which is insufficient to weaken the water retention capacity. (4) The sufficient water and heat transfer channels for latent heat transfer are necessary conditions for the occurrence of water-vapor latent heat effect[32–33]. The water in the soil is continuously drained with the increase of suction, and its amount for evaporation and transportation is little, then the water-vapor latent heat effect is greatly limited, resulting in no contribution for decreasing water retention capacity of soil.

In summary, the temperature effect on the water retention capacity of expansive soil is not the result of a single factor, it is the combined action between three phases and each phase interface. In addition, the influence of each phase on water retention capacity is not the same under different suction ranges.

5 Conclusions

(1) The water retention capacity of Nanning expansive soil decreases with the increase of temperature, while the temperature effect on the water retention capacity of compacted expansive soil depends on the suction level. The greater matric suction leads to the smaller influence. When the matric suction reaches 40 MPa, temperature has almost no effect on the water retention capacity of Nanning expansive soil.

(2) The rising temperature causes the pores between aggregates to transform to small sizes, and the free water is squeezed out, then the water retention capacity is reduced. While it has little effect on the pores in aggregates.

(3) The rising temperature weakens the binding ability of clay particles to weakly bound water, and some weakly bound water converts to free water. The decrease of water viscosity is also one of the reasons for the decrease of soil water retention capacity. In addition, rising temperature will also cause the volume of dissolved gas to expand, some free water is squeezed out and the water retention capacity of the soil is reduced.

(4) The temperature effect on the water retention capacity of expansive soil is not the result of a single factor, while it is the combined action between the three phases in the soil and each phase interface. The influence of three phases on the water retention capacity of soil is not the same under different suction ranges.

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