Experimental Study of Soil-water Characteristic Curves in the Full Suction Range of Organic Matter-containing Soils and Analysis of Their Water-holding Properties

Zeyu Song and Yue Gu*

Faculty of Civil Engineering and Mechanics, Kunming University of Science and Technology, Kunming 650500, China
gydrgui@kmust.eud.cn

Abstract. Organics have an important impact on the water-holding capacity of clay, but the law and mechanism of this impact have not been studied systematically. In this paper, samples with different contents of organic matter were prepared by taking bentonite as a matrix and adding peat, and soil-water property tests were carried out using the pressure plate method, the filter paper method and the vapour balance method., fitted to the test results and analyzed by using three kinds of models; and the fitted parameters of the soils containing organic matter were compared with those of other types of soils. Finally, the differences between the fitted parameters of the soils containing organic matter and those of the other soils were analysed. The results of the tests show that the three different tests are capable of accurately reflecting the soil-water characteristics of clays containing organic matter over the whole of the suction range; organic matter can have an effect on water retention in clays, but water retention is also a function of pore structure and the morphology of water in the pores within a particular suction range.; the Lu model is the best model for describing the soil-water characteristic curve of clay containing organic matter, and the changes in its parameters were consistent with the trends in organic matter content. By comparison, it was found that organic matter-containing soils have a higher water retention capacity, and their maximum adsorption water saturation is significantly greater than that of other soil types.

Key Words: Soil-water characteristic curves; Organic clay; Water-holding capacity;

1 Introduction

With the increasing number of geotechnical projects, soils with significant variations in organic matter content are often encountered, where peaty soils can have an organic matter content of up to 10% or more, and peat may even exceed 30% approaching 98% [1], and the water holding capacity of such soils is mainly manifested in the fact that they have a high water content. The water content of soils containing organic matter is usually above 100%, sometimes even up to 1340% [2]. Therefore, it is very easy to induce a series of engineering problems in engineering,

W. Guo et al. (eds.), *Proceedings of the 3rd International Conference on Green Building, Civil Engineering and Smart City (GBCESC 2024)*, Advances in Engineering Research 264,
https://doi.org/10.2991/978-94-6463-728-1_39

such as foundation deformation, ground cracking, and slope instability and so on. Meanwhile, with the influence of environmental factors such as large-scale groundwater extraction, extreme droughts and floods, dramatic fluctuations of the groundwater level have occurred in local areas [3], thus leaving the clay in an unsaturated state. Therefore, the study of the water retention capacity of organic matter-bearing clays will facilitate the progress of research on the treatment of organic matter-bearing clay layers.

In domestic and international scholars have used a variety of methods for comparative analysis in the field of research on soil-water characteristics of different soils. By comparing the Cloumbia sandy clay and the Palontina clay, W.P.M. Black [4] studied the effect of mineralogical composition on soil-water characteristics. Gui et al[5] showed that peat soils have a strong water holding capacity by measuring the soil water characteristic curves of highly decomposed peat soils using the filter paper method.These studies will provide a valuable basis for a more in-depth understanding of the soil water properties of different types of soil.

Relatively few studies are available in the literature on the soil-water properties of clays containing organic matter and the effect of organic matter on their water-holding capacity is not well known. For this reason, three different methods were used in this study, namely the measurement of the soil-water characteristic curve of the clay with organic matter ,and combined with three soil-water characteristic curve models, a systematic study of organic matter clays was carried out, and the water retention properties of organic matter clays were analysed in depth.

2 Test materials and sample preparation

2.1 Preparation of test materials

The composition of natural soils is complex and variable, with significant stochasticity and variability in their mineral and organic matter content, making it quite difficult to study the effect of organic matter alone.Soil samples were prepared by manual blending in this study. Bentonite was used as the matrix soil for the soil samples, and the addition of natural peat effectively regulated the organic matter content of the soil samples.. The depth of the peat sample taken was about 0.3 m. The peat had a high degree of decomposition, with a residual fiber content of about 4.5% and a burn loss of more than 97%. According to the relevant standards of JTG 3430-2020 "Highway Geotechnical Test Procedures"[6],the soil samples were tested for basic physical property indexes. Table 1 presents the indices.

Table 1 Physical properties of clay minerals and peat

Name	w_L /%	w_p /%	G_s/g cm^{-3}	SSA/m^2 -g^{-1}
Bentonite	182.5	43.1	2.58	78.5
Peat	732.3	134.8	1.36	964.1

2.2 Sample Preparation

With reference to the relevant literature[5],soil samples with different organic matter contents were successfully prepared in this study using a specific blending method. First, the appropriate amount of peat was added based on experience, and then the soil samples were analyzed for organic matter using a loss on burn test.After the test, the organic matter content of the soil were 5.15%, 9.89%, 20.57%, 30.27%, 39.65%, 50.14%, corresponding to the number of S1, S2, S3, S4, S5, S6. The other bentonite was taken to prepare the standard samples, which were numbered Y1.

3 Test Methods and Procedures

3.1 Test using the pressure plate method

For the compression plate test (0-1.5MPa), a compacted specimen 61.8 mm in diameter and 20 mm high was prepared. The ring samples were vacuum saturated and placed in a pressure film instrument manufactured by Soil moisture, USA and the desired suction value was adjusted. The test procedure of reference [7].

3.2 Filter paper method test

Refer to the literature for the specific test procedure [8]. Whatman no. 42 filter paper was used as a primary testing medium.For the determination of the rate-determination curve, reference was made to the bilinear rate-determination curve equation proposed by Leong et al.[9] based on their experimental results, namely

$$\lg s_e = 2.909 - 0.0229\, w_p \left(w_p > 47\%\right) \tag{1}$$

$$\lg s_e = 4.945 - 0.0673\, w_p \left(w_p \le 47\%\right) \tag{2}$$

S_e is the substrate suction; and W_p is the paper's moisture.

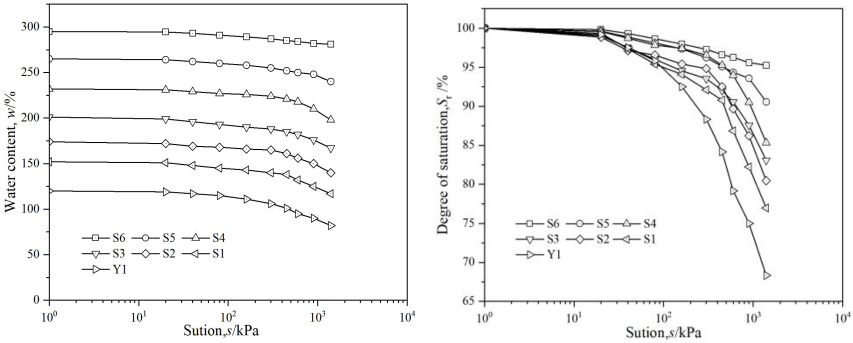
3.3 Vapor balance method test

Compacted specimens measuring 61.8 mm in diameter and 20 mm high were first prepared and vacuum saturated, then cut and placed on the divider in the desiccator. For the test, 11 supersaturated salt solutions were prepared and poured into the bottom of the desiccator, and they had different relative humidity in a sealed environment.The desiccator was maintained at a constant temperature of 20 °C to within 0.1 °C in a thermostatically controlled water tank. To minimize errors, the samples were tested several times at each relative humidity (n=4). Each RH was finally measured by averaging across tests. The Archimedes buoyancy method was used to determine the volume of the equilibrated specimen[10] , from which the saturation of the specimen was calculated, thus plotting the suction force versus moisture content and saturation.

4 Test Results Analysis

4.1 Pressure plate method test

The soil moisture characteristic curves of organic matter soil were measured using the pressure plate method and expressed as suction versus water content and saturation (s-w, s-Sr), respectively, shown in Fig 1.



a) *s-w* curve b) *s*-S_r curve

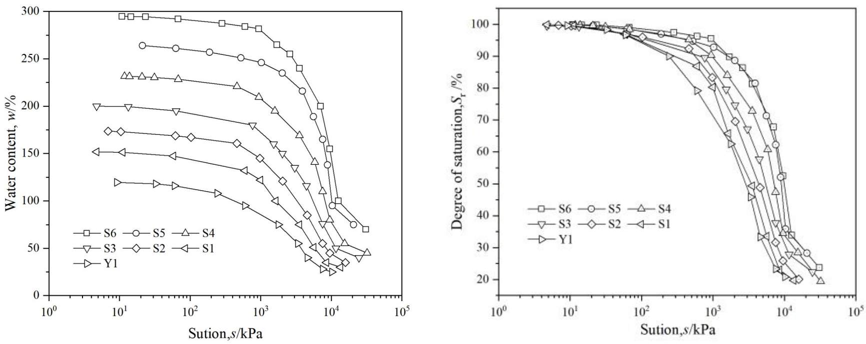
Fig. 1. Soil water characteristic curves of organic matter containing soil by pressure plate method

Water content gradually decreases with increasing aspiration, and as organic matter content increases, water content decreases more.As the organic matter content gradually increases, the saturated water content of the sample increases accordingly, and this increasing trend is very significant.

With the increment of suction, the curve first shows a flat trend and then decreases gradually. The soil sample remains saturated until the inlet value of the soil sample is reached. As soon as the suction force is greater than the inlet value, the soil sample will release a portion of the water, while the gas enters the soil sample, which transforms the soil sample into a non-saturated state. With further increase in suction value, the curve decreases sharply. Compared with bentonite Y1, the slope of the soil sample containing organic matter is smaller, and the curve is distributed above the bentonite. Indicating better water retention than bentonite in soil containing organic material.

4.2 Filter paper method test

Fig 2 shows the soil water characteristic curves of clays with different organic matter contents obtained by the filter paper method.



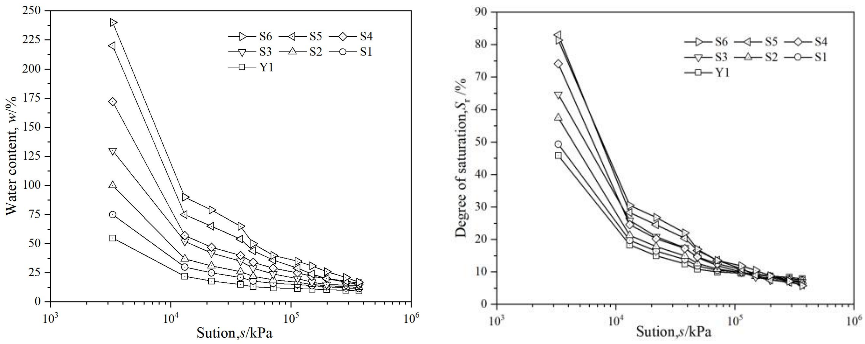
a *s*-*w* curve b *s*-S_r curve

Fig. 2 Characteristic curve of the soil water content of soils containing organic matter using the filter paper method

Provided that the water content is kept constant, the increase in the organic matter content will lead to an increase in the suction power of the clay containing organic matter.When the suction is low, there are significant differences in the soil water curves of soil samples with different contents of organic matter.; The s-w, s-Sr curves of clays containing organic matter gradually approach each other as the suction gradually increases.Indicating that the role of organic matter content in retaining water is gradually decreasing.The soil water curves of the soil containing organic matter were distributed above the bentonite, indicating that the addition of organic matter improved the water holding capacity of the soil samples.

4.3 Vapor equilibrium technique

Fig 3 shows the soil water curves of clays with different organic matter contents obtained by the vapor equilibrium technique. With the gradual enhancement of suction, the water content and saturation degree of clay with different organic matter content show a decreasing trend. It is particularly noteworthy that the suction value of organic matter-containing clay converges to 10^6 kPa when the water content is at a lower level, and this trend is consistent with the conclusion of the literature [5].However, when the suction value rises further, the soil water curves of clay containing organic matter begin to overlap. This shows that the effect of organic matter on the clay's ability to retain moisture decreases as the suction level increases.

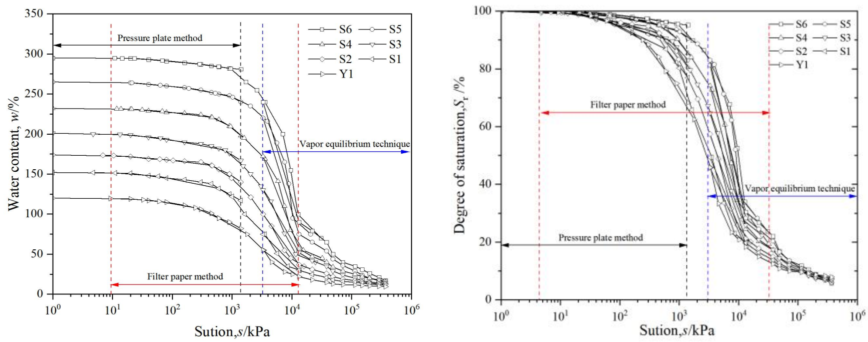


a) *s*-*w* curve b) *s*-S_r curve

Fig. 3. Soil water curve of organic matter containing soil by vapor equilibrium technique

4.4 Characteristic soil-water curves for the full suction range

Soil water characteristics of organic-rich clays over the full suction range obtained using the combined test methods are shown in Fig 4. Before the suction force reaches the inlet value of the soil samples, the soil-water characteristic curves show obvious boundary effect characteristics. But as the aspiration level gradually rises to exceed the inlet level, the airflow is reduced, the soil body gradually enters the unsaturated state, and the distribution of the soil water curve begins to become more discrete. This phenomenon indicates that the organic has a non-negligible effect on the water retention of the clay; and with the suction value gradually increasing into the high suction stage, the soil water curves of the clay containing organic matter basically overlap.In the wide suction range, pure clay is the worst at retaining water, and adding organic matter improves clay's ability to retain water.



a) *s*-*w* curve b) *s*-S_r curve

Fig. 4 Characteristic soil-water curves for organic matter-containing soils in the full suction range

5 Capillary and adsorbed water retention model

5.1 Theory of model

Water Retention Model for Capillary and Adsorbed WaterIt is useful to characterize the water retention properties of unsaturated soils by dividing the pore water into adsorbed and capillary water components, so that Sr is expressed as

$$S_{\mathrm{r}} = S_{\mathrm{r}}^{\mathrm{ads}} + S_{\mathrm{r}}^{\mathrm{cap}} \tag{3}$$

S_r^{ads} is the saturation of adsorbed water;S_r^{cap} is the saturation of capillary water.

Konrad-Lebeau model (KL model)[11]Konrad and Lebeau proposed a model for soil-water characterization curves that distinguishes between capillarity and adsorption: the model assumes that pore radii follow a two-parameter power exponential distribution. The resulting parametric model highlights the retention mechanisms of water (capillarity and adsorption).

$$S_{\mathrm{r}} = \left(1 - S_{\mathrm{r}}^{\mathrm{cap}}\right) S_{\mathrm{r}}^{\mathrm{ads}} + S_{\mathrm{r}}^{\mathrm{cap}} \tag{4}$$

$$S_{\mathrm{r}}^{\mathrm{ads}} = S_r^0 \left[1 - \ln(s) \Big/ \ln\left(s_{dry}\right)\right] \tag{5}$$

$$S_{\mathrm{r}}^{\mathrm{cap}} = \begin{cases} 1 & s \le s_a \\ 1 - \left(1 - e^{-As}\right)^{\alpha} & s > s_a \end{cases} \tag{6}$$

$$S_{\mathrm{a}} = S_{dry}^{1 - 1/S_r^0} \tag{7}$$

Where:$S_{dry}$is the pulling force that represents the dry condition of the soil., which is about 106 kPa;A and α denote the parameters related to the shape;$S_r^0$is the parameter referring to the saturated adsorbed water content.

Zhou model[12]Capillary and adsorbed water can be separated and capillary condensation can be considered in the model.The mathematical expression for this theoretical model is.

$$S_{\mathrm{r}}^{\mathrm{ads}} = \frac{\alpha A(s) - \alpha C(s) A(s)}{1 - \alpha C(s) A(s)} \tag{8}$$

$$S_{\mathrm{r}}^{cap} = \frac{C(s) - \alpha C(s) A(s)}{1 - \alpha C(s) A(s)} \tag{9}$$

$$S_{\mathrm{r}} = S_{\mathrm{r}}^{\mathrm{ads}} + S_{\mathrm{r}}^{\mathrm{cap}} = \frac{C(s) + \alpha A(s) - \alpha C(s) A(s)}{1 - \alpha C(s) A(s)} \tag{10}$$

$$C(s) = \tfrac{1}{2}\, erfc\left[\frac{\ln\left(s/s_m\right)}{\sqrt{2\theta}}\right] \tag{11}$$

$$A(s) = 1 - \frac{\ln s}{\ln s_d} \tag{12}$$

S is suction force;S_m is suction force corresponding to the mesopore;S_d is taken as 10^6 kPa;θ is the standard deviation of the logarithmically transformed radius of the pore.; α is a parameter related to the adsorption saturation.

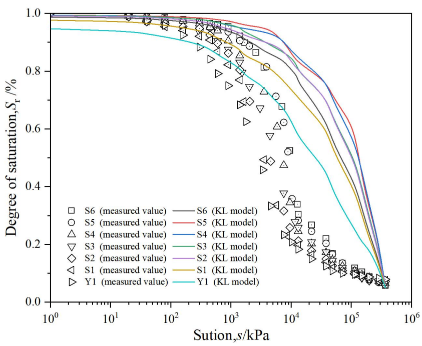
Lu model[13]Lu also proposes a model for the soil water curve, which distinguishes between capillary water and adsorbed water. all parameters are the same as in the previous SWRC model, but with a clearer physical meaning and a method for their determination.

$$S_r^{ads}(s) = S_{r\,max}^{ads}\left\{1-\left[\exp\left(-{}^{s_{max}}\!/_{s}\right)\right]^m\right\} \tag{13}$$

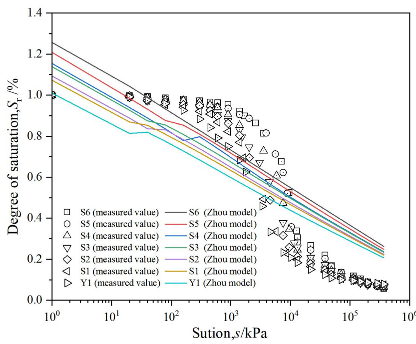
$$S_r^{cap}(s) = \left[S_S - S_r^{ads}(s)\right]\left[1+(\alpha s)^n\right]^{-m} \tag{14}$$

$S_s$is the saturation of the saturated soil, which is 100%;$S^{ads}_{r\ max}$ is the maximum adsorbed water saturation;$S_{max}$is the maximum suction;α、n、m is the parameter of the fit..

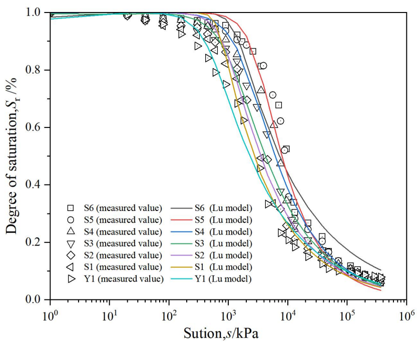
5.2 Soil-water curve model fitting



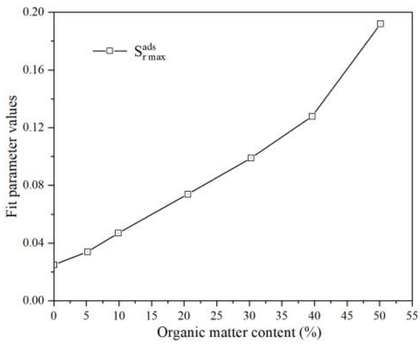
KL model fitted



Zhou model fitted



Lu model fitted



Relationship between fitting parameters and organic matter content of the Lu model

Fig. 5. Fitting results of soil water curves by different models

Modeling soil water characteristics is important for understanding the water-holding properties of organic-bearing clays. In order to evaluate the water-holding capacity of organic matter-bearing clay, this paper applies the KL, Zhou, and Lu models to fit the soil water curves of organic matter-bearing clay, and Fig 5 and Table 2 show the fitting results.

As shown in Fig 5, the Zhou model is clearly out of line with the experimental data.,while the KL model can be a rough predictor of the trend of the soil water curve, but the fitting effect is poor, and only Lu model is capable of reasonably predicting the soil water characteristics of the organic-rich clay in the full suction region The parameters of the fit of the Lu model and its coefficient of determination R^2 are listed in Table 4.,and it can be found that the coefficient of determination $R^2$is greater than 0.99 under any condition of organic matter content. Therefore, Lu model is the best model for describing the soil water curves of the organic matter-containing clay soil. In the Lu model,$S^{ads}_{r\ max}$was the maximum adsorption water saturation was linearly correlated with organic matter content;S_{max} was stable around 0.8 indicating that the maximum suction force was not related to organic matter content, but it was much larger compared to the maximum suction force of clay mineral adsorption strength of 0.4 for organic matter-containing clays, which further verified the enhancement of water capacity of the soil by organic matter. The changes in α、n、m were small and negligible. Results show that the Lu model fits well.;model parameters have clear physical significance; and the parameter changes are consistent with the trend of the soil-water curve of organic clay.

Table 2. Lu model fitting parameters

Soil sample number	$S_{r\max}^{ads}$	$S_{\max}$	α	n	m	R^2
S1	0.034	0.78	0.001	1.742	0.087	0.989
S2	0.047	0.82	0.001	1.591	0.199	0.988
S3	0.074	0.84	0.001	1.751	0.296	0.990
S4	0.099	0.86	0.005	1.838	0.313	0.988
S5	0.128	0.81	0.002	1.401	0.299	0.994
S6	0.192	0.88	0.001	1.798	0.106	0.990
Y1	0.025	0.42	0.002	1.228	0.194	0.990

5.3 Comparison of soil-water characteristic curves for organic matter-bearing clays and other soil types

The soil water curves and related data of different types of soils in different regions were obtained from domestic and foreign literature and fitted with Lu model to obtain the maximum adsorption water saturation of $S^{ads}_{r\ max}$(see Table 3). From Table 3,the water adsorption capacity of clayey soils containing organic material is generally higher than that of other soils, possibly due to the higher hydrophilic properties of organic material.

Table 3. Parameters of Lu model fitting for different types of soils

Name of soil sample	$S_{r\max}^{ads}$	R^2
Sand[14]	0.015	0.990
Shanghai soft soil[15]	0.023	0.995
Guilin lateritic clay[16]	0.028	0.992
Silty clay[17]	0.024	0.994
Palontina Clay[18]	0.026	0.991
Cloumbia sandy soil[18]	0.017	0.987

In order to explore this phenomenon in depth, the soil-water interaction mechanism of organic matter-containing clays under different suction stages needs to be further analysed, as shown in Fig. 6. The water holding capacity of the soil is mainly controlled by the capillary action between the particles in the low suction phase.Due to the presence of organic matter, the inter-particle connections may be tighter, which improves the ability of the soil to hold water. Simultaneously, the hydrophilic nature of the organic material helps increase the water retention capacity of the parent material.

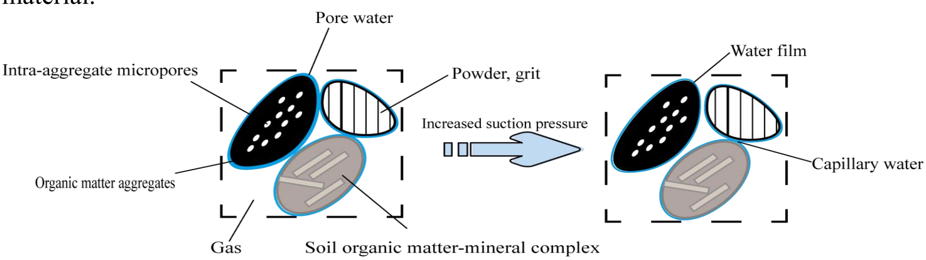


Fig. 6. Schematic representation of the change in pore water with increasing suction in soil containing organic matter

As the suction value increases, the soil body in unsaturated state is affected by more adsorption. At this point, the structure of the double electrical layer on the surface of the soil particles is as follows and the water-holding capacity of the soil is dominated by the interactions between the molecules of the organic.Due to the complex structure of the organic matter, a more stable bond may be formed with the soil particles, thus slowing down the water loss rate of the soil body to some extent. Upon entering the high suction phase, the water-holding properties of the soil are more influenced by the water bound within the soil particles and organic matter molecules. At this stage, the soil-water curves of both pure clay and organic matter-containing clay tend to coincide, indicating that under high suction conditions, the water retention performance of the soil is mainly governed by the nature of the soil particles and organic matter molecules themselves, and has little to do with their relative contents.

6 Conclusion

In this study, the soil-water curves of clays with different organic matter contents were comprehensively measured using various technical means,and the following conclusions were drawn:

(1) A combination of three methods was used to measure the suction values of organic matter-containing clays in different suction ranges, and the soil-water characteristic curves of organic matter-containing clays in the process of dehumidification in the full suction range can be clearly demonstrated.

(2) Influence of the organic matter on the ability of the clay to retain water is not a fixed one. In the initial stage,organic clay has better water retention than bentonite.; when entering the stage of high suction, the soil-water curves of specimens with different organic matter contents almost overlap, indicating that organic matter has relatively little effect on clay water retention.

(3) The goodness-of-fit analysis showed that the Lu model fitted the organic matter-containing soils better. Compared with general clayey soils, chalky soils, gravelly soils and non-organic matter soils such as loess and red clay, the maximum adsorption water saturation of organic matter-containing soils is larger, indicating that they have a stronger water-holding capacity.

Acknowledgement

This study was financially supported by the National Natural Science Foundation of China (Grant Nos. 52068039). The opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily represent the views of the sponsors.

Declarations

Conflicts of interests: The authors declare that they have no competing interests.

References

1. HUAT B B K, KAZEMIAN S, PRASAD A, et al. State of an art review of peat: general perspective. International Journal of Physical Sciences, 6(8): 1988-1996, 2011,.
2. Mesri G, Ajlouni M. Engineering Properties of Fibrous Peats. Journal of geotechnical and geoenvironmental engineering,133(7):850-866, 2007.
3. Meng Guotao. Research on ground subsidence in the southern city of Kunming. Kunming: Kunming University of Science and Technology, 2004.
4. Black W P M.A method of estimating the Californiabearing ratio of cohesive soils from plasticity data.Ge'otechnique, 12(8):271-282, 1962.
5. GUI Yue, LIU Rui, ZHAO Zhenxing, et al. Research on soil-water characteristic curve of peat soil with high degree of decomposition. Journal of Disaster Prevention and Mitigation Engineering, 41(3): 622-628, 2021.

6. Ministry of Transportation of the People's Republic of China, Institute of Highway Science, Ministry of Transportation. Test Methods of Soils for Highway Engineering: JTG 3430-2020 . Beijing: People's Transportation Press, 2020.
7. Sun D.A., Zhang J.R., Lv H.B.. Soil-water characteristic curves of Nanyang expansive soil in full suction range . Geotechnics, 34(7):1839-1846, 2013.
8. LI Mingyu, SUN Wenjing, HUANG Qiang, et al. Soil-water properties of biochar-clay hybrid soils in full suction range. Geotechnical Mechanics, 43(10):2717-2725, 2022.
9. LEONG E C, HE L, RAHARDJO, H. Factors affecting the filter paper method for total and matric suction measurements. Geotechnical Testing Journal, 25(3): 322-333, 2002.
10. Sun W.J., Sun D.A., Liu S.Q., et al. Soil-water-mechanical properties of Gaomiaozi calcium-based bentonite under high suction. Journal of Geotechnical Engineering, 36(2):346-353, 2014.
11. KONRAD J M, LEBEAU M. Capillary-based effective stress formulation for predicting shear strength of unsaturated soils. Canadian Geotechnical Journal, 52(12): 2067-2076, 2015.
12. ZHOU A, HUANG R, SHENG D. Capillary water retention curve and shear strength of unsaturated soils. Canadian Geotechnical Journal, 53(6): 974-987, 2016.
13. LU N. Generalized soil water retention equation for adsorption and capillarity. Journal of Geotechnical and Geoenvironmental Engineering, 142(10): 04016051, 2016.
14. Tian H N, Kong L W. Experimental research on effect of fine grains on water retention capacity of silty sand.Rock and Soil Mechanics,31(1): 56-60,2010.
15. Ye W M, Tang Y Q, Cui Y J. Measurement of soil suction in laboratory and soil-water characteristics of Shanghai soft soil. Chinese Journal of Geotechnical Engineering 2005,27(3): 347-349,2005
16. Sun D A, Liu W J, Lyu H B.Soil-water characteristic curve of Guilin lateritic clay,.Rock and Soil Mechanics,35(12):3345-3351,2014
17. Lan T, Qin W X， Hu H R, et al. Experimental study on impacts of clay content on soil-water characteristics of silty clay,.Science Technology and Engineering, 18(28):128-132,2018
18. Black W P M.A method of estimating the Californiabearing ratio of cohesive soils from plasticity data,.Ge'otechnique,12(4):271-282,1962.