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Measurement and curve fitting for the soil-waterer characteristic curve of mural plaster at Mogao Grottoes

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Abstract: Mural plaster deterioration poses great threat to the long-term preservation and daily maintenance. The migration of soluble salts by moisture movement is one of the most important factors that causes mural plaster deterioration. The plaster plays an important role in supporting the murals. The soil-water characteristic of the mural plaster is related to the formation and development of mural deterioration. In order to study the soil-water characteristic curve (SWCC) of mural plaster in full suction range, laboratory reconstituted plasters were prepared by the same materials as the mural plaster in Mogao Grottoes, and the pressure plate test method and vapor equilibrium technique were employed. The SWCC test data was fitted by van Genuchten (VG) model and Fredlund Xing (FX) model. The SWCC of the reconstituted plaster samples with different compositions showed different characteristics, while the morphological differences between the coarse plaster and the fine plaster on the SWCC were not obvious. Under the same suction condition, the moisture content of the coarse plaster is higher than that of the fine plaster, and the coarse plaster has the characteristics of rapid release of moisture in the high suction range. By analyzing the trend of the SWCC in the high suction range, it is recommended that the humidity in the Mogao Grottoes should not exceed 58% in daily maintenance, and the humidity should be stable with no major fluctuations. Based on the experimental data in the full suction range, highly accurate SWCC can be obtained.

Keywords: Mogao Grottoes; mural plaster; soil-water characteristic curve (SWCC); pressure plate method; vapor equilibrium technique; full suction range

1 Introduction

Dunhuang Mogao Grottoes is not only a bright pearl on the Silk Road, but also a world-famous treasure house of human art. However, after thousands of years of wind and frost attack, the murals are suffering from a variety of deteriorations, such as crisp alkali, nail peeling, herpes and pulverization. Li[1] summarized the research on various deterioration of murals in Mogao Grottoes and found the harmful effects of water and salt on murals. Zhang et al.[2] made an in-depth study of the crisp alkali in the mural and came to the conclusion that "salt moves with the water, and if there is water, there will be trouble." The Getty Conservation Institute of the United States has carried out systematic protection and research work on Cave 85 of Mogao Grottoes[3]. The focus of protection works and researches are also on the deterioration caused by water and salt migration. Zehnder[4] made a long-term monitoring study on a church mural and found that moisture in the air is also the main cause of mural disease. In summary, the deterioration of murals is caused by the movement of water in the surrounding rock of caves and the plaster layer of murals, which leads to the migration of soluble salt. The mural plaster layer is in an unsaturated state for a long time, and the change of suction of the mural plaster layer is related to the change of its moisture content, and its soil-water characteristics determine the law of water transport in the mural plaster layer, which further affects the transport and accumulation of salt. This process is very important for the formation and development of mural deterioration. Therefore, an accurate understanding of the soil-water characteristics of the plaster layer is a prerequisite for in-depth understanding and study of the development mechanism of mural deterioration.

Soil-water characteristic curve (referred to as SWCC) is a curve that reflects the relationship between soil moisture content and suction stress. It can reflect the permeability and strength properties of unsaturated soil[5]. For the research on the soil-water characteristics of the mural plaster, some work has been carried out by the previous researchers. Yan[6] calculated the unsaturated permeability coefficient of the mural plaster using the existing model, and Zhao et al. [7] used the pressure plate equipment to measure the soil-water characteristic curve of the Chengban (DB) soil that makes up the mural plaster. Zhang et al. [8] carried out the capillary rise experiment to simulate salt migration, and discussed the transport law of soluble salt. At present, there is little research on the

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soil-water characteristic curve of mural plaster with different material compositions, and there is no discussion on the soil-water characteristic curve at the high suction range.

In this paper, the mural plaster of Mogao Grottoes is thoroughly investigated. The mural plaster samples of different components are prepared, and the soil-water characteristic curve of mural plaster is measured by using axial translation technique and humidity control technology. The change of water content of simulated plaster under the change of suction is obtained. The relationship between the change of the material composition of the plaster is emphatically analyzed, and the classical soil-water characteristic curve model is selected to fit the measured curve, and the corresponding parameters are obtained. The experimental results provide theoretical support for the further study of the deterioration caused by the migration of water and salt in plaster.

2 Sample preparation and test method

Most of the murals are layered structures, ranging from 2 to 7 layers due to different craftsmanship. The mural plaster is a very important layer in the mural, and it is the direct carrier of the paint layer or the background color layer. According to the previous scholars' research on the plaster layer of murals in Mogao Grottoes[9–11], most of the mural plaster layers in Mogao Grottoes are divided into two layers, and the bottom layer is called coarse mud layer or grass mud layer, which is made of soil, sand and grass knots mixed with water and directly smeared on the support body, in which the grass knots effectively improve the strength of the coarse mud layer and strengthen the connection with the surrounding rock of the grottoes. Above the coarse mud layer is the fine mud layer, also known as the hemp layer, which is made of soil, sand, cotton and hemp. The addition of cotton and hemp effectively prevents the cracking of the plaster, and the smaller cotton and hemp fiber make the plane of the painting flatter. Figure 1 shows the structural diagram of the murals in Cave 85 of Mogao Grottoes.

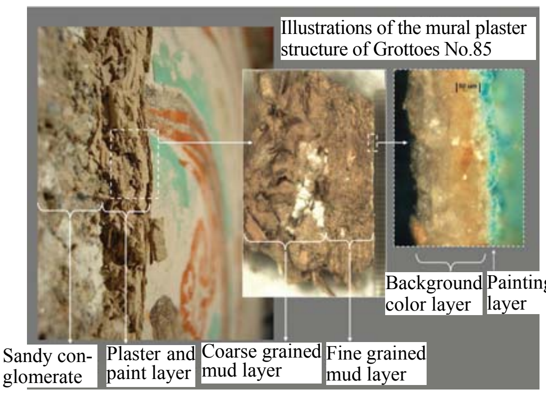


Fig. 1 Sketch of wall painting in Cave No.85[3]

2.1 Sample preparation

The researches from Li[1] and Zhao et al[11] show the mural plaster materials of Mogao Grottoes incorporate pure soil, fine sand, grass knots and cotton and hemp. Most of the plaster from the Sixteen Kingdoms period to the Yuan Dynasty contain coarse mud layer and fine mud layer distinguished, and in some periods there is only a single coarse mud layer or fine mud layer, and the absence of reinforcement is only found in a very few periods, in which plaster is only composed of Chengban soil (hereinafter referred to as CB soil) and fine sand. According to the previous research data, this study selects the sedimentary soil (CB soil) from the Dangquan River bed in front of the Mogao Grottoes as the main material, and the silty sand, grass knots and cotton and hemp near the Mogao Grottoes as the auxiliary materials to make the reconstituted plaster. In order to make sure the reconstituted plaster is consistent with that of the real plaster, the production of simulated plaster and the proportion of material composition are carried out according to the existing research data of murals in Mogao Grottoes. Due to the high salinity of Dangquan River water, the salt content of natural CB soil is relatively high[12]. In order to eliminate the influence of soluble salt in CB soil, desalination treatment is needed for CB soil. In addition to the existing types of plaster, two kinds of blank groups before and after desalination were added, and five kinds of simulated plaster samples were made, namely, the natural CB soil samples, the desalted CB soil samples, the CB soil samples with sand, the coarse mud layer samples and the fine mud layer samples. The proportions of sample material composition are listed in Table 1.

Table 1 Proportion of the sample material composition

Sample type	Constitutes（weight%）
Natural CB soil	100% natural CB soil
Desalted CB soil	100% desalted CB soil
CB soil with sand	64% desalted CB soil +36%fine sand
Coarse mud layer	62% desalted CB soil +35%fine sand +3%grass knots
Fine mud layer	62% desalted CB soil +35%fine sand+3%cotten/hemp

The desalination of Chengban soil was carried out according to the *Standard for soil test method* (GB/T50123-1999) [13]. The electrical conductivity of the leaching solution was 1 433 μs/m before desalination and 157 μs/m after washing salt for 4 times. In order to obtain the parameters of the test materials, the basic physical indexes of Dengban soil were determined. Table 2 gives the basic physical indexes of CB soil. The ionic concentrations of CB soil before and after desalination were measured using ISC-2500 ion chromatograph. Table 3 shows the ionic contents of CB soil before and after desalination. The particle size distributions of CB soil before and after desalination were analyzed by Mastersize-2000 laser particle size analyzer. Figure 2 plots the particle size distribution curves of CB soil before and after desalination.

Table 2 Basic physical properties of CB soil

Soil type	Specific gravity	LL / %	PL / %	PI	Swelling index / %	classification
CB soil	2.75	43.77	18.89	24.88	19	CL

Table 3 Ionic contents before and after desalting

Sample	Ionic concentrations / (mg • L^{-1})						
	Cl^-	NO_3^-	SO_4^{2-}	Na^+	K^+	Mg^{2+}	Ca^{2+}
Before	170.28	61.19	189.99	144.90	10.50	21.67	47.98
After	12.70	4.12	26.94	17.13	3.11	4.69	13.19

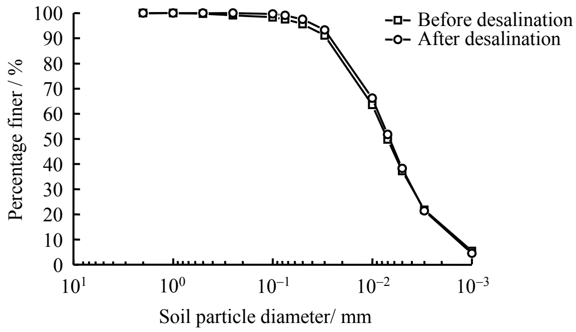


Fig. 2 Particle size distribution curves of CB soil

Before making the reconstituted mural plaster, the CB soil was sieved with a 2 mm sieve and the silty sand was sieved with a 0.2 mm sieve. Due to the small size of the simulated plaster, grass knots and cotton and hemp need to be cut to about the length of 1cm. The soil and sand that passing the sieve and the shredded grass knots and cotton and hemp were mixed into mud according to the target mixing ratios, and then stored in a sealed bag for 24 hours. After that, the test samples were uniformly placed in a mold with a diameter of 4 cm and a height of 1cm, and pressed into a cube sample with a designed dry density of 1.75g/cm^3. The prepared sample will be naturally airdried.

2.2 Test method

At present, there are many kinds of suction measurement technique, which include axial translation, tensiometer, isobaric humidity control technology and etc. [14]. However, considering that the main scope of this study is on the mural plaster in the Mogao Grottoes, which is mainly affected by the capillarity of liquid water in the west wall of the cave and the adsorption of water and vapor in the cave under high humidity, the pressure plate test method is selected to determine the low suction section that dominated by the capillary effect. The vapor equilibrium method was used to measure the soil-water characteristic curve at the middle-high suction range that is dominated by the adsorption.

2.2.1 Pressure plate method

The pressure plate test was done by adopting the 1500 pressure plate equipment made by American Soil Moisture Instrument Co., Ltd., which is mainly composed of pressure device (air compressor), pressure vessel and high air entry value porous ceramic plate (1.5 MPa). In the test, operating the pressure device gradually increased the pore air pressure in the pressure vessel, and the porous ceramic plate with high air entry value is used to maintain the pore water pressure, so that the suction can be controlled directly. Since the maximum pressure provided by the pressurizing device used in the test was 750 kPa, the maximum pressure was stopped by 700 kPa.

The pressure plate method uses drying process to characterize the soil water characteristic curve of the sample, so the sample needs to be saturated first. Three parallel samples were set for each type of soil, and the average water content of the parallel sample was taken as the test result. Before the test, place the prepared sample in a ring with an inner diameter of 4cm and a height of 1cm. Place the ring on the porous ceramic plate after saturation, and start the drying process. The pressure path is 20 kPa→50 kPa→70 kPa →100 kPa→200 kPa→400 kPa→700 kPa. When there was no water flowing out of the outlet pipe for 24 hours under the first stage pressure, it was considered that the balance has been achieved under this suction, and then the next stage pressure was added to reach the balance, and the pressure balance of each stage needed about 10 days.

2.2.2 Vapor equilibrium technique

Vapor equilibrium technique is a method of constant pressure and humidity control process. In a isothermal environment, the saturated salt solution and vapor in a closed small container will reach the ther- modynamic equilibrium state. The relative humidity (RH) in the space above the saturated salt solution will approach a fixed and balanced value[15].

In 1871, Thomson[16] proposed a formula to describe the relationship between the change of suction and the relative humidity above the water air interface. It is called the Kelvin formula, which can be expressed as

$$\psi = -\frac{RT}{v_{\mathrm{w}}} \ln \mathrm{RH} \tag{1}$$

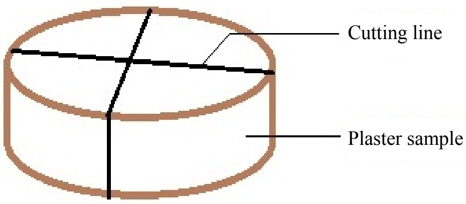
where ψ is suction (kPa); R is a general gas constant (J·mol^{-1}·K^{-1}); T is the thermodynamic temperature (K); v_{w}_is the partial molar volume of water vapor (m^3/mol); and RH is the relative humidity (%).

According to the Kelvin formula, the humidity value of the test environment can be controlled to indirectly obtain the suction. Seven types of saturated salt solutions with different humidity values were prepared in this experiment. Table 4 shows the standard humidity[17] of saturated salt solutions at 20 ℃ given by the national physical and chemical standards metrology committee, China, and the corresponding suction values of 7 types of saturated salt solutions calculated using Kelvin formula.

Table 4 Relative humidity of saturated salt solution and corresponding suction

Saturated salt solution	RH / %	Suction / MPa
LiCl	12.0	286.70
$CaCl_2$	23.0	198.00
K_2CO_3	43.2	113.50
NaBr	59.1	71.12
NaCl	75.1	38.00
Na_2SO_4	87.0	12.90
K_2SO_4	97.6	3.29

In order to achieve the balance quickly, smaller airtight containers were selected, and the prepared plaster samples were cut into small test blocks as shown in Fig. 4, and the test is carried out after drying. Three parallel samples were set up for each type of sample under each humidity gradient, and the moisture content was taken as the average value. The test instrument and schematic diagram are shown in Fig. 5. During the test, the ambient temperature was controlled at 20 ℃, and the mass of the test piece was measured every 5 days. When the mass difference of the sample measured twice was less than 0.001g, it was considered that the suction of the sample in the sealed tank was balanced with the vapor pressure of the corresponding saturated salt solution. The time for a group of samples to reach equilibrium was about 25 days.

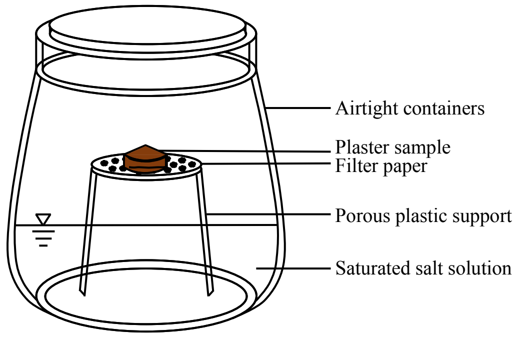


(a) Cutting plaster sample

(b) Sample block after cutting

Fig. 4 Plaster sample and plaster blocks after cutting

(a) Experimental instrument



(b) Schematic diagram

Fig. 5 Schematic diagram of experimental instrument

3 Test results and analysis

3.1 Pressure plate test

Figure 6 illustrates the soil-water characteristic curves of the middle and low suction range of the reconstituted plaster specimen tested by the pressure plate equipment. The volumetric moisture contents of all samples decrease with the increase of suction. Two groups of curve can be clearly identified. The upper two curves denoting the natural CB soil and desalted CB soil, respectively have relatively similar shape in one group, while the lower three curves representing the mixed soil samples, respectively, i.e. the CB soil with and, coarse mud layer and fine mud layer, are grouped into one group. Under the same suction condition, the moisture content of plain soil samples is higher than that of mixed soil samples. In the curve, there is little difference in the air entry point of each samples. According to the test results of the pressure plate tests on coarse mud layer and fine mud layer, the water content of coarse mud layer is higher than that of fine mud layer under the same suction condition. The soil-water characteristic curves of the two samples are approximately parallel. The research of Wei et al. [18] shows that the internal structure of grass knot is complex and there are many honeycombed pores. Although the material mixing ratios and dry densities of coarse mud layer sample and fine mud layer sample are the same, there are more water storage pores in the sample because the grass fiber is more porous than the cotton and linen fiber. This allows the coarse mud layer sample to store more water than the fine mud layer sample under the same suction condition.

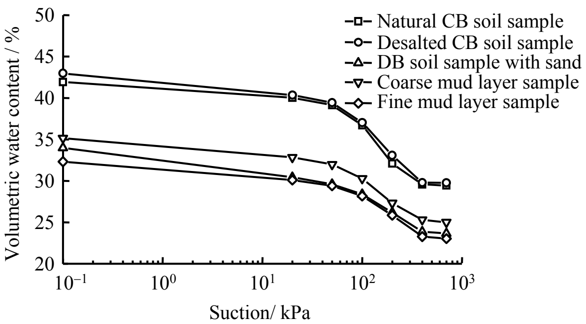


Fig. 6 SWCC of reconstituted plaster samples (pressure plate method)

Tian et al.[19] used the pressure plate method to measure the soil-water characteristics curve of unsaturated sand with different fine grain contents. The results showed that the increase of fine particles will significantly improve the water-holding capacity of the soil. The most obvious difference between the plain soil sample and the mixed soil sample is that the 1/3 in the mixed soil sample is replaced by silty sand, and the content of fine particles is greatly reduced, resulting in an obvious difference in water-holding capacity between the two types of samples, therefore, the soil-water characteristic curve observed in Fig. 6 could be divided into upper and lower two groups.

McQueen et al.[20] defined the soil-water characteristic curve as a three-stage model. According to the suction from low to high, the curve was divided into capillary action section (0–10^2kPa), water film adsorption section (10^2–10^4kPa) and firm adsorption section (10^4–10^6kPa). The pore water in the firm adsorption section is maintained in the soil by the hydrogen bond formed between water molecules and the surface of soil minerals. The pore water in the water film adsorption section is attached to the surface of the soil particles in the form of a thin layer of water film due to electric field force, van der Waals force, etc. The amount of water held in these two regimes is a function of the surface area of soil particles, the charge density on the surface of soil particles, and the type and valence of exchange cations. When the thickness of water film adsorbed on the surface of soil particles increases gradually and exceeds the influence range of short-range interaction, the soil-water characteristic curve will enter into the capillary regime, and the pore water in the capillary range is mainly affected by capillarity. The moisture held in the capillary section is a function of soil pores and soil particle size characteristics. The soil-water characteristic curve measured from the pressure plate test is in the range between the capillary section and part of the water film adsorption section. After the addition of fine sand to the desalted CB soil, the constitutes of the original soil was changed, therefore, a large number of silt particles were added to the parent clay. Because the clay has the higher particle specific surface area and particle surface charge density, the plain soil sample holds more water than the mixed soil sample under the condition of short-range adsorption. This is also the mechanism that the test curve is divided into two groups.

In the pressure plate test, there is almost no water removal from the outlet pipe when the suction is increased from 400 kPa to 700 kPa. This shows that the pore water within the capillary section and part of the water film adsorption section has been completely eliminated, and only if the suction is large enough to overcome the force between soil particles and water molecules, it can continue to make the sample yield water. As a result, the test ends in the middle and low suction sections and the SWCC curve tends to be smooth.

In the past, research works that focused on the soil-water characteristics of plasters are mostly centered on the middle and low suction range. By comparing the test results of Chengban soil samples with the data measured by Zhao et al. [7], the results show that the two are close to each other..

3.2 Vapor equilibrium technique

Figure 7 shows the soil water characteristic curves of the simulated plaster within the high suction section measured by the vapor equilibrium technique. Over the full range of high suction regime, the volumetric moisture content of the sample decreases quickly as the suction increases, especially in the section with a suction less than 10^5 kPa, the increase of suction leads to a quick decrease of water content. Under the same suction condition, the moisture content of plain soil sample is still higher than that of the mixed soil sample. However, in the section with a suction higher than 10^5kPa, the slope of the SWCC tends to be gentle with the change of suction, and the difference between water holding capacities of all kinds of samples gradually reduces. When the suction is close to 3×10^5kPa, the moisture content of each type of sample is about 1%. According to Fredlund et al.[21], when the suction reaches 10^6 kPa, the water content is 0. The test results in this paper are close to the theoretical values. In terms of the coarse mud layer and the fine mud layer, when the suction is less than 3.8×10^4 kPa, the water content of the coarse mud layer is higher than that of the fine mud layer due to the addition of larger reinforcement which increase the pore size under the same suction condition. However, the soil water characteristic curves of the two parts are almost overlapped when the suction is higher than 3.8×10^4 kPa.

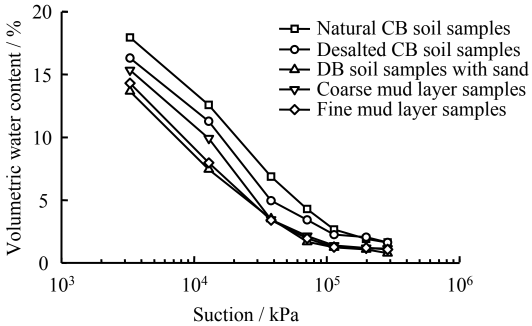


Fig. 7 SWCC of simulated plaster samples (Vapor equilibrium method)

In the area where the suction is lower than 10^5 kPa, the relationship between suction and moisture content of plain soil is nearly linear. Due to the addition of silty sand, grass knots and cotton and hemp, the water adsorption and desorption of the mixed soil samples depend not only on the effect of CB soil, but also on the additions, especially in the high suction section, which makes the shape of the soil-water characteristic curve of the mixed soil samples different from that of plain soil samples. The study of Wang et al.[22] revealed that in the high suction section, the influence of various factors of the sample on the soil-water charac- teristic curve gradually decreased. This is the reason why the water holding capacity of all kinds of samples is gradually close to each other and the difference decreases in the area where the suction is higher than 10^5kPa.

After analyzing the soil-water characteristic curve within the middle and low suction sections, Yan[6] concluded that the abrupt water release will occur in the coarse mud layer under the change of suction due to existence of grass knot, i.e., the decrease rate of water content in the sample would accelerate abruptly after the steady increase of suction. On the other hand, due to the small size of cotton and flax fiber, the fine mud layer releases water continuously. In the high suction section, the migration of water is no longer in the form of liquid water. When the water content in the soil is lower than or higher than the corresponding water content of the corresponding suction, water is adsorbed or desorbed between pores in the soil in the form of water vapor because of the short-range inter-action between solid and liquid. In our research, a similar process of sudden water release in the coarse mud layer is also identified on the curves when the suction is in the range of 1.29×10^4 kPa to 3.80×10^4 kPa. The interior of plain soil samples, CB soil samples with sand and fine mud layer samples with small fibers contain mostly soil pores and the structure is relatively simple. Therefore, the possibility of sudden release of water is very low. However, the complex internal structure and honeycomb pores in the coarse mud layer provide the possibility for the abrupt water release. As the connecting body between the surr-ounding rock of the cave and the fine mud layer, the abrupt water release characteristics of the coarse mud layer should be carefully investigated. The method of controlling suction in the high suction section is mainly achieved by changing the relative humidity, which indirectly reflects that the change of the moisture content of the mural plaster is more obvious when the humidity changes. It also indirectly shows that the mural plaster has a strong ability to capture water, and the change of moisture content has a great influence on the formation and development of salt damage in murals, therefore, in the daily maintenance of murals, the humidity in the grottoes should not fluctuate greatly.

3.3 Curve fitting of the soil-water characteristic curve of mural plaster

The soil-water characteristic curve of the mural plaster in Mogao Grottoes in the full suction range is obtained by using both the pressure plate test and vapor equilibrium technique. However, the test for measuring the soil-water characteristic curve usually only provides a series of discrete data points to reveal the relationship between suction and water content. If the soil-water characteristic curve is used to predict the water flow process, stress, strain and other phenomena occurring in unsaturated soil, the measured data need to be transformed into the form of continuous function expression. According to the existing models and their applicability, Van Genuchten (VG) model [23] and Fredlund-Xing (FX) model[21] are selected to fit the measured data points of soil-water characteristic curve of mural plaster. The expressions of the VG model and the FX model are presented as follows [21–23]:

$$\frac{\theta-\theta_{\mathrm{r}}}{\theta_{\mathrm{s}}-\theta_{\mathrm{r}}}=\left[\frac{1}{1+(a\psi)^{n}}\right]^{1-\frac{1}{n}} \tag{2}$$

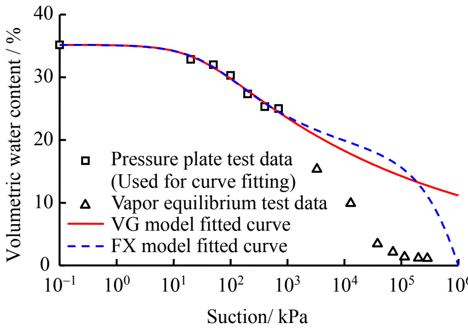
$$\frac{\theta}{\theta_{\mathrm{s}}}=C(\psi)\left[\frac{1}{\ln\left(\mathrm{e}+(\psi/\alpha)^{n}\right)}\right]^{m} \tag{3}$$

where a, α, n and m are all fitting parameters; θ is the volumetric water content (%); θ_{r} is the residual water content (%); θ_{s} is the saturated water content (%); ψ is the suction (kPa); $C(\psi)$ is the correction factor, which contributes to the suction value in the FX model when the moisture content is 0, the suction is 10^6 kPa. Among the fitting parameters, the values of a and α are related to the air entry pressure value; the par-ameter n is related to the pore size distribution of the sample; and the m value is related to the overall symmetry of the characteristic curve.

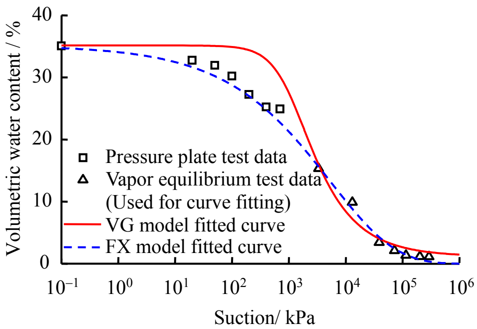
The samples of coarse mud layer and fine mud layer are the most typical samples of mural plaster in Mogao Grottoes, therefore, these two kinds of samples are analyzed and the model fitting process is carried out. Because the two test methods aim to control suction to obtain the moisture content in the corres-ponding state. And the ambient temperatures of the tests are the same, and the difference between the sample itself is small. Thus, we first fitted the test data from each single test, then we combined the two kinds of test data and applied the mathematical model to fit whole suction range.

Figure 8 (a) shows the fitting curves of the coarse mud layer by using the data from the pressure plate test alone. Obviously, when only the data points from the pressure plate test are fitted, whether it is the VG model or the FX model, though the fitted data matched well in the low suction section, the fitting results are far away from the measured data in the area where the suction is higher than 10^3 kPa. This also indicates that it is unscientific for previous scholars to simply rely on the data of soil water characteristics of mural plaster in the middle and low suction section to reflect the overall soil water characteristics of mural plaster, and also shows the importance of measuring the soil water characteristic curve of mural plaster in high suction section. Figure 8 (b) is the fitting curves based on vapor balance method data alone. The two fitting models still show different results. When the suction is lower than 700 kPa, the fitting result of VG model is much higher than the measured data, while the fitting result of FX model is lower than the measured water content. In general, the fitting of soil-water characteristic curve of coarse mud layer in the high suction section by FX model is better than that by VG model. The curves are fitted by combining two kinds test data, and the results are shown in Fig. 8 (c). The two models can better reflect the trend of the measured data, thus the soil-water characteristic curve with high precision on the full suction regime can be obtained by combining different test results, however, the fitting accuracy of FX model is slightly higher than that of VG model.

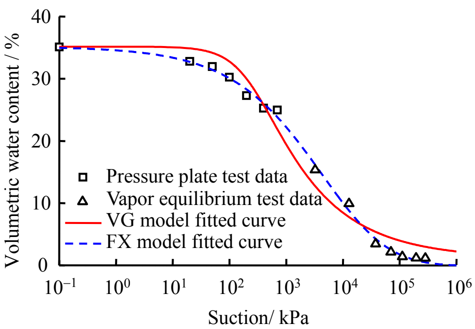
Figure 9 exhibits the fitting results of the fine mud layer sample, which is the same as that of the coarse mud layer sample, while the curve of the fine mud layer sample is quite different when fitting with different test data. For example, only using pressure plate test data results in obvious differences between



(a) Pessure plate test data only

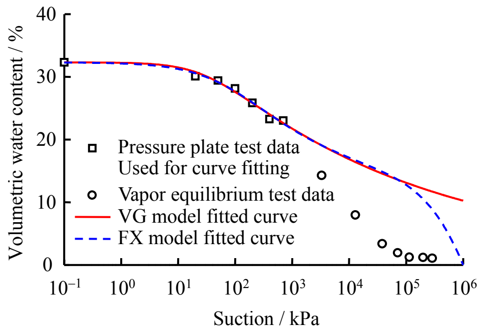


(b) Vapor equilibrium test data only

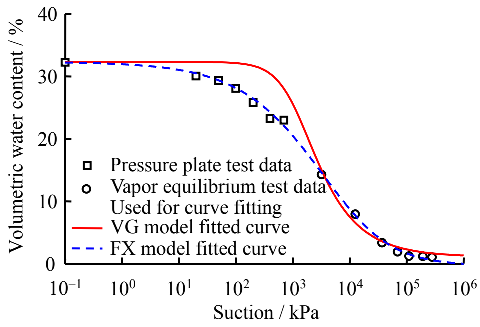


(c) Test data from both pressure plate test and vapor equilibrium test

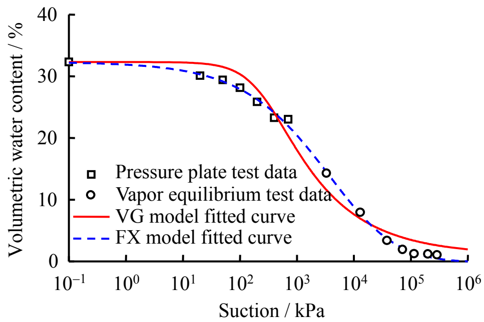
Fig. 8 Fitting curves of coarse plaster sample



(a) Pressure plate test data only



(b) Vapor equilibrium test data only



(c) Test data from both pressure plate test and vapor equilibrium test

Fig. 9 Fitting curves of fine plaster sample

the predicted trend and the measured values in the high suction range (Fig.9(a)). The predicted curves can not accurately describe the soil water characteristics in the middle and low suction section if only the measured data from the vapor equilibrium test are used (Fig.9(b)). Combining the two methods can reflect the changing trend in the full suction section well (Fig.9 (c)). The research of Tan et al.[24] shows that the curve fitting has multiple solutions of parameters under a single test condition, and the fitting with high precision can be achieved when the data points are distributed on the full suction regime. Our experiment also proves that the soil-water characteristic curve model of mural plaster can be well fitted and predicted by the combination of two kinds of experimental data. The fitting parameters of coarse mud layer and fine mud layer are shown in Table 5.

Table 5 Model fitting parameters

Sample type	Fitting parameters					
	Pressure plate test		Vapor equilibrium test		Combined test	
	VG	FX	VG	FX	VG	FX
Coarse mud layer	a=0.036 kPa^{-1} n=1.12 R^2=0.981	α=38.17 n=1.01, m=0.32 R^2=0.983	a=0.001 kPa^{-1} n=1.69 R^2=0.939	α=84 326 n=0.41, m=21.4 R^2=0.984	a=0.004 kPa^{-1} n=1.41 R^2=0.972	α=30 010 n=0.49, m=6.94 R^2=0.997
Fine mud layer	a=0.03 kPa^{-1} n=1.12 R^2=0.979	α=68.83 n=0.81, m=0.44 R^2=0.982	a=0.001 kPa^{-1} n=1.72 R^2=0.969	α=8 602 n=0.55, m=4.47 R^2=0.995	a=0.004 kPa^{-1} n=1.41 R^2=0.976	α=13 327 n=0.52, m=5.26 R^2=0.998

4 Discussion

During the suction measurement, the total suction and matrix suction are distinguished. The pressure plate equipment is often used to measure the matrix suction, while the vapor equilibrium method is used to measure the total suction. In this paper, because the test materials (except CB soil samples) are desalted, it is considered that the values of the two suction components are equal. The previous researchers have made a preliminary study on the soil-water characteristic curve in the middle and low suction sections of the mural plaster by using the pressure plate test, but neglected the slightly insufficiency in using the experimental data of the low suction section to describe the soil-water characteristic curve of the mural plaster. In our study, this problem was solved well by using the measured data in high suction section.

According to the results of Mogao Grottoes 85 by Liu et al.[25], the relative humidity in Mogao Grottoes 85 varies from 10% to 80%. Because the grotto itself is a relatively closed environment, the change of humidity in the cave controls the change of suction, which leads to a constant adsorption and desorption of moisture in the mural plaster. In this study, it is found that in the high suction section, the moisture content of the mural plaster varies greatly with the suction, therefore, the change of moisture content caused by the change of humidity in the grotto is more severe. When the humidity increases slightly, the water content of the plaster will increase, and when the humidity of the cave increases from 12% to 87%, the moisture content of the mural plaster will increase by nearly 15% when reaches stabilization. Because the water content of the coarse mud layer is higher than that of the fine mud layer at the same humidity, and the coarse mud layer is located inside the plaster, this moisture absorption process will continue. Previous studies on fresco crisp alkali, herpes and other deterioration concluded that "salt moves with water, if there is water, there is trouble". This humidity change leads to the process of moisture absorption and dehumidification of the plaster layer, which will greatly promote the development of mural deterioration.

Although the Mogao Grottoes will not be directly damaged by liquid water under the current daily maintenance, the relative humidity in the grottoes will rise rapidly due to the summer rainfall or the opening to a large number of tourists. The soil-water characteristic curve in the high suction section indicates that when the suction of the plaster is higher than 3.8×10^4 kPa, the soil-water characteristic curves of the coarse mud layer and the fine mud layer approximately overlaps, the change of water content is no longer drastic with the change of suction, and the corresponding water content is very low. According to the Kelvin formula, the suction of 3.8×10^4 kPa corresponds to 58% of the relative humidity at 20 ℃, therefore, it is recommended that the relative humidity in the daily maintenance of the Mogao Grottoes should not be higher than 58%, and the lower the better, and the relative humidity should not change greatly.

The soil water characteristic curves of Chengban soil before and after desalting are different, which shows that the salt in the plaster also has a significant influence on the soil water retention behaviors. It can be seen from the curve that the curve of suction is approximately overlapped only when it is higher than 3.8×10^4 kPa, indicating that the effect of salt may disappear when the plaster is nearly dry. However, in the section with suction less than 3.8×10^4 kPa, the water content of the sample without desalting is higher than that of the sample after desalting, which may be due to the fact that the salt in the soil layer can help the soil capture more water. This has also been confirmed by the moisture absorption and dehumidification test of plaster with different salt contents carried out by Su et al.[26] Further study is needed on the impact of the salt in the plaster on the soil water characteristics behaviors.

5 Conclusions

The pressure plate test and vapor equilibrium technique are used to measure the soil-water characteristic curve of the simulated mural plaster and the following conclusions are drawn:

(1) Combined with different test methods, the reliable soil-water characteristic curves of mural plasters with different material compositions in the full suction range are obtained.

(2) The difference of soil-water characteristic curve between coarse mud layer and fine mud layer is not significant, but the water content of coarse mud layer is higher than that of fine mud layer under the same suction because there are many pores in coarse mud layer. The coarse mud layer also has the characteristic of abrupt water release in the high suction range.

(3) Based on the changes of the soil-water characteristic curve in the high suction sections of the coarse mud layer and the fine mud layer, it is recommended that the humidity in the Mogao Grottoes should not be higher than 58% in the daily maintenance, and the humidity should be stable and should not fluctuate greatly.

(4) There is a great difference in fitting the soil-water characteristic curve of mural plaster by using the results of a single test data, but the soil-water characteristic curve with high precision can be obtained by combining the test data of the total suction range.

References

[1] LI Z X. Deterioration and treatment of wall paintings in grottoes along the silk road in china and related conservation efforts[C]//Conservation of Ancient Sites on the Silk Road: Proceedings of the Second International Conference on the Conservation of Grotto Sites, Mogao Grottoes. Los Angeles: Getty Conservation Institute, 2010: 46–55.

[2] ZHANG Ming-quan, ZHANG Hu-yuan, ZENG Zheng-zhong, et al. The mechanisms of efflorescent disaster of wall-paintings in Mogao Grottoes[J]. Journal of Lanzhou University (Natural Science Edition), 1995, 31(1): 96–101.

[3] LORI W, NEVILLE A. The conservation of Cave 85 at the Mogao Grottoes, Dunhuang: a collaborative project of the Getty Conservation Institute and the Dunhuang Academy[R]. Los Angeles: Getty Conservation Institute, 2013: 57–88.

[4] ZEHNDER K. Long-term monitoring of wall paintings affected by soluble salts[J]. Environmental Geology, 2007, 52(2): 353–367.

[5] LU N, LIKOS W. Soil mechanics for unsaturated soils[M]. Translated by WEI Chang-fu. Beijing: Higher Education Press, 2012.

[6] YAN Geng-sheng. Study on the unsaturated permeability of the base in mural[C]//Proceedings of the 16th CSRME Annual Academic Conference. Wuhan: China Electric Power Press, 2010: 80–85.

[7] ZHAO Tian-yu, ZHANG Hu-yuan, YAN Geng-sheng, et al. The soil-water characteristics of base coat in Mogao Grottoes murals[J]. Dunhuang Research, 2011(6): 36–42.

[8] ZHANG Hu-yuan, JIANG Xiao, WANG Jin-fang, et al. A study on the mechanism of capillary-driven transport of soluble salt in mural plaster[J]. Rock and Soil Mechanics, 2016, 37(1): 1–11.

[9] DUAN Xiu-ye. Study on the materials of the mural in Mogao Grottoes[J]. Dunhuang Research, 1988(3): 41–59.

[10] ZHANG Ming-quan, ZHANG Hu-yuan, ZENG Zheng-zhong, et al. Material composition and microstructure characteristics of the plaster at Mogao Grottoes[J]. Dunhuang Research, 1995(3): 23–28.

[11] ZHAO Lin-yi, LI Yan-fei, YU Zong-ren, et al. The technique and materials about making the wall paintings of the Mogao Grottoes on the Silk Road[J]. Dunhuang Research, 2005(4): 75–82.

[12] GUO Qing-lin. Origin of water and salts responsible for wall paintings disease at Dunhuang Mogao Grottoes[D]. Lanzhou: Lanzhou University, 2009.

[13] Ministry of Water Resources of the People's Republic of China. GB/T 50123 − 1999 Standard for soil test method[S]. Beijing: China Planning Publishing House, 1999.

[14] HU P, YANG Q, LI P Y. Direct and indirect measurement of soil suction in the laboratory[J]. Electronic Journal of Geotechnical Engineering, 2010, 15(3): 1–14.

[15] GREENSPAN L. Humidity fixed points of binary saturated aqueous solutions[J]. Journal of Research of National Bureau of Standards,1997, 81A: 89–96.

[16] THOMSON W L X. On the equilibrium of vapour at a curved surface of liquid[J]. Philosophical Magazine, 1871, 42(282): 448–452.

[17] International Organization of Legal Metrology. R121 Standard relative humidity of saturated salt solution[S]. [S. l.]: China Metrology Press, 2000.

[18] WEI Li, CHAI Shou-xi, CAI Hong-zhou, et al. Research on tensility of wheat straw for reinforced material[J]. Rock and Soil Mechanics, 2010, 31(1): 128–132.

[19] TIAN Hu-nan, KONG Ling-wei. Experimental research on effect of fine grains on water retention capacity of silty sand[J]. Rock and Soil Mechanics, 2010, 31(1): 56–60.

[20] MCQUEEN I S, MILLER R F. Approximating soil moisture characteristics from limited data: empirical evidence and tentative model[J]. Water Resources Research, 1974, 10(3): 521–527.

[21] FREDLUND D G, XING A. Equations for the soil-water characteristic curve[J]. Canadian Geotechnical Journal, 1994, 31(4): 521–532.

[22] WANG Dong-lin, LUAN Mao-tian, YANG Qing. Experimental study of soil-water characteristic curve of remolded unsaturated clay[J]. Rock and Soil Mechanics, 2009, 30(3): 751–756.

[23] VAN GENUCHTEN T H M. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils1[J]. Soil Science Society of America Journal, 1980, 44(5): 892.

[24] TAN Xiao-hui, YU Wei, SHEN Meng-fen, et al. Experimental study and curve fitting of soil-water characteristic curve[J]. Rock and Soil Mechanics, 2013, 34(Suppl.2): 51–56.

[25] LIU Gang, XUE Ping, HOU Wen-fang, et al. Monitoring micro-meteorological environment of Cave 85 of Mogao Grottoes[J]. Dunhuang Research, 2000 (1): 36–41.

[26] SU Bo-min, CHEN Gang-quan. Compare on velocity of absorbing water and evaporation of simulated wall paintings plaster contained salts in different amounts[J]. Dunhuang Research, 2005(5): 62–65.