Original Research

Effect of Substrate Ratio on Soil's Water-Holding Capacity and Shrinkage

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Abstract

In order to explore the effect of substrate ratio on soil's water-holding characteristics and soil shrinkage, the soil of Lanzhou New Area (China) was selected as the test soil, while pure soil was used as the control group (CK). Four kinds of mixed substrates T1 (1:1:1), T2 (1:1:2), T3 (4:2:4), T4 (3:3:4) were prepared by mixing mushroom residue, cow dung and vermiculite in different volume ratios. The characteristic curves of the moisture in soil for different substrate ratios were constructed and fitted with Van Genuchten and Brooks-Corey models. The influence of substrate ratios on soil hydraulic parameters was systematically studied, and the soil's water-holding capacity and shrinkage for various treatments were analyzed. The results showed that, compared with CK, the T1, T2, T3 and T4 treatments significantly improved the soil saturated water content, field water-holding capacity and effective water content in the study area within the suction range of 0-7000 cm. Moreover, the T2 treatment had a significant effect on soil effective water content. The soil's water-holding capacity of the five treatments was found to lie in the following descending order: T1>T2>T4>T3>CK. Furthermore, VG-M (m, n), VG-M (1-1/n, n), BC-M, VG-B (m, n), VG-B (1-2/n, n) and BC-B could fit the characteristic curves of the moisture in soil for the five treatments. Among them, the VG model could be used as the optimal model to fit the characteristic curves of the moisture in soil for the five treatments at the same time. With the soil dehydration, the soil's effective linear shrinkage rate increased with the increase of suction, whereas the two had a good logarithmic relationship. Additionally, the addition of substrate was found to be effective. The soil's shrinkage was inhibited. The study provides a theoretical basis for the improvement of soil's physical properties and ecological restoration in arid areas.

Introduction

China's agricultural waste production is huge, and includes annual livestock manure up to 3.8 billion tons, crop straw up to about 900 million tons, and vegetable waste up to about 260 million tons [1]. The burning of crop straw and the large emission of livestock, poultry and rural domestic manure have caused damage to agricultural ecosystem and environment, whereas the problem of agricultural non-point source pollution is particularly prominent [2]. Resource utilization from agricultural waste, such as crop straw and livestock

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manure, is a major challenge facing the world. Scientific and rational utilization of agricultural waste is of great significance to improve the benefits that can be obtained from the agriculture [3-4]. Zhao [5] mixed agricultural waste compost, straw and clay to make a cultivation substrate for drought resistance and root promotion, which had the ability to save water and retaining fertilizer, and could provide a good growth environment for plants. It is one of the feasible ways to improve the utilization efficiency of agricultural waste. In addition, the combination of agricultural waste into organic substrate can effectively improve the physical structure of soils, increase the water-holding capacity of soils, maintain and improve soils' organic matter, increase the reserves of nutrients in the soil, effectively promote the growth and development of crop roots, improve their disease resistance, and save production materials [6-8]. It is an effective measure to improve the ecological environment of farmlands, modern irrigation agriculture, and dry farming. It is an important technical support for cost-saving and increasing the efficiency of agriculture. Moreover, it is also an effective means to improve the sustainable development of non-tillage (desert and saline-alkali land) agriculture.

The soil moisture characteristic curve represents the relationship between the moisture contents and the suction of soil, which not only reflects the water-holding capacity of soil, but also indirectly reflects the pore distribution. It is an important parameter for simulating the movement of moisture and the transport of solute within the soil, and plays an important role in studying and evaluating the water-holding characteristics of soil and the solute transport in soil's moisture movement [9-13]. The moisture characteristic curve of soil is mainly affected by soil's texture, bulk density, especially soil's structure and many other factors [14-16]. At present, it is difficult to theoretically calculate the relationship between the water potential and water content of soil. Empirical model is often established after the data are measured using experimental methods. The models for fitting the soil's water characteristic curve are mainly the Van Genuchten model and its correction model, Brooks and Corey model, dual-porosity model, lognormal distribution model [17-19]. Among them, the Brook and Corey model and Van Genuchten and its correction model are the most widely used models.

Wet swelling and drying shrinkage are two of the most basic properties of soil. Farmlands with serious soil expansion and contraction are prone to drought and waterlogging disasters, resulting in a large loss of nutrients and obvious damage to crop's physiology, which is one of the main obstacles to the improvement of regional farmland's foundation fertility [20]. Haines [21] proposed the concept of shrinkage curve to describe the relationship between the volume of soil and the pore water. During the process of centrifugation, under the action of strong centrifugal force, the soil continuously loses water, which leads to the gradual decrease of soil's moisture content and the gradual

increase of bulk density, resulting in the deformation of soil and the change of volume shrinkage. Many studies assume that the volume of soil is constant during drying and wetting, whereas the water-holding capacity and soil shrinkage are independent phenomena, ignoring the influence of soil shrinkage on soil's water-holding capacity.

In short, in the current paper, centrifugation is used to determine the soil's water characteristic curve under different mixing ratios of substrate, and the influence of different mixing ratios of substrate on soil's water characteristic curve was analyzed. The influencing mechanism of different substrate ratios on soil's water-holding capacity was revealed, and the suitability of different treatment models was analyzed. The multivariate dynamic relationship between the volumetric water content and suction of soil was explored, and the shrinkage during the loss of water by soil was analyzed. The study aims at providing a theoretical basis for soil improvement and ecological restoration.

Materials and Methods

Experimental Materials

The soil used in the experiments was taken from Lanzhou New District, Lanzhou City, Gansu Province, China, whereas the samples were taken from 0-30 cm tillage soil layer. According to the international soil texture classification standard, the soil texture was loam and the pH was 8.5. The substrate materials were mushroom residue, cow dung and vermiculite. The physical and chemical properties of the basic materials forming the composite substrate are presented in Table 1. The roots and stones of the collected soil were removed, and the soil was naturally dried under dark conditions. After passing through 2 mm sieve, the pure soil was set as the control group (CK). Four kinds of mixed substrates, called T1 (1:1:1), T2 (1:1:2), T3 (4:2:4) and T4 (3:3:4) [22], were prepared by mixing mushroom residue, cow dung and vermiculite according to different volumetric ratios. The mixed soil samples were loaded into the ring knife (volume was 100 cm^3) according to the bulk density of 1.1 g/cm^3. Before the test, all the ring-knife samples were saturated in distilled water for 48 h, and then, dried in a 105ºC incubator for 24 h to calculate the soil's moisture content. Each treatment was repeated three times, and the mean value was taken as the final result.

The moisture characteristic curve of soil was determined using Nissan CR21GII high-speed constant-temperature freezing centrifuge. The temperature was maintained at 4ºC during the measurement. The soil sample was put in the centrifuge. The corresponding equilibrium time increased with the increase of suction. After each centrifugation, the moisture content in the soil was obtained using the gravimetric method

Table 1. Physical and chemical properties of basic materials.

Materials	Test weight (g/cm³)	Water holding capacity (%)	Total porosity (%)	Ventilation pores (%)	Water holding pores (%)	EC (uS·c-m⁻¹)	pH	N (%)	P (%)	K (%)
Mushroom residue	0.45	246.66	87.23	20.91	66.22	3687	7.5	3.17	1.33	2.22
Cow dung	0.4	167.38	60.65	27.12	32.80	7870	6.9	6.32	2.76	2.31

and converted into volumetric moisture content. The distance between the soil's surface and the top of the ring knife was measured using vernier caliper and used to determine the soil's shrinkage during centrifugation.

Research Methods

(1) Van Genuchten (VG) model.

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{\left(1+|ah|^n\right)^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \tag{1}$$

where θ is the volumetric water content (cm³/cm³), θs is the saturated volumetric water content (cm³/m³), θr is the residual volumetric moisture content (cm³/cm³), h is the negative pressure (m), α is the reciprocal of the intake value, and m and n are the shape coefficients, where m is irrelevant to n or $m = 1-1/n$ or $m = 1-2/n$.

(2) Brooks-Corey(BC) model

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \begin{cases} (\alpha h)^{-n} & \alpha h > 1 \\ 1 & \alpha h \leq 1 \end{cases} \tag{2}$$

where S_e is the saturation.

(3) Estimation of soil suction

In the determination of soil moisture characteristic curve using the centrifugation method, the soil suction can be determined according to angular velocity and corresponding centrifugal radius. The suction, corresponding rotational speed and the equilibrium time are presented in Table 2.

$$h = \frac{\rho_w \cdot \omega^2}{2g}\left(R_1^2 - R_2^2\right) \tag{3}$$

where h is the soil suction (pressure head; cm), R_1 is the radial distance from the centrifuge's axis to the center of the soil sample (cm), R_2 is the radial distance from the centrifuge's axis to the bottom of the soil sample (the free surface, cm), ρ_w is the water density (g/cm³), ω is the angular velocity (rad/s), and g is the gravitational acceleration (cm/s²).

(4) Soil moisture constant

Saturated water content, available water content, field water-holding capacity and wilting coefficient can express the characteristics of soil's water-holding capacity. Saturated water content is measured by experiments. Effective water content is the difference between the field water-holding capacity and the wilting coefficient. Field water-holding capacity and the wilting coefficient are expressed by soil water content when the negative pressures are 33 kPa and 1500 kPa [23-24].

(5) Soil shrinkage

During the measurement of soil's moisture characteristic curve using centrifugal method, the soil volume shrinks with the decrease of soil's moisture content. In the experiments, the soil sample was limited by the outer ring knife, and the soil was limited to vertical one-dimensional shrinkage. Due to the different substrate ratios, the saturated expansion rate of soil changes to varying degrees. Therefore, the initial heights of the soil samples for each treatment are different when measuring the shrinkage characteristics. In order to analyze the variation pattern of soil's vertical unidirectional shrinkage distance and avoid the influence of initial height of the soil sample, the effective linear shrinkage rate r_e is introduced as an indicator to measure the change in soil's shrinkage, which can be expressed using Equation (4).

$$r_e = \frac{Z}{Z_0} \times 100\% \tag{4}$$

Table 2. Rotational speed and equilibrium time of each suction.

Suction/cm	Rotating speed/(r/min)	Equilibrium time/min
10	310	10
50	693	17
100	981	26
300	1698	42
500	2193	49
700	2594	53
1000	3101	58
3000	5371	73
5000	6934	81
7000	8204	85

where *Z* is the height of the soil surface falling or rising (cm) and Z_0 is the initial height of the saturated soil (cm).

Data Processing

Based on Origin11.0 software, the soil's moisture characteristic curves for different substrate ratios were plotted, and the soil's moisture characteristic curves were fitted using RETC software. Based upon the results, the suitable empirical model was determined.

Results and Discussion

Effect of Substrate Ratio on Soil's Water Characteristic Curve

During the centrifugation process, the soil's bulk density changes at all times. Therefore, when calculating the volumetric water content, the dry bulk density of the soil involved was calculated after each centrifugation process reached equilibrium. The characteristic curve of soil moisture measured by experiment is shown in Figure 1. It can be seen from Fig. 1 that, when the suction was less than 1000 cm, the slope of the soil's moisture characteristic curve under each treatment was large and densely distributed, whereas the drainage was mainly carried out in large pores. Therefore, even if the soil suction changed a little, it could cause significant indigenous changes in soil's moisture content. Therefore, within the range of suction, the soil moisture characteristic curve presented a "steep" shape, and the soil sample rapidly lost water. When the suction was greater than 1000 cm, the slope of the curve showed an obvious decreasing trend. During this period of suction, only small pores could retain soil moisture, and the soil had a large suction for water. Therefore, the change in soil's moisture content with suction head was not obvious. Within this period of suction,
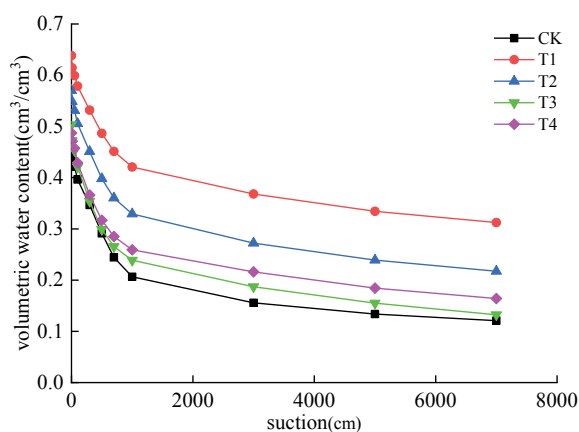

Fig. 1. Soil moisture characteristic curve of different substrate ratios.

the soil's moisture characteristic curve showed a "gentle" shape, and the water loss rate of soil samples decreased. Specifically, the saturated water contents of T1, T2, T3 and T4 treatments increased by 19.77%, 12.97%, 6.26% and 4.65% compared to that of CK, respectively. When CK, T1, T2, T3 and T4 treatments were subjected to the suction of 7000 cm, the volumetric water content under each centrifugation suction decreased by 0.45-31.98%, 2.39-32.61%, 2.18-35.31%, 3.1-37.09% and 1.6-32.32% compared with the initial saturated water content, respectively.

Determination of Optimum Model of Soil Water Characteristic Curve

Two widely used models, Van Genuchten (VG) and Brooks-Corey (BC), were selected to fully consider the relationship between m and n in the parameters of VG model, and combined with the unsaturated soil hydraulic conductivity models (the Mualem and Burdine models). Therefore, in this study, six models including VG-M (*m*, *n*), VG-M (1-1/*n*, *n*), BC-M, VG-B (*m*, *n*), VG-B (1-2/*n*, *n*) and BC-B were used to conduct the suitability analysis on the experimental data of soil's moisture characteristic curves for different substrate ratios. By comparing these models, the error between the measured and fitted values of soil's volumetric water content under different suctions was analyzed, and the fitting accuracies of the models were characterized by calculating the sum of squares (*SSQ*) and the determination coefficient (R^2). This way, the optimal fitting model was determined. The fitting statistical eigenvalues of each model are listed in Table 3.

The hydraulic parameters in each model could be determined by fitting the measured soil's moisture characteristic curve. Based on this, the soil's volume under each suction head could be further obtained, and the error analysis could be carried out by comparing it with the corresponding measured volumetric water content. It can be seen from the results presented in Table 3 that each fitting model had good applicability to the tested soil of different treatments. The determination coefficient was greater than 0.9054, whereas the relative error was small. Moreover, the fitting accuracy was high. The VG and BC models were also compared. The measured soil volumetric water content of the VG model was closer to the fitting value and had higher accuracy. VG model combined with the unsaturated hydraulic conductivity model (Mualem and Burdine model) was also considered. However, the Mualem model's fitting accuracy was higher. Combined BC model with different unsaturated hydraulic conductivity models, the difference of soil water characteristic curve fitting was not obvious. Therefore, this paper selected the VG-M (*m*, *n*) model with the highest correlation coefficient, the smallest *SSQ,* the largest R^2 and superior simulation effect as the optimal model.

Table 3. Fitting values and fitting errors of hydraulic parameters of each model.

Substrate ratio	Fiting model	θr cm³·cm⁻³	θs cm³·cm⁻³	α cm⁻¹	n	R^2	SSQ
CK	VG-M(m, n)	0.0650	0.4625	0.0086	1.0050	0.9992	0.0002
	VG-B(m, n)	0.0123	0.4537	0.0254	2.0050	0.9949	0.0010
	VG-M(1-1/n, n)	0.0283	0.4579	0.0198	1.3981	0.9981	0.0004
	VG-B(1-2/n, n)	0	0.4525	0.0283	0.0283	0.9961	0.0007
	BC-M	0	0.4511	0.0325	0.2963	0.9942	0.0011
	BC-B	0	0.4511	0.0325	0.2963	0.9942	0.0011
T1	VG-M(m, n)	0.1936	0.6291	0.0041	1.0427	0.9955	0.0006
	VG-B(m, n)	0.2591	0.6217	0.0046	2.005	0.9163	0.0114
	VG-M(1-1/n, n)	0	0.6287	0.0078	1.1742	0.9948	0.0007
	VG-B(1-2/n, n)	0	0.6197	0.0098	2.1589	0.9924	0.0010
	BC-M	0.1650	0.6077	0.0066	0.2772	0.9845	0.0021
	BC-B	0.1650	0.6077	0.0066	0.2772	0.9845	0.0021
T2	VG-M(m, n)	0.1154	0.5613	0.0047	1.1427	0.9964	0.0006
	VG-B(m, n)	0.1636	0.5555	0.005	2.005	0.9262	0.0121
	VG-M(1-1/n, n)	0	0.5615	0.0075	1.2387	0.9958	0.0007
	VG-B(1-2/n, n)	0	0.5522	0.0095	2.2173	0.9935	0.0011
	BC-M	0	0.5501	0.0126	0.1951	0.9859	0.0023
	BC-B	0	0.5501	0.0126	0.1951	0.9859	0.0023
T3	VG-M(m, n)	0.0365	0.4929	0.0064	1.0968	0.9961	0.0007
	VG-B(m, n)	0.0875	0.4873	0.0070	2.005	0.9054	0.0166
	VG-M(1-1/n, n)	0	0.4898	0.0091	1.3056	0.9957	0.0008
	VG-B(1-2/n, n)	0	0.4815	0.0118	2.2758	0.9925	0.0013
	BC-M	0	0.4878	0.0215	0.2270	0.9801	0.0035
	BC-B	0	0.4878	0.0215	0.2270	0.9801	0.0035
T4	VG-M(m, n)	0.1022	0.4812	0.0057	1.2843	0.9968	0.0005
	VG-B(m, n)	0.1268	0.4787	0.0060	2.005	0.9410	0.0083
	VG-M(1-1/n, n)	0	0.4839	0.0089	1.2596	0.9959	0.0006
	VG-B(1-2/n, n)	0	0.4763	0.0115	2.2353	0.9957	0.0006
	BC-M	0	0.4720	0.0137	0.2188	0.9913	0.0012
	BC-B	0	0.4720	0.0137	0.2188	0.9913	0.0012

Note: When the fitted value of θ_r was less than 0.001, the RETC software automatically selected its value to be 0.

Effect of Substrate Ratio on Soil's Hydraulic Parameters

According to the soil's water characteristic expression for each treatment obtained by fitting, the corresponding field water-holding rate, wilting coefficient and effective water content were calculated, and the corresponding results are presented in Table 4.

From Table 4, it can be seen that the addition of substrate increased the saturated moisture content and the field water-holding rate of soil, whereas the effective moisture content also got improved. The effect of T2 treatment on the effective moisture content was obvious. The effects of T3 and T4 treatments on water constants were mostly insignificant. With the addition of substrate, the increase in the saturated water content of the test soil indicates that the total porosity increased after saturation, which may have been caused by the large

Table 4. Volumetric fraction of water constant.

	Measured saturated water content/%	Field water retention/%	Wither coefficient/%	Effective moisture content/%
CK	47.76	22.77	7.28	15.49
T1	63.84	51.11	27.41	23.7
T2	57.04	42.84	18.18	24.66
T3	50.33	33.29	10.90	22.39
T4	48.72	34.90	13.58	21.32

particle density of the substrate itself. Each treatment in this experiment was filled with the same bulk density (1.1 g/cm³), which was bound to cause the decrease in the volumetric ratio of dry matter per unit volume in the treatment that he addition of substrate to increase the total porosity, thereby increasing the saturated water content. The addition of substrate increased the effective moisture content, indicating that the addition of substrate was more conducive to maintaining the soil water required for crops in the study area.

Effect of Substrate Ratio on Soil's Shrinkage Characteristics

Fig. 2 shows the variation characteristics of soil's volume during the determination of soil's water characteristic curve. Due to the centrifugal force, with the increase of rotational speed and pressure, the soil's moisture content decreased gradually, and the soil sample was compressed. Moreover, the volume decreased gradually, indicating that one-dimensional shrinkage occurred. As can be seen from Fig. 2, for five treatments, in the low suction section (h = 0-1000 cm), with the increase of suction, soil shrinkage increased significantly, indicating that the soil shrinkage effect was obvious. In the high suction section (h = 1000-7000 cm), with the increase of suction, the soil shrinkage increased. However, the increase rate decreased, indicating that the soil's shrinkage effect was not obvious. This is due to the low suction. There are many large pores in the soil, and the water is also discharged through the pores. Therefore, during the determination of soil's water characteristic curve, the soil samples had obvious shrinkage changes. With the increase of suction, the number of macropores in soil decreased, and the soil's drainage also gradually transited from macropore drainage to small and medium pore drainage. At this time, the potential of soil shrinkage was greatly reduced. Therefore, although the soil samples were still compressed, the degree of shrinkage was gradually weakened. The comparison of results presented in Figs 1 and 2 shows that the change of volumetric water content under the same suction condition was negatively correlated with the change of soil's shrinkage rate.

As shown by the results presented in Table 5, for CK, T1, T2, T3 and T4, there was a good logarithmic
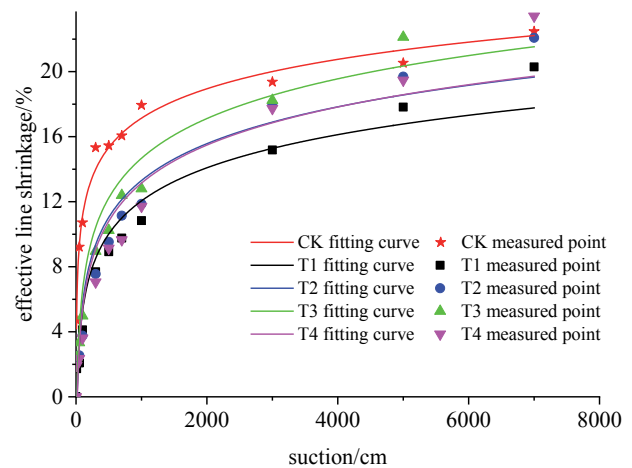

Fig. 2. Effective shrinkage curves of different substrate ratios.

relationship between the effective shrinkage and suction, indicating that $S = a \cdot ln(h) + b$. The corresponding fitting coefficients are listed in Table 4, which are consistent with the results of Lv [25]. In the logarithmic model, the parameter a can characterize the slope of the fitting curve, representing the change in soil's shrinkage with suction. The soil shrinkage was found in the following descending order: CK>T3>T4>T2>T1. The shrinkage of soil with additional substrate was generally smaller than CK. Furthermore, the parameter b represents the change of soil's expansion and contraction under near saturation, and it is found that all treatments caused expansion ($b<0$). Therefore, the addition of substrate inhibited the contraction to a certain extent.

Table 5. Soil shrinkage parameters for different substrate ratios.

	a	*b*	*R²*
CK	3.610	-8.906	0.991
T1	2.939	-8.256	0.938
T2	3.270	-9.284	0.924
T3	3.526	-9.683	0.928
T4	3.379	-10.203	0.905

Discussion

Soil water retention capacity is critical to maintaining soil ecosystems and ensuring food production. In the centrifugation process, the low suction section is mainly the capillary water of large pores, whereas the medium and high suction sections are mainly determined by the surface adsorption of soil particles [26]. Therefore, in the low suction range, the soil moisture characteristic curve decreased rapidly, and a flat area appeared with the increase of suction, which was consistent with the study of Amoakwah [27]. Soil moisture characteristic curve is affected by soil type, centrifugation time, centrifugal suction and certain other factors. The volumetric water content of soil, mixed with different proportions of substrate, gradually decreased with the increase of centrifugal speed and the centrifugal suction. The decrease rate of soil's volumetric water content under high suction was greater than that under low suction, and the longer the centrifugation time, the lower the soil's volumetric water content. The simulation results of VG and BC models show that VG model was more suitable to simulate the water characteristic curve of soil that was mixed with different proportions of substrate. Xing and Zhang [28] compared the simulation results of soil's moisture characteristic curves of VG model with those of other models, and found that the accuracy of VG model was the highest. Zhao [29] compared the soil's moisture characteristic curves of sandy land with different planting years, and found that the fitting accuracy of Van Genuchten model was higher than that of the Brooks-Corey model. The saturated moisture content of soil having substrate was higher than that of the blank group, which was consistent with the results of Gan [30]. Saturated water content of T1 treatment was higher than other treatments, indicating that T1 treatment was more effective in improving soil's water-holding capacity.

The changes in soil's porosity and its structural composition, caused by the substrate, are the main factors affecting the physical properties of farmland soil. The results of this study show that the use of substrate can improve the water retention capacity of soil, increase the field water retention rate and improve the available water of plants in soil, which is consistent with the results of Hansena V [31], who found that the application of substrate in soil could improve soil's porosity and the number of soil aggregates, improve soil's physical and chemical properties, and have a positive impact on crop yield.

The improvement of soil shrinkage can increase soil's water-holding capacity, reduce soil moisture and nutrient loss, and promote root development and growth of crops. The results of this study showed that mixing different proportions of substrate in soil could effectively inhibit soil's shrinkage, whereas the soil's linear shrinkage of each treatment increased with the increase of suction. Moreover, the two parameters showed a logarithmic relationship, which was consistent with the results of Xing [32]. Wang [33] found that the organic matter in soil could effectively inhibit the shrinkage of soil. Peng [34] reported that the shrinkage of soil was positively related with the content of organic matter in soil, and the addition of substrate increased the content of organic matter in soil.

The laboratory results of this study should further promote the long-term fixed-point positioning research in the field environment, further verify and deepen the cognition of the influence of substrate ratio on soil's water-holding capacity and shrinkage, and the potential of substrate improvement in low-utility land quality.

Conclusions

In this paper, five soil samples of CK, T1, T2, T3 and T4 were analyzed for soil moisture characteristic curve and the optimal model was determined. Meanwhile, the effects of different substrate ratios on soil's hydraulic characteristic parameters and the shrinkage characteristics were studied. Moreover, the soil's moisture characteristic curves were also analyzed. Based upon the results, following conclusions are drawn.

Within the range of 0-7000 cm suction, the addition of substrate significantly increased the saturated moisture content, field water-holding capacity and effective moisture content of soil. Furthermore, T2 had a stronger effect on the improvement of soil's effective moisture content. Compared with CK, the saturated moisture contents of T1, T2, T3 and T4 increased by 19.7%, 12.97%, 6.26% and 4.65%, respectively. Additionally, CK, T1, T2, T3 and T4 were centrifuged for 85 min. Compared with the initial saturated water content, the volumetric water content under each centrifugal suction decreased by 0.45-31.98%, 2.39-32.61%, 2.18-35.31%, 3.1-37.09% and 1.6-32.32%, respectively. The soil's water-holding capacity of the five treatments was found in the following descending order: T1>T2>T4>T3>CK.

The six models of VG-M (m, n), VG-M (1-1/n, n), BC-M, VG-B (m, n), VG-B (1-2/n, n) and BC-B could well fit the water characteristic curves of the five tested soils. The VG model had the highest correlation coefficient, the lowest SSQ and the highest R^2, which can be used as the optimal model to fit the soil's water characteristic curves of five different tested soils.

With soil dehydration, the soil's effective linear shrinkage increased with the increase of suction, and the two had a good logarithmic correlation. Soil shrinkage was negatively correlated with the volumetric water content, and the addition of substrate effectively inhibited the shrinkage of soil.

Acknowledgments

Conflict of Interest

The authors declare no conflict of interest.

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