Simulation Study on Soil-Water Characteristic Curve of Graphite Tailings in Typical Area

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Abstract. The soil-water characteristic curve (SWCC) is a crucial parameter for studying the movement of water in unsaturated soils. This study established three bulk densities (1.45, 1.55, and 1.65 g/cm³) to simulate tailings at different depths, utilizing the centrifuge method to determine their SWCCs and evaluate the applicability of various models. The results indicate that the water retention capacity of the tailings at a depth of 0~20 cm is the lowest, while that at 40~60 cm is the highest, with the 20~40 cm depth exhibiting intermediate retention capacity. Both the van Genuchten model and the Gardner model showed satisfactory fitting results; however, the Brooks-Corey model yielded residual water contents that were inconsistent with physical reality. In summary, the van Genuchten model demonstrated the highest fitting accuracy and is therefore suitable for modeling the SWCC of graphite tailings.

Keywords: graphite tailings; ecological restoration; SWCC; model fitting

1 Introduction

China has abundant graphite resources, which have made significant contributions to economic development and technological progress. However, the production of 1 ton of graphite generates approximately 10~15 tons of tailings [1]. The management and disposal of these tailings pose serious threats to the ecological environment and human health in mining areas. Therefore, there is an urgent need for ecological restoration of tailings storage facilities.

The ecological restoration of tailings storage facilities relies on vegetation reconstruction. However, China's major mineral resources are primarily concentrated in arid and semi-arid regions, where water scarcity limits plant growth on tailings. Therefore, studying the water-holding capacity of tailings soil is crucial for effective ecological restoration.

The soil-water characteristic curve describes the relationship between soil water potential and moisture content, reflecting the effectiveness and retention capability of soil water. It is an essential parameter for studying unsaturated soils. Wang et al. [2] investigated the effects of different soluble salt contents on the soil-water characteristic

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curve of loess in Yili, Xinjiang, and fitted the data using the Gardner model. Li et al. [3] determined the SWCCs of coarse and fine-grained soils, aiming to establish a predictive model that considers the impacts of hysteresis effects, stress states, and soil structure. Hedayati et al. [4] compared and evaluated the accuracy of field versus laboratory testing of moisture characteristic curves for road embankments. Dang et al. [5] studied the effects of landfill age and dry density on the SWCCs of solid waste landfill soils. Existing research has primarily focused on the water retention properties of loess or agricultural soils, with relatively limited data available on the water retention capacity of tailings. As a special category of soil, tailings exhibit differences in water retention capabilities compared to conventional soils. Additionally, various soil water characteristic curve fitting models established in previous studies are designed for specific soil types and may not be well-suited for tailings materials. In light of this, the present study utilized a centrifuge method to determine the soil-water characteristic curves of tailings at different depths and applied the van Genuchten(VG), Brooks-Corey(BC), and Gardner(G) models for data suitability analysis. This research aims to provide a theoretical basis for tailings soil improvement, thereby facilitating the ecological restoration of tailings storage facilities and enhancing land reclamation outcomes.

2 Materials and Methods

2.1 Materials

The tailings used in this experiment were collected from a graphite tailings storage facility in Heilongjiang Province. After air drying and grinding, the material was sieved through a 2 mm mesh to remove impurities, and the resultant tailings were set aside for further analysis. The primary minerals in the tailings include quartz, muscovite, calcite, and potassium feldspar, as depicted in Fig. 1. The dominant particle size ranges are 0~0.075 mm and 0.075~0.25 mm, with a uniformity coefficient (Cu) of 4 and a coefficient of gradation (Cc) of 1.373, indicating poorly graded sand.

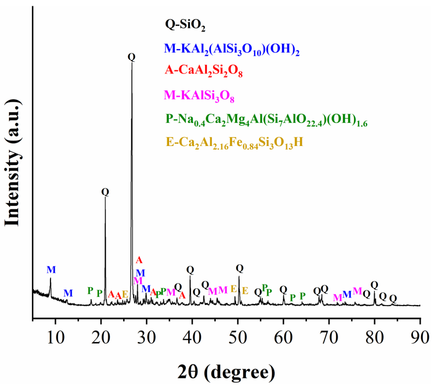


Fig. 1. Mineral composition of graphite tailings.

2.2 Sample Preparation

Based on multiple in-situ bulk density tests, the bulk densities of the tailings at depths of 0~20 cm, 20~40 cm, and 40~60 cm were approximately 1.45, 1.55, and 1.65 g/cm^3, respectively. Therefore, three different bulk densities were established in this experiment to simulate the field conditions of the tailings. To avoid uneven compaction caused by human factors, a ring cutter was used to prepare remolded soil samples, with the ring cutter having a volume of 100 cm^3. The required mass of wet soil to be placed in the ring cutter for each specified bulk density was calculated based on the predetermined bulk density, moisture content, and ring cutter volume. The corresponding mass of wet soil was then weighed and placed into the ring cutter, followed by vertical compression to form the samples.

2.3 Test Method

2.3.1 Determination of Soil-Water Characteristic Curve.

The advantages of using the centrifuge method to determine the soil water characteristic curve include speed, accuracy, a wide range of applicability, and minimal environmental influence. Therefore, this study employed the high-speed constant-temperature centrifuges CR21G and CR22N produced by HITACHI, Japan, for the measurements.

Firstly, the prepared ring knife samples were immersed in water for 24 hours to ensure full saturation. Secondly, the samples were correctly positioned and leveled in the centrifuge, after which the lid was securely closed. The centrifuge was then operated at pre-calculated speeds and durations, recording the mass of the centrifuge tubes after each centrifugation stage. After completing the final stage of the experiment, the soil samples were removed, dried at 105°C, and then cooled. Finally, the volumetric water content of the soil samples was calculated based on the experimental data corresponding to different matric potentials.

2.3.2 Fitting Model.

The VG model, BC model, and G model have been widely applied due to their good applicability to different types of soils. Therefore, this study selects the VG model, see Eq. (1), BC model, see Eq. (2), and G model, see Eq. (3) to investigate their suitability for soil-water characteristic curves (SWCC) of tailings at various depths.

$$\theta(S) = \frac{\theta_s - \theta_r}{[1+(S/a)^n]^m} + \theta_r \tag{1}$$

$$\theta(S) = \frac{\theta_s - \theta_r}{(S/a)^n} + \theta_r \tag{2}$$

$$\theta(S) = \frac{\theta_s - \theta_r}{1+(S/a)^n} + \theta_r \tag{3}$$

Where S is matric suction; $\theta(S)$ is the volumetric water content when the matric suction is S; θ_s is saturated volumetric water content; θ_r is the residual volume water content; a is a parameter related to the intake value, corresponding to the inflection point of the curve; n is a parameter related to the pore size distribution, corresponding to the slope of the curve; For the VG model, $m = 1 - 1/n$.

2.3.3 Evaluation Index of Model Prediction Accuracy.

The predictive accuracy of the models is evaluated using the mean error (E_m), the sum of squared errors (SSE), the root mean square error ($RMSE$), and the coefficient of determination (R^2) between observed and predicted values. The specific equations are as follows:

$$E_m = [\sum_{i=1}^{n}(\theta_i - E_i)]/n \quad (4)$$

$$SSE = \sum_{i=1}^{n}(\theta_i - E_i)^2 \quad (5)$$

$$RMSE = \sqrt{[\sum_{i=1}^{n}(\theta_i - E_i)^2]/n} \quad (6)$$

$$R^2 = 1 - [\sum_{i=1}^{n}(\theta_i - E_i)^2]/[\sum_{i=1}^{n}(\theta_i - \bar{\theta})^2] \quad (7)$$

Where n is the number of measured values of volumetric water content of tailings; θ_i is the measured volumetric water content under a certain matric suction; E_i is the volumetric water content obtained by model fitting under a certain matric suction. $\bar{\theta}$ is the average value of measured volumetric water content.

3 Result and Discussion

3.1 Characteristics of Soil-Water Characteristic Curves

The soil-water characteristic curves (SWCCs) for tailings at different depths are presented in Fig. 2. For analytical convenience, the curves can be categorized into three segments: low suction range (0~20 kPa), medium suction range (20~100 kPa), and high suction range (100~1000 kPa). In the low suction range, the volumetric water content decreases rapidly with increasing matric suction, representing the primary phase of soil drainage. In the medium suction range, the rate of decrease in volumetric water content gradually slows, indicating a slower drainage process. In the high suction range, the curves exhibit a nearly horizontal trend, indicating that the soil experiences negligible drainage.

As the depth increases, the saturated volumetric water content of the tailings gradually decreases. This phenomenon may be attributed to an increase in bulk density, leading to a more compact soil structure with reduced pore spaces between soil particles, thereby restricting the entry of free water. At identical matric suction conditions, higher curves indicate greater water retention capacity. Thus, the tailings at 0~20 cm depth exhibit the lowest water retention capacity, while those at 40~60 cm depth demonstrate the highest capacity. This observation suggests a positive correlation between the water retention capacity of tailings and bulk density.

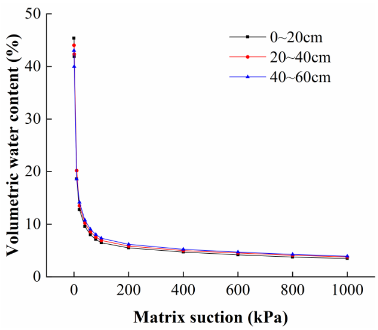


Fig. 2. Soil-water characteristic curves of tailings at different depths.

3.2 Soil-Water Characteristic Curve Model Fitting

The fitted curves of different models are shown in Fig. 3, where it is evident that the predicted values of the BC model deviate significantly from the measured values. The fitting parameters of the models are presented in Table 1. The residual volumetric water content obtained from the BC model fitting is negative, which does not align with actual conditions. Therefore, the BC model is not suitable for fitting the soil-water characteristic curves of this tailings.

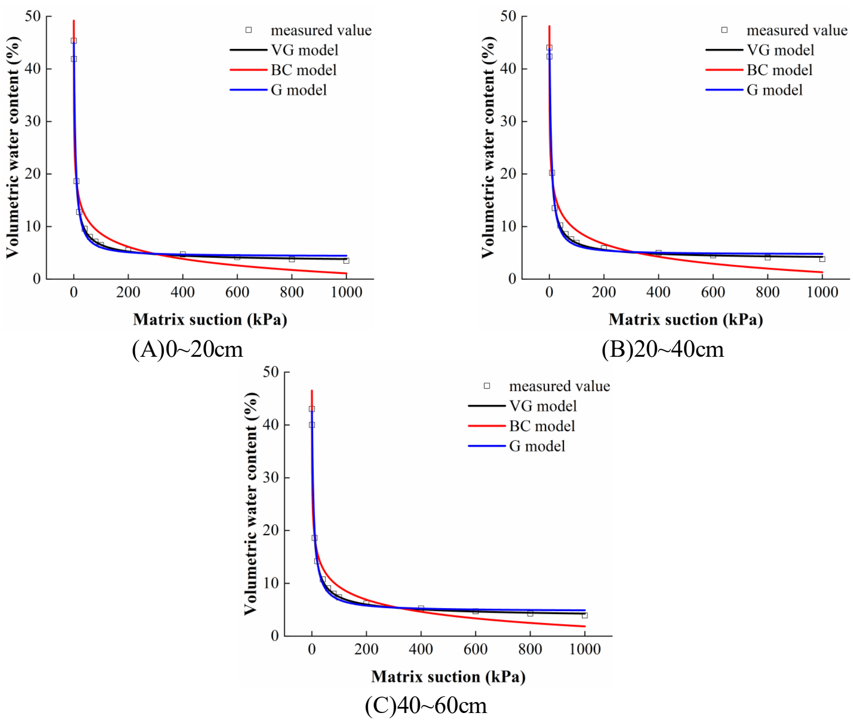


Fig. 3. Fitting results of soil-water characteristic curves for tailings at different depths.

From Table 1, the fitting results for parameter a and θ_r from the G model are greater than those from the VG model, while the parameter n shows the opposite trend. For both models, the fitted parameters exhibit a trend of first increasing and then decreasing with increasing depth, reaching their maximum values between 20~40 cm.

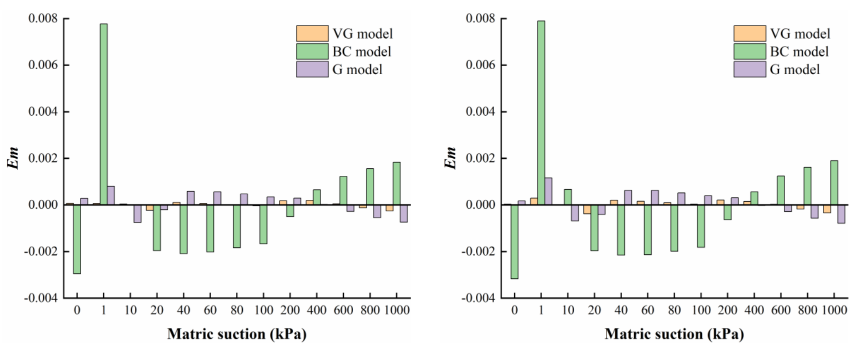
Table 1. Fitting parameters of the models for tailings at different depths.

Depths	Model	a	n	m	θ_r
	VG model	2.326	1.665	0.399	3.072
0~20cm	BC model	0.158	0.121	—	-22.363
	G model	6.313	1.135	—	4.322
	VG model	3.209	1.734	0.423	3.641
20~40cm	BC model	0.172	0.102	—	-28.850
	G model	7.558	1.199	—	4.705
	VG model	2.243	1.590	0.371	3.193
40~60cm	BC model	0.161	0.105	—	-25.726
	G model	6.893	1.048	—	4.697

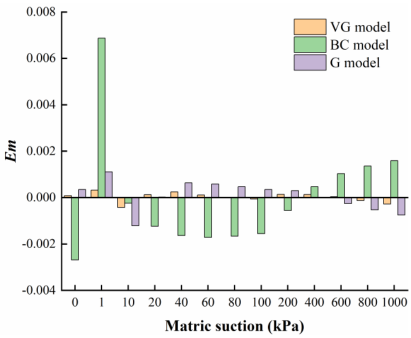
3.3 Fitting Accuracy of Different Models

The E_m of volumetric water content for tailings at different depths is illustrated in Fig. 4. Overall, the BC model exhibits the largest fluctuation in mean error, while the G model shows a moderate level of mean error. In contrast, the VG model demonstrates the smallest fluctuation in mean error.

As shown in Table 2, the SSE for the VG model across different depths of tailings is 0, with an $RMSE$ ranging from 0.002 to 0.003. The G model shows an SSE of 0.001 and an $RMSE$ between 0.007 and 0.008. The BC model exhibits an SSE ranging from 0.012 to 0.017, with an $RMSE$ between 0.031 and 0.036. Notably, the VG model achieves remarkable coefficients of determination (R^2) of 0.9998, 0.9996, and 0.9996 for depths of 0~20 cm, 20~40 cm, and 40~60 cm, respectively. Comparatively, the VG model demonstrates the highest fitting accuracy, making it suitable for modeling the SWCCs of graphite tailings.



(A)0~20cm (B)20~40cm



(C)40~60cm

Fig. 4. The mean error of volumetric water content for tailings at different depths.

Table 2. Evaluation of model accuracy for tailings at different depths.

Depths	Model	SSE	$RMSE$	R^2
0~20cm	VG model	0.000	0.002	0.9998
	BC model	0.016	0.035	0.9330
	G model	0.001	0.007	0.9977
20~40cm	VG model	0.000	0.003	0.9996
	BC model	0.017	0.036	0.9258
	G model	0.001	0.007	0.9968
40~60cm	VG model	0.000	0.003	0.9996
	BC model	0.012	0.031	0.9407
	G model	0.001	0.008	0.9960

4 Conclusions

The saturated water content of tailings decreases gradually with increasing soil depth. As matric suction increases, the volumetric water content of the tailings also decreases. The water retention capacity being the lowest in the 0~20 cm depth range and the highest in the 40~60 cm depth range. The Brooks-Corey model is not suitable for fitting the soil-water characteristic curves of this tailings. The fitting parameters of both the van Genuchten model and the Gardner model exhibit a trend of initially increasing and then decreasing with increasing depth, reaching their maximum values at a depth of 20~40 cm. In comparison, the van Genuchten model demonstrates higher fitting accuracy for the soil-water characteristic curves of tailings at different depths than the Brooks-Corey and Gardner models, making it an ideal model for fitting the soil-water characteristic curves of these tailings. This study primarily determined the soil-water characteristic curves of tailings at varying depths and identified the optimal fitting models through screening. This undoubtedly benefits subsequent tailings remediation efforts. However, it should be noted that these curves represent the SWCC of pure tailings. Future research could explore the selection of suitable amendment materials to enhance the water retention capacity of tailings, thereby achieving the ultimate goal of ecological restoration of tailings.

References

1. Wang Z, Li B, Liu H, et al. Degradation characteristics of graphite tailings cement mortar subjected to freeze-thaw cycles. J. Construction and Building Materials, 234: 117422.
2. Wang Y, Zhang A, Ren W, et al. Study on the soil water characteristic curve and its fitting model of Ili loess with high level of soluble salts. J. Journal of Hydrology, 578: 124067.
3. LI Y, Vanapalli S. Models for predicting the soil-water characteristic curves for coarse and fine-grained soils. J. Journal of Hydrology, 612(C): 128248.
4. Hedayati M, Ahmed A, Hossain M, et al. Evaluation and comparison of in-situ soil water characteristics curve with laboratory SWCC curve. J. Transportation Geotechnics, 23: 100351.
5. Dang M, Chai J, Xu Z, et al. Soil water characteristic curve test and saturated-unsaturated seepage analysis in Jiangcungou municipal solid waste landfill, China. J. Engineering Geology, 264: 105374.