Water Vapor Adsorption-Desorption Properties of Unsaturated Loesses

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Abstract. To study the water vapor adsorption and desorption characteristics of unsaturated loess under different initial moisture contents and environmental humidity changes, isothermal adsorption tests were conducted at various humidity levels. The experimental results indicated that relative humidity is a decisive factor in the water vapor adsorption and desorption of unsaturated loess. The mode of adsorption changes with different humidity levels, shifting from monolayer adsorption to multilayer adsorption and then to capillary condensation. Moreover, the higher the humidity, the greater the initial adsorption rate and equilibrium adsorption capacity, while the opposite is true for desorption. When the moisture content varies, the desorption rates are similar and the isothermal adsorption curves are alike. The equilibrium adsorption capacity increases, the desorption amount decreases, and the monolayer adsorption capacity increases with higher moisture content. Additionally, the water vapor adsorption capacity is directly related to the distance from the adsorption sites to the adsorption surface. If the distance is too large, adsorption cannot be completed. However, during desorption, this distance only affects the initial desorption rate, with the equilibrium desorption amount remaining consistent.

Keywords: Unsaturated loess; Water vapor adsorption; Desorption; Isothermal adsorption curves

1 Intorduction

Loess is widespread in the northwest region, and when the water content is low, its mechanical strength is high. However, it is prone to structural changes and a decrease in strength upon contact with water, leading to building damage and geological disasters. The rainy season in this area falls between June and September, but landslides still occur frequently in October, indicating a lag effect of rainfall on landslides. With the increase in rainfall and humidity, it becomes crucial to study the impact of water vapor adsorption on loess[1-4].

Domestic scholars such as Wang Tiehang[5], and Pan Zhenhui[6] have studied the effects of temperature, humidity, density, and water content on soil-water characteristics and found that humidity, density, and water content significantly affect the matrix suction and soil microstructure, while temperature has a smaller impact. Wang

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Tiehang[7] discovered through isothermal adsorption tests that there is an inflection point on the adsorption isotherm, and the adsorption mode changes from electrostatic attraction and physical-chemical adsorption to multilayer adsorption. Chen Qiong[8] and Feng Dong[9] conducted water vapor adsorption tests and low-temperature nitrogen gas adsorption-desorption tests, researching the BET specific surface area, pore distribution, and pore surface fractal dimension of slip zone soils, as well as the adsorption behavior of water on clay minerals, and analyzed the impact of water saturation on pore distribution.

In relatively dry soil, the movement of water is mainly due to the diffusion, flow, and adsorption of vapor[10]. The adsorption process of water vapor in soil generally includes: at low relative humidity, it is mainly micropore filling, influenced by the force between water vapor and pore walls; as relative humidity increases, monolayer and multilayer coverage appear on the surface of mesopores and macropores, followed by capillary condensation within mesopores[11].

Comprehensive analysis indicates that an increase in humidity leads to a rapid decrease in the strength of loess. By adjusting external humidity and initial conditions, the amount of water vapor adsorption in loess can be controlled, thereby affecting its strength. Therefore, it is necessary to study the water vapor adsorption-desorption characteristics and isothermal adsorption curves of unsaturated loess under different factors.Comprehensive analysis indicates that loess strength is significantly affected by moisture, with an increase in moisture leading to a rapid decrease in strength. By adjusting external humidity and initial moisture content, the adsorption of water vapor by loess can be controlled, thereby affecting its strength. Therefore, this article investigates the vapor adsorption-desorption characteristics and isothermal adsorption curves of unsaturated loess under different factors through isothermal adsorption tests, which is of certain significance to the study of unsaturated loess.

2 Water Vapor Adsorption and Desorption Test

2.1 Basic Physical Property Tests

The particle size, content, and mineral composition of loess all affect its ability to adsorb water vapor. Therefore, through basic tests such as compaction tests, liquid-plastic limit determination, and particle size analysis, the key physical parameters such as the optimum moisture content and maximum dry density of the test loess were determined. Detailed results can be found in Table 1.

Table 1. Basic Physical Indicators of Loess

Optimum moisture content	Maximum Dry Density	Plastic limit	Liquid limit	Particle composition/%		
/%	g/cm^3	/%	/%	≤0.005mm	0.005-0.075mm	0.075-2mm
14	1.885	16.4	26.1	6.21	72.83	20.54

2.2 Test Plan and Testing Methods

The study selected ring cutter samples for experiments. The preparation process of the samples used a ring cutter sample compactor, and the dimensions of the samples were uniformly set to φ61.8mm in diameter and 20mm in height. The samples were prepared according to the standard of maximum dry density and compaction degree of 0.93. In the experiment, the PRX-600C intelligent artificial climate box was used to control a constant temperature of 25°C for conducting water vapor adsorption tests, as shown in Figure 1. Humidity levels of 25, 35, 45, 55, 65, 75, 85, and 95 percent were selected, with four different adsorption surfaces and moisture contents of 8, 11, 14, 17, and 20 percent[12]. Measurements were taken using a balance with a precision of one ten-thousandth. Given the initial rapid changes, the measurement time on the first day was set to 0, 1, 2, 3, 6, 9, 12, and 24 hours, and then every 12 hours thereafter. When the continuous change was less than 0.1%, it was considered that the sample had reached a state of water vapor equilibrium, and the measurement was stopped.

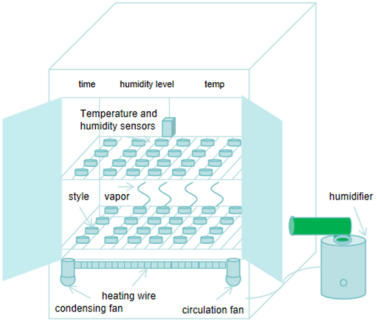


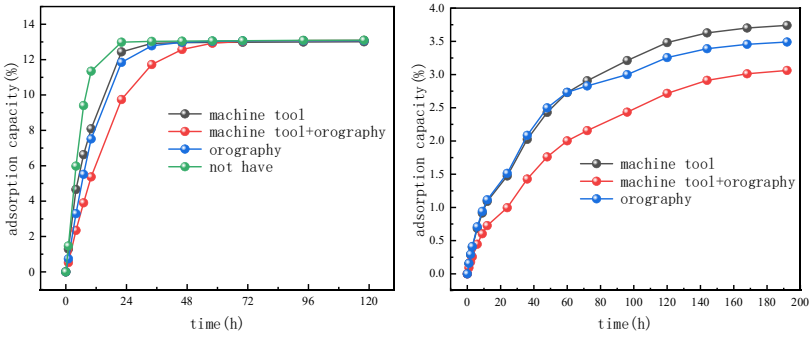
Fig. 1. PRX-600C Intelligent Artificial Climate Chamber

3 Experiment Resulrs Analysis

3.1 Study on Desorption Characteristics under Different Influencing Factors

Figure 2(a) shows the water vapor desorption curve at a moisture content of 14% and a relative humidity of 25RH, involving four different scenarios: double adsorption surface, only upper adsorption surface, upper and side adsorption, and completely exposed surface. The desorption rate is positively correlated with the contact area, but the stable moisture content is similar, indicating that the contact area affects the desorption rate. The exposed area of the ring knife sample is smaller than that of the lid sample, but the water at the bottom of the lid sample is difficult to reach, resulting in a slightly lower desorption rate. Figure 2(b) indicates that the adsorption rate is also positively correlated with the contact area, but there are differences in the total amount of adsorption. After 60 hours, the adsorption rate and amount of the lid sam-

ple are lower than those of the ring knife sample, because the water at the bottom is difficult to reach.



(a) 25RH water vapor desorption at different contact surfaces

(b) 85RH water vapor adsorption at different contact surfaces

Fig. 2. Water vapor adsorption and desorption at different contact surfaces

Figure 3 shows the moisture desorption behavior of a soil sample with a moisture content of 14% under different humidity conditions. As humidity increases, the amount of water retained in the soil sample increases, and the stable desorption amount shows a decreasing trend. Within the RH25-55 range, the stable desorption amount remains stable because the easily lost free water and weakly bound water have been essentially lost, giving the soil body a higher strength. When humidity reaches RH65, the stable desorption amount significantly decreases, and the soil retains more water. Humidity levels of RH55 and below are considered low humidity environments, where the soil sample loses approximately 90% of its water. As humidity continues to rise, desorption amount drops sharply, desorption rate slows down, and the time to reach a stable state is extended. At this point, the water content inside the soil is high while the strength is low.

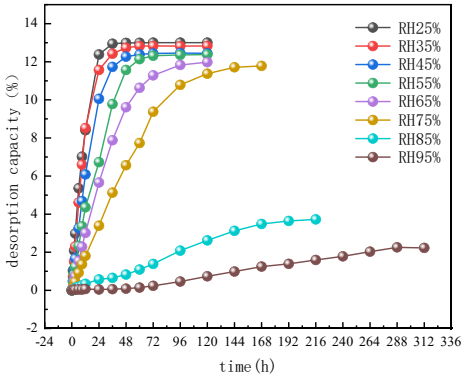


Fig. 3. Water vapor desorption by humidity

Figure 4 shows the results of the 25RH water vapor desorption experiment using soil samples with moisture contents ranging from 8% to 20%. It was observed that there was no significant difference in initial desorption rates, but the steady-state desorption amount was similar to the moisture content. The desorption amount increased with the moisture content, and the samples could not be completely dehydrated at low humidity. There was a positive correlation between the desorption amount and the initial moisture content.

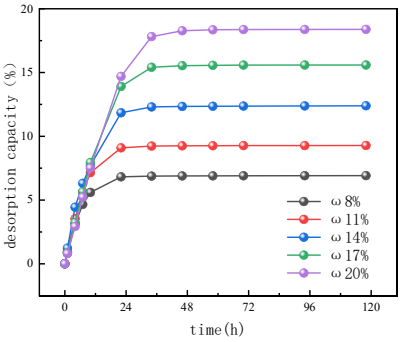
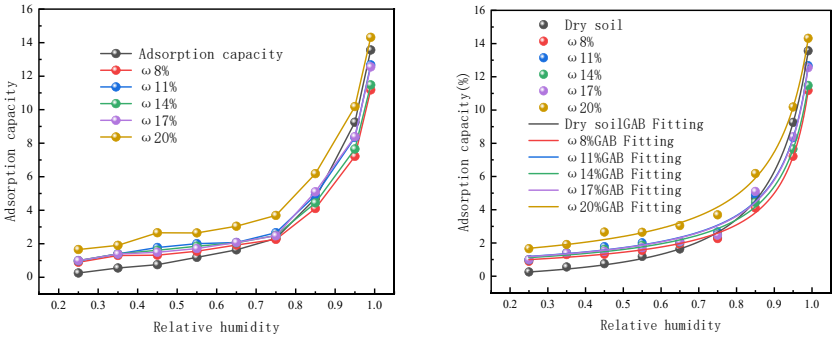


Fig. 4. 25RH desorption for different moisture content

3.2 Non-saturated Loess Isothermal Adsorption Study

Figure 5(a) shows the isothermal adsorption test of soil samples with moisture contents ranging from 8% to 20% under different humidity conditions. The results indicated that the higher the initial moisture content, the greater the pore volume of the soil samples after drying, and the stronger their adsorption capacity for water vapor. When the relative humidity exceeds 75%, the adsorption mechanism changes from monomolecular layer adsorption to multilayer adsorption or capillary condensation, and the adsorption curve rises sharply.



(a) Isothermal adsorption curves of soil samples with different initial water contents

(b) GAB fitting of isothermal adsorption curves

Fig. 5. Isothermal adsorption curve

There are many mathematical models that can be used to describe isothermal adsorption, among which the GAB model assumes that multilayer adsorption occurs on the solid surface, and introduces a multilayer adsorption energy constant k, suitable for isothermal adsorption curve fitting in the relative humidity range (RH=5%～95%),the fitting results are shown in Figure 5 (b), and its mathematical expression is shown in the formula (1):

$$q = \frac{N_m kcx}{(1-kx)\left[1+(c-1)kx\right]} \tag{1}$$

In the formula, q represents the amount of gas adsorption; N_m is the maximum adsorption capacity of a monolayer; x denotes the relative humidity; the value of c indicates the rate of multilayer formation, with a higher c value meaning faster formation; k is the multilayer adsorption energy constant, reflecting the difference between the interaction forces of adsorbed water molecules and those in the bulk phase, and is related to the adsorption characteristics.

Table 2. Water vapor adsorption GAB model fitting parameters

Soil	c	k	N_m	R^2
Dry soil	0.424	0.905	1.792	0.9988
ω8%	1.77E+44	0.941	0.764	0.9968
ω11%	-6.99E+44	0.938	0.912	0.9947
ω14%	-4.32E+44	0.935	0.857	0.9963
ω17%	4.32E+44	0.938	0.902	0.9908
ω20%	2.91E+45	0.919	1.294	0.9954

The fitted parameters as shown in Table 2 indicate that the isothermal adsorption curve matches the measured values very closely, with R^2 values all exceeding 0.99, indicating that as the initial moisture content increases, the maximum monolayer adsorption capacity N_m of the soil samples rises. That is, the higher the initial moisture content, the stronger the monolayer adsorption capacity of the soil samples. At low humidity, the adsorption curve of the soil samples with higher moisture content is higher. The N_m value of loose dry soil is the highest, indicating its strongest monolayer adsorption capacity, possibly due to the largest number of pores. The k value reflects the difference in the ability to adsorb multilayer water, and the k value of soil samples with higher moisture content is smaller, indicating weaker binding capacity for multilayer adsorbed water. The k value of loose dry soil is the smallest, and the pores have difficulty in retaining multilayer adsorbed water, possibly because under high humidity conditions, water is easily converted into free water.

4 Conclusion

1) Soil desorption and adsorption rates are influenced by the exposed area of the soil sample and the distance from the center to the contact surface. The larger the contact

area with the outside world and the shorter the distance, the faster the rates of adsorption and desorption. For soils that have reached the optimal moisture content, under different humidity conditions, the desorption phenomenon shows a trend where the lower the humidity, the greater the desorption rate and amount. In addition, there is a distinct inflection point on the desorption curve; once this point is exceeded, the desorption rate drops sharply. The higher the initial moisture content, the greater the total amount of water vapor desorbed, and the longer the time required to reach desorption equilibrium. Soils with different initial moisture contents have similar rates in the early stages of desorption, indicating that the release process of multilayer water vapor is independent of the moisture content.

2) Studies on water vapor adsorption phenomena reveal that with increasing humidity, the adsorption curve shows a clear inflection point, indicating a transition in the adsorption mechanism, from monolayer adsorption to multilayer adsorption, and ultimately to capillary condensation. When the initial moisture content is high, the pore volume is larger, and the corresponding isothermal adsorption curve rises. Through fitting analysis using the GAB model, it is found that an increase in the initial moisture content leads to an increase in the maximum adsorption capacity of the monolayer N_m, but the adsorption capacity of the multilayer is relatively weakened.

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