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Experimental Study of Shear Strength of Loess under Freeze-thaw Cycles

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Abstract

In order to study the shear strength characteristics of loess under the action of freeze-thaw cycle, through the freeze-thaw test, straight shear test, to analyze the change rule of water content and freeze-thaw cycle on loess cohesion, internal friction angle and shear strength. The test results show that: loess cohesion gradually decreases with the increase of water content and the number of freeze-thaw cycles, when the freeze-thaw 7 times, the change of cohesion gradually tends to stabilize; the angle of internal friction decreases gradually with the increase of water content and the number of freeze-thaw cycles, but the rate of decrease is smaller than the rate of cohesion; the change of shear strength is affected by the cohesion more than the angle of internal friction, and the shear strength at different times of freezing and thawing increased linearly with the vertical stress, and the relationship equations between the shear strength and the water content and the number of freezing and thawing cycles were established.

Keywords

Loess; Freeze-thaw Cycle; Cohesion; Internal Friction Angle; Shear Strength.

1. Introduction

In the seasonal permafrost region, due to the change of ambient temperature, the soil structure of loess can be altered by repeated freeze-thaw cycles, which make its mechanical properties change. Scholars at home and abroad have carried out a lot of research on the characteristics of loess after freezing and thawing, Zhang Hui et al [1] studied the change rule of strength of loess after freezing and thawing cycles, with the increase of the number of freezing and thawing cycles, the cohesion of loess decreased exponentially, but the effect of freezing and thawing cycling action on the angle of internal friction was not obvious; Zhang Quan et al [2] found that the spatial structure of loess was damaged due to freezing and thawing cycling, and the type of contact of the soil particles and the area of contact changed, thus reducing the shear strength of the soil; Wang Zha Quan et al[3] studied the Xi'an Q3 in situ loess, its internal friction angle has no obvious regular change with the number of freezing and thawing, while the cohesion tended to decay exponentially with the increasing number of freeze-thaw cycles; Wu Dan [4] through the indoor simulation of freezing and thawing cycle test, loess in the freezing and thawing cycle, the cohesion is reduced more obvious, the internal friction angle change is very small, and the change rule of the shear strength is basically the same as that of cohesion; Chou Yaling et al[5] analyzed the effect of freezing and thawing on the shear strength and related indexes of loess specimens with different water content and different cement content; Ni Wankui et al[6] studied the microstructure and shear strength change rules of loess under repeated freeze-thaw action; Zhou Zhijun et al[7] explored the change rule of physical and mechanical indexes of loess specimens after freeze-thaw cycles, such as cohesion and angle of internal friction, with different water content without rehydration and at different temperatures; Dong Xiaohong et al[8] investigated the law of deterioration of shear strength of

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loess under repeated freeze-thaw cycles, and established the deterioration model of shear strength.

In seasonal permafrost region, with the change of climate in four seasons, the soil body experiences the action of freeze-thaw cycle, which changes the original mechanical properties of the slope soil body, and has a significant impact on the safety of highway slopes in the seasonal permafrost region. Therefore, it is of great significance to study the change rule of loess mechanical properties under the action of freezing and thawing.

2. Shear Strength Test of Loess under the Action of Freeze-Thaw Cycle

2.1. Test Materials

The loess used in the test was taken from the slope of a road graben in Dacha section of Ji-A liaison line of Erguang Expressway, and the depth of the soil taken was 2~2.5m, which belonged to Q3 loess. The basic physical parameters of the soil samples were obtained through indoor geotechnical tests: natural water content of 13.95%, liquid limit of 29.3%, plastic limit of 19.8%, natural dry density of 1.55 g/cm^3, optimum water content of 13.88%, maximum dry density of 1.93 g/cm^3.

2.2. Sample Preparation

Using the pre-wetting method, the loess after passing through 2mm sieve was prepared with moisture content of 12%, 14%, 16% and 18% specimens, and dry density of 1.55 g/cm^3. After the smothering was completed, the soil samples were made into Standard straight shear specimens with a diameter of 61.8mm, a height of 20mm and flat at both ends using a sample maker by static pressure method, and then the prepared specimens were wrapped with parafilm and then put into ziploc bags to prevent the loss of water during freezing and thawing and storage.

2.3. Freeze-thaw Test and Straight Shear Test

The freeze-thaw cycle test is carried out in a temperature-controlled freezer, and the specimen is subjected to one freeze-thaw cycle for 24h, and the freezing and thawing times are both 12h. Combined with the climate and temperature conditions in the area where the site is located, the freezing temperature and thawing temperature of -15 ℃ and 20 ℃, respectively. The number of specimen freezing and thawing cycles were 0 times (no freezing and thawing), 3 times, 5 times, 7 times, 10 times, 15 times, and the specimens were made in batches to carry out the freezing and thawing cycle test.

Table 1. Test results of loess c and φ values

Number of freeze-thaw cycles (times)	Water content (%)							
	12		14		16		18	
	c(KPa)	φ(°)	c(KPa)	φ(°)	c(KPa)	φ(°)	c(KPa)	φ(°)
0	45.725	31.337	34.729	27.547	24.694	25.507	19.242	24.930
3	38.270	29.111	29.516	25.661	19.257	23.825	14.443	22.813
5	31.373	29.284	23.146	24.780	16.097	23.239	13.760	22.313
7	26.795	28.658	22.016	24.586	15.431	23.137	12.640	21.815
10	24.187	28.015	17.945	24.050	14.099	22.626	12.126	21.478
15	22.814	27.873	16.076	23.747	13.793	22.421	11.973	21.403

At the end of the freeze-thaw cycle of each batch of specimens, the straight shear test was carried out for each group of specimens under the vertical stresses of 50Kpa, 100Kpa, 200Kpa and 300Kpa respectively. Straight shear test using ZJ-type strain-controlled straight shear

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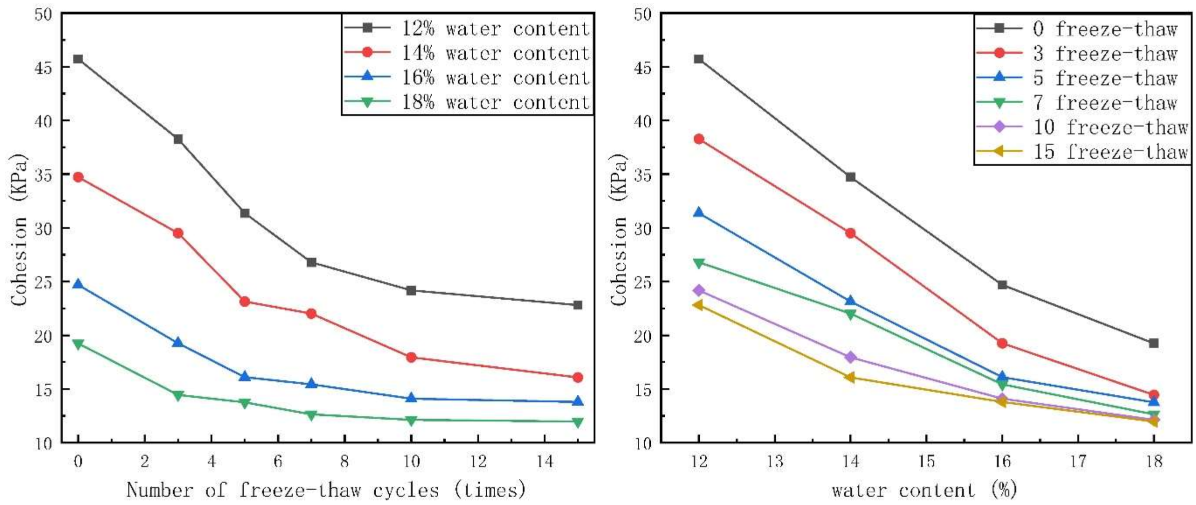
instrument, shear rate of 0.8mm/min fast shear test and data collection. The experimental data were processed through *Origin* software to obtain the values of shear strength parameter cohesion c and angle of internal friction φ of the soil samples, as shown in Table1.

3. Analysis of Loess Shear Strength

3.1. Influence of Freeze-thaw Cycling on Loess Cohesive

The effect of freeze-thaw cycles on the cohesion c of loess is shown in Figure1. As can be seen from Figure1, the values of cohesion c of loess specimens with different water content all decrease gradually with the increase of the number of freeze-thaw cycles, and the values of cohesion c of loess specimens after different numbers of freeze-thaw cycle actions decrease gradually with the increase of water content. In the pre-freezing and thawing period, the water content is low, the rate of decrease of loess cohesion c is fast, when the rate of change of cohesion c gradually tends to moderate after 7 times of freezing and thawing.

During the freezing process, the freezing and expansion of the water in the soil causes the spacing of the soil particles to increase and the structure of the soil to be damaged, and when the frozen soil thaws, the soil particles rearrange themselves causing the structure of the soil to change; When the water content of the soil body increases, there is more free water in the internal pores of the soil, which increases the distance between the soil particles, and the mode of stress transfer also changes from particle transfer to pore water transfer, making the cementation and occlusion between soil particles weaker[10]. The action of freezing and thawing cycles and the increase of soil water content reduce the cohesive of thawed loess, and with the increase in the number of freeze-thaw cycles, the internal structure of the soil body tends to stabilize, and the cohesion also tends to stabilize.



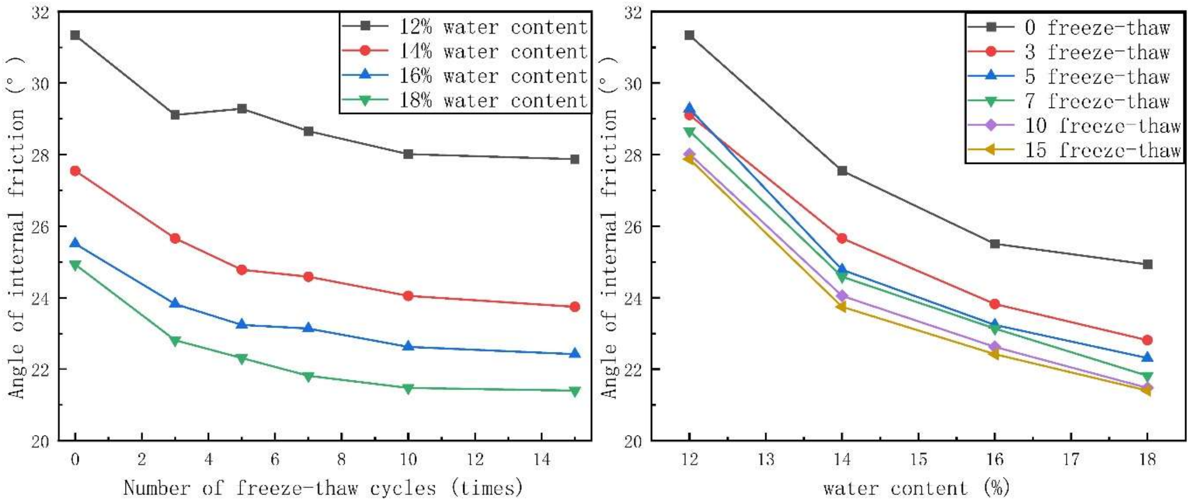
(a) Different water content (b) Different number of freeze-thaw cycles

Figure 1. Change curve of loess cohesion under freeze-thaw action

3.2. Influence of Freeze-thaw Cycling on the Angle of Internal Friction of Loess

Figure2 shows the variation curve of the internal friction angle φ of loess under the action of freeze-thaw cycles. It can be seen from Figure2 that the angle of internal friction φ of loess decreases gradually with the increase of the number of freeze-thaw cycles and the increase of water content. In the pre-freeze-thaw cycle action, the internal friction angle φ is greatly affected by the freeze-thaw action, and the decrease is more obvious, and the internal friction angle φ tends to stabilize gradually with the increase of the number of freeze-thaw cycles when the freeze-thaw cycle is 7 times.

The angle of internal friction φ of the soil body is mainly affected by the contact area between soil particles and the shape of soil particles, and freezing and thawing cycles cause the structure of the soil body to break down, and the particle size of the soil particles to become smaller, the contact area between the soil particles is reduced, the occlusion between the soil particles is weakened, and the friction force is reduced; increased water content increases the amount of free water in the internal pores of the soil, resulting in reduced friction and occlusion between soil particles. Freezing and thawing cycles and the increase of soil water content make the internal friction angle φ of thawed loess gradually decrease, but the decrease rate is smaller than the decrease rate of cohesion, which indicates that the change of the internal friction angle by the freezing and thawing cycles and the change of water content is less than the cohesion.



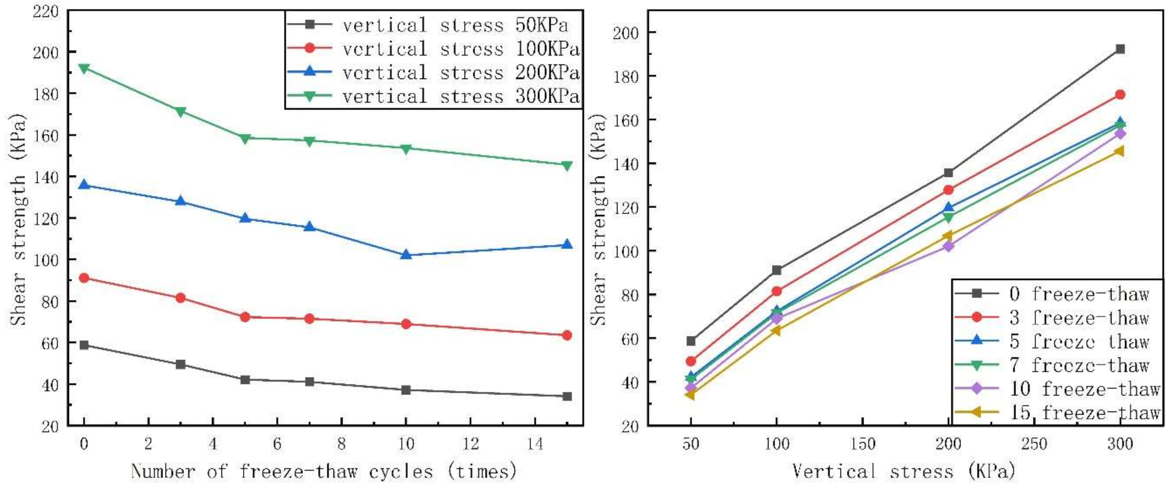
(a) Different moisture water content (b) Different number of freeze-thaw cycles

Figure 2. Change curve of internal friction angle of loess under freeze-thaw action

3.3. Influence of Freeze-thaw Cycling on the Shear Strength of Loess

The cohesion c and the angle of internal friction φ of the soil are the two main parameters that directly respond to the magnitude of the shear strength τ_f of the soil, and freeze-thaw cycling action destroys the structure of loess and the contact mode between soil particles, which makes the cohesion c and the angle of internal friction φ of the soil samples change, thus causing the change of loess shear strength τ_f.

Figure3 shows the graph of shear strength variation of loess specimens with 14% water content at different vertical stresses. From Figure3, it can be seen that the shear strength τ_f of loess specimens with 14% water content at different vertical stresses (50 KPa, 100 KPa, 200 KPa, and 300 KPa) shows the same trend in terms of change with the increase in the number of freeze-thaw cycles. In the pre-freeze-thaw cycle action, the shear strength τ_f varied greatly, and the trend of variation gradually stabilizes when the freeze-thaw action was carried out for 7 times. When only considering the effect of vertical stress, the shear strength τ_f increases linearly and significantly with the increase of vertical stress, and the change rule is not affected by the number of freezing and thawing. Meanwhile, from the aforementioned effects of freeze-thaw cycles on cohesion c and internal friction angle φ, it can be seen that the change of shear strength τ_f is more affected by cohesion c than internal friction angle φ.



(a) Different vertical stresses (b) Different number of freeze-thaw cycles

Figure 3. Change curve of shear strength of loess under freeze-thaw action

4. Modeling of Shear Strength Deterioration after Freeze-thaw Cycles in Loess

4.1. Influence of Freeze-thaw Cycling on Loess Cohesive

According to the results of the basic physical test of the soil, the shear strength data of the selected soil samples under P=100KPa with different water content and different number of freeze-thaw cycles are shown in Table2, and the data are plotted as shown in Figure4.

Table 2. Shear strength test results at 100KPa vertical pressure (KPa)

Number of freeze-thaw cycles (times)	Water content (%)			
	12	14	16	18
0	106.74	91.14	78.68	69.65
3	95.16	81.52	69.12	59.92
5	92.40	72.31	60.57	58.71
7	84.38	71.50	61.41	55.18
10	82.72	68.97	57.62	52.41
15	78.52	63.53	56.76	52.34

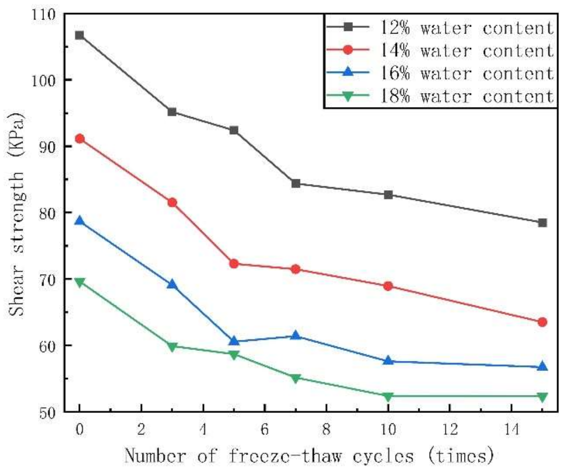


Figure 4. Variation curve of shear strength of loess at P=100KPa

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As can be seen from Table2 and Figure 4, the shear strength of loess specimens with different water content decreases gradually with the increase in the number of freeze-thaw cycles, and the decrease rate decreases and gradually tends to stabilize when the number of freeze-thaw cycles reaches a certain number. By comparing the functional relationships obtained from the fitting, the fitting using Eq.(1) has a high correlation coefficient.

$$\tau_f = a + be^{tn} \tag{1}$$

Where: τ_f is the shear strength; n is the number of freeze-thaw cycles; a, b, t are constants.

The shear strength of loess with different water contents was fitted to the number of freeze-thaw cycles, and the fitting results are shown in Table3.

Table 3. Parameter fitting results

Water content	a	b	t	Correlation coefficient R^2
12%	74.6142	32.1943	-0.14294	0.98341
14%	61.4568	29.8533	-0.15995	0.97589
16%	55.7077	23.2610	-0.23072	0.96950
18%	51.2444	18.3059	-0.21783	0.98382

From Table3, it can be seen that the parameters a, b with the change of water content presents a certain rule of change, and analysis found that the parameter a and water content in line with the exponential function relationship between, and the parameter b and the water content in line with the quadratic function of the relationship between, fitting as shown in Eq.(2) and Eq.(3), fitting parameters and correlation coefficients as shown in Table4. The parameter t has a relatively small effect on the shear strength values, so the average value of -0.18786 is selected comprehensively.

$$a = A_1 + A_2 e^{A\omega} \tag{2}$$

$$b = B_1\omega^2 + B_2\omega + B_3 \tag{3}$$

Where:$A, A_1, A_2, B_1, B_2, B_3$ are the fitting parameters.

Table 4. Fitting parameters and fitting coefficients

<table>
<tr><th>Water content</th><th>a</th><th>Parameters</th><th>Correlation coefficient R^2</th><th>b</th><th>Parameters</th><th>Correlation coefficient R^2</th></tr>
<tr><td>12%</td><td>74.6142</td><td rowspan="4">$A = -31.65559$
$A_1 = 47.48596$
$A_2 = 1207.35591$</td><td rowspan="4">0.9981</td><td>32.1943</td><td rowspan="4">$B_1 = -1633.78125$
$B_2 = 248.84732$
$B_3 = 26.1535$</td><td rowspan="4">0.9855</td></tr>
<tr><td>14%</td><td>61.4568</td><td>29.8533</td></tr>
<tr><td>16%</td><td>55.7077</td><td>23.2610</td></tr>
<tr><td>18%</td><td>51.2444</td><td>18.3059</td></tr>
</table>

Substituting the results of each fitting into Eq. (1), the expression of the deterioration model for the variation of loess shear strength with the number of freeze-thaw cycles at different water contents can be obtained, i.e.

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$$\tau_f = 47.48596 + 1207.35591e^{-31.65559\omega}$$
$$+(-1633.78125\omega^2 + 248.84732\omega + 26.1535)e^{-0.18786n} \quad (4)$$

Where: τ_f is the shear strength; n is the number of freeze-thaw cycles; ω is the water contents. Substituting the four water contents into Eq. (4) and comparing with the actual measured values, the correlation coefficients in Table5 show that the fitting results are good.

Table 5. Water content fitting correlation coefficient

Water content	Correlation coefficient R^2	Water content	Correlation coefficient R^2
12%	0.97571	16%	0.96379
14%	0.97314	18%	0.98095

5. Conclusion

In this paper, the shear strength characteristics of loess specimens with different water contents under different numbers of freeze-thaw cycles were experimentally investigated, and the main findings were as follows:

(1) The cohesion of loess specimen decreases gradually with the increase of the number of freeze-thaw cycles, and decreases gradually with the increase of water content. Loess cohesion c decreases faster during the pre-freeze-thaw period and when the water content is low, and when it is frozen and thawed for 7 times, the change rate of cohesion c gradually tends to moderate.

(2) The angle of internal friction φ of loess decreases with the increase of the number of freeze-thaw cycles and the increase of water content, but the rate of decrease is smaller than that of cohesion, and the change of the angle of internal friction by the freezing and thawing cycle and the change of water content is smaller than that of cohesion.

(3) The change rule of the shear strength of loess with the increase of the number of freeze-thaw cycles presents a rapid decrease in the pre-freeze-thaw period and a gradual stabilization after 7 times of freeze-thaw. At the same time, the change of shear strength value is influenced by cohesion more than the influence of internal friction angle.

(4) The shear strength deterioration model of loess affected by freeze-thaw cycling was established by the results of shear tests, and the comparison between them and the experimental values revealed a high correlation coefficient.

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