Study on the Effect of Freeze-thaw on the Unconfined Compressive Strength of Silt

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Abstract. Using typical silt from the west bank of Qinghai Lake as the research object, we prepared silt specimens with Initial moisture contents of 21%, 24%, 27%. We investigated the effects of the freeze-thaw cycle times and the initial water content on the unconfined compressive strength of the silt through indoor freeze-thaw cycle tests and unconfined compressive strength tests. The results indicate that the stress-strain characteristics of the silt are significantly influenced by both the initial moisture content and freeze-thaw cycle times.The effects of freezing- thawing notably deteriorate the strength of the silt, with the most considerable attenuation occurring after the first cycle. Additionally, the strength of the silt decreases as the initial moisture content increases, with freeze-thaw cycling has a greater effect on silts with higher initial moisture content. Based on these observations, we fitted a function to the test data and found that the strength of the silt follows an approximate natural exponential decay relationship with the freeze-thaw cycle times. Consequently, we established a predictive model for strength under the combined influence of the freeze-thaw cycle times and the initial water content.

Key Words: freeze-thaw cycles; silt; unconfined compressive strength; water content; prediction methods.

1 Introduction

Qinghai Lake plays a crucial role in maintaining the regional hydrological cycle. Due to environmental influences, numerous water meadows exist in the western coastal area of the Qinghai Lake basin, where the silt is classified as a regionally undesirable soft soil with medium-high compressibility. In recent years, regional economic development has necessitated the construction of an increasing number of projects on these water meadows. The west coast area of the Qinghai Lake Basin is a typical seasonal freezing region with extensive seasonal permafrost. The seasonal freeze-thaw cycles significantly impact the soil [1], leading to freezing and swelling,

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subsidence, and strength attenuation. As a typical regional deep soft soil, the mechanical properties of the silt in the water meadows on the west bank of Qinghai Lake are inevitably affected by these freeze-thaw cycles.

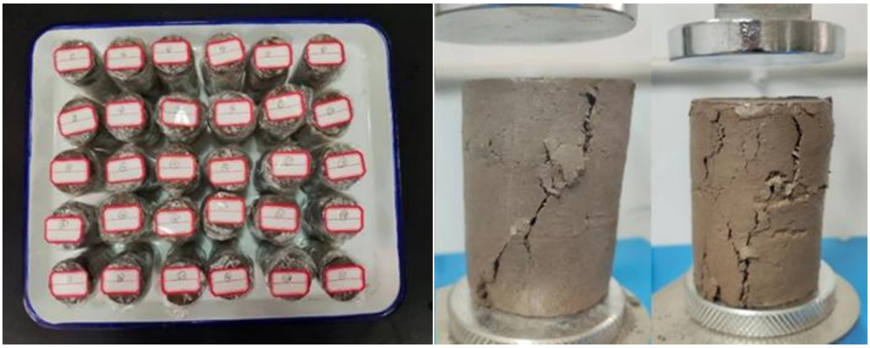
Numerous studies have investigated the impact of freeze-thaw cycles on the mechanical properties of various soil types. Wang Dayan et al. [2] analyzed changes in destructive strength, modulus of elasticity, and shear strength index of Qinghai-Tibetan clay in relationship to the freeze-thaw cycle times, using triaxial compression tests under different peripheral pressures. Their results indicate that freeze-thaw cycles transition the soil from an unstable to a dynamically stable state. Chen Yong et al. [3] examined northern frontier expansion soil with varying water contents through unconfined compressive strength tests under freeze-thaw conditions. They found that increasing water content decreases the soil's hardening characteristics, with significant effects on unconfined compressive strength. Meeravali K et al. [4] explored the geotechnical properties of soft soils under freeze-thaw cycles, revealing that these cycles affect soil porosity, leading to increased permeability and decreased shear strength. Miao et al. [5] conducted shear tests using a low-temperature dynamic triaxial instrument on clayey soil. Their results demonstrated that the internal friction angle of clay increased exponentially with increasing freeze-thaw cycles, while shear strength and cohesion exhibited opposite trends. Lu et al. [6] investigated clayey soils under freeze-thaw cycles and observed that these cycles caused surface cracks to develop gradually. Their analysis concluded that the phase change of moisture is crucial for crack formation. Tang et al. [7] studied expanded soils through solidification undrained triaxial tests, finding that there is a threshold of freeze-thaw cycle times beyond which the modulus of elasticity, effective shear strength, and other parameters significantly decrease. Beyond this threshold, further freeze-thaw cycle times have minimal impact on soil strength.

This study investigates the effects of freeze-thaw cycles on engineering projects, focusing on a highway constructed near Qinghai Lake. It examines the typical aquatic grassland silt from the lake’s western bank. By conducting indoor freeze-thaw cycle tests and unconfined compressive strength tests on remodeled samples, the research explores how freeze-thaw cycle times and initial water content influence the unconfined compressive strength of the silt. The findings aim to offer valuable insights for engineering projects in the region.

2 Test soil samples and sample preparation

2.1 Preparation of test soil samples

The test soil samples were collected from the aquatic grassland on the western bank of Qinghai Lake. The procedure involved air-drying the silt, crushing it, sieving through a 2mm mesh, and then sealing for storage after recording the moisture content. Geotechnical tests determined that the liquid limit is 38.1%, the plastic limit is 20.5%, and the max dry density is 1.721g/cm^3, with an optimal moisture content of approximately 21%.



(a) (b)

Fig.1. (a)Preparation of soil samples; (b)Specimen failure form diagram.

2.2 Sample Preparation

This test in the optimal water content conditions to consider the degree of compaction of 0.9, will be prepared in accordance with the initial water content of 21%, 24%, 27% of the soil samples mixed with water and sealing stuffing 24h, and then in accordance with the literature [8] requirements, in three layers of soil samples hammered into the mould (the inner wall of the coating of a thin layer of Vaseline) made of 39.1mm in diameter, 80mm high specimen, layered In the process of compaction, attention was paid to the fact that after each layer was compacted to the required height, it was necessary to shave the surface of the upper layer of soil before compacting the next layer to ensure the homogeneity of the specimen. In the test design, the freeze-thaw cycles of the specimens were carried out under closed conditions, so the specimens were sealed with plastic film and adhesive tape to prevent the moisture loss of the specimens. Pictures of the field experiment are shown in Fig.1.

3 Test Methods and Procedures

3.1 Freeze-thaw cycles test

This study aimed to elucidate the relationship between the freeze-thaw cycle times and the unconfined compressive strength of silt, given varying initial water contents. Initial water content and freeze-thaw cycle times were the chosen variables. Su Yongqi et al. suggest that the mechanical properties of fine-grained soils generally stabilize after 6 to 8 cycles [9]. Consequently, the testing protocol for specimens with three different water contents included cycles numbering 0, 1, 3, 5, 7, 9, and 11. The experiments utilized a freeze-thaw machine (see Fig. 2(a)), capable of temperature adjustments from -25°C to 25°C with 1°C precision. Engineering requirements and test conditions dictated setting the freezing temperatures at -15°C and the thawing temperatures at 15°C. Each cycle, lasting 24 hours for both freezing and thawing, ensured complete phase transitions. After achieving the designated number of cycles, Unconfined compressive strength tests were performed on the specimens,while others continued in subsequent cycles.

3.2 Strength test

The unconfined compressive strength test instrument adopts ZJ type strain control unconfined compression instrument as shown in Fig.2(b), the prepared specimen is placed smoothly on the lower pressure plate of the instrument, and the lower pressure plate is elevated, so that the upper end of the specimen is just in contact with the upper pressure plate. Zero the displacement gauge and the force gauge respectively. When pressure was applied, the lower pressurised plate was raised at a rate of 2% per minute. According to literature [8] when the reading of axial force reaches peak or stable, the test can be stopped by continuing the axial strain of 3% to 5%.

(a) (b)

Fig.2. (a) Freeze-thaw test machine; (b) Strain-controlled unconfined pressure gauge.

4 Results

4.1 Stress-strain relationship curve analysis

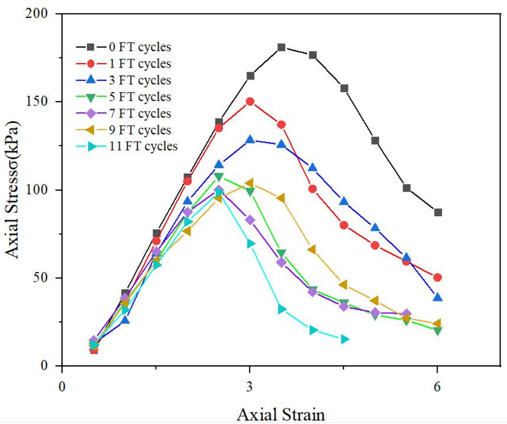


Fig. 3. ω=21% stress-strain graph.

Fig. 3 shows the stress-strain relationship curves of typical silt from Qinghai Lake under different freeze-thaw cycle times, and the water content is the optimal water content, which means that the water content at this time is 21%.The curve for silt not subjected to freeze-thaw cycles demonstrates a nearly linear increase in stress with strain until an axial strain of 3.5%, at which point it peaks, indicating the unconfined compressive strength of 181.09 kPa. Beyond this peak, the axial stress diminishes, signifying structural damage to the specimen, characterized by brittle failure and strain softening behavior. The peaks of the stress-strain curves and their corresponding axial strains generally decline but stabilize after approximately 5 cycles, as the number of freeze-thaw cycles increases.

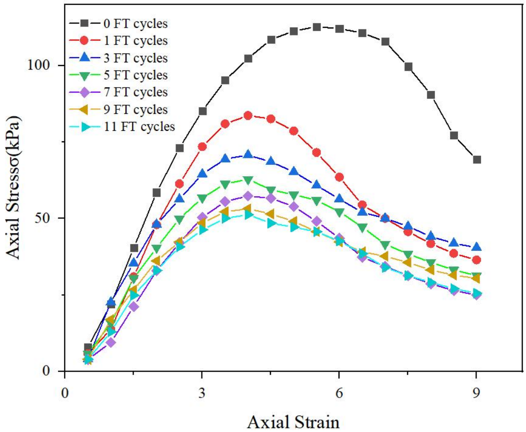


Fig. 4. ω=24% stress-strain curve.

Fig. 4 presents the stress-strain relationship curve for silt with an initial water content of 24%. The curve increases almost linearly up to an axial strain of 3.0%, after which the curve enters into a transitional stage,before peaking at an axial strain of 4.0%, after which it begins to decline. In comparison to the curve at optimal moisture content, this peak is lower, occurs at a higher axial strain, and exhibits a distinct transition phase. Moreover, with repeated freeze-thaw cycles, the stress-strain curve initially shows a tendency towards strain softening but shifts towards strain hardening as the cycles continue. The damage initially appears brittle, with a gradual shift towards plastic damage. The axial strain at the peak reduces after the first cycle, with minimal changes subsequently. The peak of the stress-strain curve generally decreases with additional freeze-thaw cycles but tends to stabilize after 9 cycles .

As shown in Fig. 5, when the initial moisture of the soil reaches 27%, both the linear and transition phases of the curve increase compared to those at an initial moisture of 24%, while the peak value significantly decreases. The damage characteristics and stress-strain relationship curve of the silt with 27% initial water content are similar to those with 24% initial water content. The axial strain at the peak of the curve goes up with higher initial water content. However, with more freeze-thaw cycles, both the peak axial strain and overall axial strain decrease, eventually stabilizing.

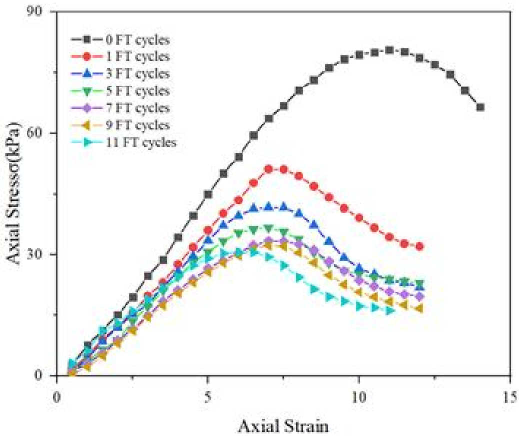


Fig. 5. ω=27% stress-strain curve.

4.2 Analysis of unconfined compressive strength

Fig. 6(a) depicts how unconfined compressive strength evolves across successive freeze-thaw cycles [10]. It's evident that these cycles markedly impair the compressive strength of silt, with the initial cycle causing the most substantial degradation. When the initial water content is consistent, there is a sharp decline in compressive strength as the freeze-thaw cycle times increases, though it eventually reaches a plateau. Moreover, when the silt begins with a higher level of moisture, its compressive strength will be lower, yet the detrimental impacts of the freeze-thaw cycles on its strength become increasingly severe.

To compare and analyze the deterioration freeze-thaw effect on the compressive strength of silt with different initial moisture contents, the compressive strength values of silt were normalized [11]. These findings are depicted in Fig 6(b), where the symbol α denotes the relative change rate in unconfined compressive strength. This is calculated as the proportion of the residual compressive strength of silt following the freeze-thaw cycles compared to its initial strength before undergoing any cycles.

As demonstrated in Fig. 6(b), the impact of freeze-thaw cycles on the unconfined compressive strength of silt is substantial, with the extent of degradation varying according to the initial moisture levels. Silt with the optimal moisture content shows the most significant decrease in strength during the initial freeze-thaw cycle, by approximately 17%. The decrease in strength from the first through the fifth cycle exhibits an almost linear trend. Beyond the 11th cycle, the compressive strength plateaus, maintaining around 55% of its original strength, which corresponds to a cumulative decline of 45%. The detrimental effects of freeze-thaw cycles are more severe with higher initial moisture levels. Specifically, in the first cycle, the strength drops by 26% for silt with a 24% water content and by 37% for those with a 27% water content. By the end of 11 cycles, the strength diminishes to 46% and 38% of the initial strength for 24% and 27% water content respectively.

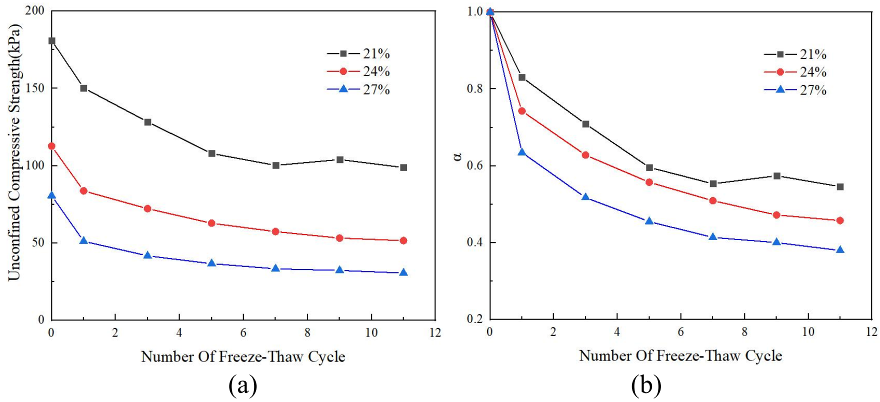


Fig. 6. (a)Intensity change curve; (b)Relative rate of change curve.

4.3 Analysis of the decay mechanism of compressive strength

The physical characteristics of soil are deeply interconnected with its structural features. The water content within the soil is significantly influenced by freeze-thaw cycles, which lead to fundamental structural changes [12]. During these cycles, soil water undergoes alternate freezing and thawing, transforming the soil's composition. As the water transitions from liquid to solid, it expands, leading to an increase in volume and the expansion of the space it occupies. This causes an enlargement of soil pores and aggravation of pre-existing microcracks, with the impact becoming more severe as the initial water content rises. Once the ice melts, the expanded pores and cracks fail to revert to their former dimensions. The disappearance of the ice that once supported the soil's structure results in fewer contact points between soil particles. This decline in contact points weakens the mechanical bonding and cohesive forces among soil particles, culminating in a diminished unconfined compressive strength of the soil [3,9,11,13]. The magnitude of this reduction increases with higher initial water content. With successive freeze-thaw cycles, the number of contact points, the migration of water, and the pore structure within the soil reach a new equilibrium, stabilizing the unconfined compressive strength.

5 Curvilinear regression analysis

To more accurately predict the influence of freeze-thaw cycles and initial moisture on the compressive strength of silt in monsoon freezing zones, we utilized Origin software for curve fitting. The resulting fitting curves are displayed in Fig. 7, and the fitted functional equation is

$$q_u = a + b * \exp(cn) \quad (1)$$

where q_u is the unconfined compressive strength; n is the freeze-thaw cycle times; a, b and c are the coefficients that are influenced by the initial moisture content, as shown in Table 1.

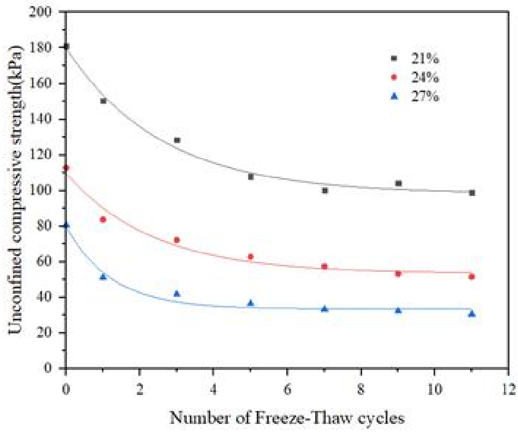


Fig. 7. Fitted curve.

Table 1. Fitting parameter values at different moisture contents

water content	Fitting parameter values			
	a	b	c	R^2
21%	98.23	81.70	-0.39	0.9844
24%	53.38	56.35	-0.43	0.9594
27%	33.53	46.24	-0.81	0.9664

By analyzing Fig. 7 alongside Table 1, it becomes evident that, at a constant water content, the strength of silt follows an approximate natural exponential pattern in relation to the freeze-thaw cycle times. The sum of coefficients a and b approximates the strength of silt absent any freeze-thaw cycles, whereas coefficient c indicates the rate at which strength deteriorates. The combined values of a and b decrease progressively as the initial water content increases, confirming that higher initial water content in silt correlates with lower strength in the absence of freeze-thaw cycles. Additionally, the absolute value of coefficient c diminishes with increasing water content, suggesting that higher initial water content leads to greater strength attenuation due to freeze-thaw cycles. The R^2 value exceeds 0.95 across all three data sets, underscoring the superior fit of the applied function and the accuracy of the functional equation. Despite some discrepancies between the empirical data and the fitted equation, the formulated function in this study provides a valuable reference for assessing the compressive strength degradation of typical silt from Qinghai Lake in engineering applications.

According to the data in Table 1, the fitted parameters also showed a certain pattern with the change of initial moisture , the data in the table were fitted, and the fitted function equation was adopted by analysing the data in the form of (2) and (3), respectively:

$$y = A_1 \omega^{B_1} \tag{2}$$

$$y = A_2 + B_2\omega \tag{3}$$

Where y is the fitted parameter value; ω is the initial water content; A_1, A_2, B_1, B_2 are the coefficients affected by the fitted parameters,as shown in Table 2.

Table 2. Fitting function formula of fitting parameters and moisture content

Fitting parameters	Fit parameter values					
	A_1	B_1	R_1^2	A_2	B_2	R_2^2
a	0.104	-4.387	0.9978	320.513	-1078.333	0.9052
b	1.978	-2.378	0.9697	203.270	-591	0.8840
c	-74.244	3.480	0.7622	1.137	-7	0.6414

From Table 2, we can see that the fit of (2) type is higher, so (2) type is adopted, and the specific function expression is:

$$a = 0.104\omega^{-4.387} \tag{4}$$

$$b = 1.978\omega^{-2.378} \tag{5}$$

$$c = -74.244\omega^{3.480} \tag{6}$$

Bringing equation (4) (5) (6) into equation (1) gives:

$$q_u = 0.104\omega^{-4.387} + 1.978\omega^{-2.378} * \exp\left(-74.244\omega^{3.480} n\right) \tag{7}$$

Where n=0,1,3,5,7,9,11 and $21\% \le \omega \le 27\%$

Therefore, the simple model (7) can be used to predict the changes in unconfined compressive strength of typical silt on the west shore of Qinghai Lake due to freeze-thaw cycles. This test measured the compressive strength for silt with three initial water contents: ω = 21%, 24%, and 27%. Consequently, the fitting function is limited to predicting the unconfined compressive strength within this range of water contents. Future modifications and improvements are needed to extend the model's applicability。

6 Conclusion

This research explored the influence of freeze-thaw cycles on the unconfined compressive strength of silt found on Qinghai Lake’s western shore, utilizing both freeze-thaw and unconfined compressive strength tests. Key findings include:

(1)The properties of the stress-strain curves for silt are deeply affected by the freeze-thaw cycle times and the level of initial moisture. At 21% initial moisture, the stress-strain curve demonstrates a strain-softening pattern. With moisture contents of

24% and 27%, similar softening occurs, though the pattern shifts towards strain-hardening as freeze-thaw cycles progress. As moisture content escalates, the axial strain at the peak of the curve increases. Conversely, with an increasing number of freeze-thaw cycles, both the axial stress and strain at the peak point diminish and eventually level off.

(2)Freeze-thaw cycles significantly deteriorate the unconfined compressive strength of silt, with the most pronounced effect occurring during the first cycle. As the number of cycles increases, the unconfined compressive strength gradually converges to a constant value. Higher initial water content leads to a gradual decrease in unconfined compressive strength, and the detrimental effect of freeze-thaw cycles on the strength increases with higher initial water content.

(3)Function fitting of the test data indicates that the strength of silt follows an approximate natural exponential decay relationship with the freeze-thaw cycle times. A predictive model for compressive strength under the combined influence of freeze-thaw cycles and water content has been established, providing a valuable reference for analyzing the strength decay of typical silt in Qinghai Lake for engineering applications.

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DECLARATIONS

Conflicts of interests: The authors confirm that they have no competing interests.

References

1. Yang M.X., Yao T.D.: Daily freeze-thaw cycles in surface soils of the Tibetan Plateau[J]. Science Bulletin,(16):1974-1976 (2006).
2. Wand D.Y., Ma W., et al: Influence of freeze-thaw cycles on the physico-mechanical properties of Tibetan clays[J]. Journal of Rock Mechanics and Engineering,(23):4313-4319 (2005).
3. Chen Y., Huang Y.H., Zhu X., Wu M., Wang S., Zhu R.: Effects of freeze-thaw cycles on deformation and mechanical properties of expansive soils[J]. Journal of Water Resources and Water Transportation Engineering, (05): 112-119 (2021).
4. Meeravali K., Alla S., et al: An analysis of freeze-thaw cycles on geotechnical properties of soft-soil [J]. Materials Today: Proceedings, 27 (Pt 2): 1304-1309 (2020).
5. Miao W., Shangjiu M.,Yiqiang S , et al: Shear strength of frozen clay under freezing-thawing cycles using triaxial tests [J]. Earthquake Engineering and Engineering Vibration, 17 (4): 761-769 (2018).

6. Lu Y., et al: Fractal analysis of cracking in a clayey soil under freeze–thaw cycles [J]. Engineering Geology, 208 93-99 (2016).
7. Tang L., Cong S., et al: The effect of freeze-thaw cycling on the mechanical properties of expansive soils [J]. Cold Regions Science and Technology, 145 197-207 (2018).
8. Ministry of Water Resources of the People's Republic of China. Standard for geotechnical test methods:GB/T50123-2019.Beijing: China Planning Press, (2019).
9. Su Y.Q., Ma W., et al: Experimental study on the effect of freeze-thaw cycle on damping ratio of remodeled Qinghai-Tibetan chalky clay [J].Journal of Rock Mechanics and Engineering, 40(S1):2960 -2967 (2021).
10. Qin C.H.,Song J.: Test of unconfined compressive strength of fly ash modified expansive soil[J]. Journal of Chongqing Institute of Science and Technology (Natural Science Edition),15 (05):113-115+134 (2013).
11. Wang L.L., Ding Z.P.: Evolution of unconfined compressive strength of expansive soils with different humidity with freeze-thaw cycles[J]. Highway Traffic Science and Technology, 38 (05): 18-22+30 (2021)
12. Liu Q.,Zhang Z.,Zhang S.R.,et al: Fractal characteristics of sandy soil grain group changes under freeze-thaw cycles and their correlation analysis with long-term strength [J]. Glacial permafrost, 2022, 44 (06): 1820-1832 (2022).
13. Wei Y., Yang G.S., et al: Analytical factorisation experiments on the unconfined compressive strength of freeze-thawed loess [J]. Journal of Xi'an University of Science and Technology, 2019, 39 (01): 103-111 (2019).