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Experimental Study on the Effect of Fine-Grained Soil Content on the Freezing Strength of Aeolian Sand-Cement Interface

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Abstract: In cold regions, understanding the freezing strength of the interface between soil and structure is crucial for designing frost-resistant foundations. To investigate how the content of cement powder in aeolian sand affects this strength, we conducted direct shear tests under various conditions such as different fine-grained soil content, normal stress, and initial moisture content of the soil. By analyzing parameters like soil properties, and volume of ice content, and using the Mohr-Coulomb strength theory to define interface strength, we aimed to indirectly measure the cementation strength of the interface. Our findings revealed that as the particle content increased, the interface stress-strain curves became noticeably stiffer. We also observed a positive linear relationship between freezing strength and silt content, while the initial moisture content of the soil did not significantly impact the strengthening effect of fine-grained soil on freezing strength. Moreover, we discovered that as the powder content increased, the force binding the ice to the interface decreased, while the friction angle at the interface increased. However, the cohesion force at the interface remained relatively unchanged. Overall, our analysis suggests that the increase in freezing strength due to fine-grained soil content is primarily due to the heightened friction between aeolian sand and the interface.

Keywords: Fine-grained soil content; Contact area; Freezing strength; Influencing factors

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1. Introduction

China's seasonal and perennial permafrost areas are widely distributed. In order to support national economic development, the construction of transportation, energy, and water conservancy projects in these permafrost areas has become common practice. During the construction in cold areas, soil particles and the foundation of the structure bond together into a single body due to the ice cementation effect. This bonding force is known as the freezing strength of the interface between the soil and the foundation. The value of this freezing strength is referred to as the tangential freezing force of the foundation [1]. The freezing strength of the interface between frozen soil and structures is crucial to the stability of the structure. For instance, in frozen soil with high ice content, the structural bearing capacity of pile foundations and other structures mainly depends on the freezing strength of the interface between the frozen soil and the pile foundation [2]. If the tangential freezing force experienced by the foundation exceeds the freezing strength between the interfaces, it can lead to serious freezing and pulling hazards for the foundation, ultimately affecting the service life of the structure. Therefore, the study of the freezing strength between contact surfaces is particularly important.

Many scholars have conducted in-depth research on interface freezing strength and have made significant progress in this area. For example, Wen *et al.* [3,4] performed experimental studies on the freezing strength of Qinghai-Tibet frozen silt in contact with concrete and fiberglass-reinforced plastic (FRP). Their findings indicated that water content, temperature, and normal stress have substantial effects on freezing strength. Additionally, Yasushi [5] investigated the changes in the freezing strength of frozen sandy soil and clay with structural surfaces under the influence of normal pressure alone, discovering that the freezing strength of frozen sandy soil increased at a faster rate with normal pressure. Sun *et al.* [6] conducted orthogonal direct shear tests at various moisture contents, temperatures, and dry densities for the contact surface of silt and concrete, determining the primary and secondary order of influence of each factor on freezing strength to be moisture content > temperature > dry density. Furthermore, Shi *et al.* [7] developed a large-scale permafrost direct shear instrument and carried out direct shear tests of artificially frozen sandy soil and structural contact surfaces. Their comprehensive analysis of various factors on the freezing strength of the contact surface led to the development of an empirical formula for the ultimate freezing strength as a function of contact surface temperature, normal stress, and roughness, which can be used for predicting the freezing strength limit. These studies have significantly contributed to our understanding of freezing strength between contact surfaces [8].

Currently, numerous scholars have conducted extensive research on the factors influencing the freezing strength of contact surfaces. However, there is limited reporting on the influence of sand containing varying levels of fine-grained soil content on freezing strength. Therefore, this study aims to investigate the impact of wind-deposited sand with different fine-grained soil content on the freezing strength of cement interfaces through direct shear tests [9]. Additionally, it considers the influence of varying initial water content and normal pressure and introduces the parameter of volumetric ice content. This study also involves the simultaneous measurement of the strength of interfacial ice cementation and the validation of its plausibility. Finally, based on the experimental results, it analyzes the reasons for the change in freezing strength due to the variation in fine-grained soil content [10].

2. Specimen preparation and test program

The soil samples used in the test were collected from the Zhangbei area of Zhangjiakou, characterized as natural wind-deposited sand with particles larger than 0.25 mm, accounting for 71.8% of the total mass. Following the classification method outlined in the “Design Code for Building Foundation” (GB5007-2011), this type of soil was categorized as medium sand [11].

To investigate the impact of fine-grained soil content on the characteristics of the cement interface and to highlight the freezing strength of the contact surface. The sand and fine-grained soil content were meticulously sorted before preparing different powder particle specimens. Fine particles smaller than 0.1 mm in the original soil samples were excluded, and powder particles were then mixed in based on the percentage of mass [12]. The powder particles consisted of finely milled kaolinite with particle sizes ranging from 0.043 mm to 0.075 mm. The net powder particle content was varied at 0%, 25%, 40%, 50%, and 65%. Each sandy soil sample with different powder content underwent a compaction test, yielding the maximum dry density and optimum moisture content of the soil samples under each powder content, as detailed in **Table 1**.

Table 1. Maximum dry density and optimal water content of aeolian sand with different fine-grained content

Fine-grained soil content/%	25%	40%	50%	65%
Optimum moisture content (%)	12.5	13	14	14.8
Maximum dry density ($g \cdot cm^{-3}$)	1.93	1.91	1.83	1.8

2.1. Specimen preparation

The first step involved producing cement mortar test blocks with a diameter of 61.8mm and a height of 20mm. These blocks were created by mixing and maintaining a water-ash-sand mass ratio of 1:1:2. To ensure uniformity in surface roughness, the test blocks were ground with an angle grinder after 7 days of maintenance. Subsequently, the polished specimens were placed into a 40 mm high specimen bin (stacked by two ring knives), and then aeolian sand with different fine-grained soil content, pre-configured, was added to the bin and compacted to form the contact surface. Finally, The entire assembly was wrapped with plastic wrap and placed into a high and low-temperature alternating box set at a constant temperature of -8 °C, where it was frozen for 24 hours before commencing the low-temperature straight shear test [13].

2.2. Test program

In this test, a strain-controlled direct shear apparatus was utilized to measure the freezing strength at the interface between sand and cement. The normal stress levels for the test were set at 50kPa, 100 kPa, and 200 kPa, with a constant shear rate of 0.8 mm/min. Based on previous experiments, it was observed that forming soil samples in the ring knife was challenging when the fine-grained soil content in the sandy soil mixture was 25% and the water content exceeded 13%. As a result, to investigate the variation in freezing strength with water content, the water content of the specimen was set at 10%, 11.5%, and 13%. Additionally, the negative freezing temperature was set at -8°C and 19°C, with the latter temperature chosen to compare the specimen under the same working condition at -8°C. This approach was taken to derive the change in freezing strength with the content of powder particles and to validate the reasonableness and accuracy of the volume ice content parameter [14].

3. Test results and analysis: Effect of fine-grained soil content on interfacial shear strength indexes

The freezing strength comprises three primary components. Firstly, it involves the adhesive force generated between ice crystals and the contact surface due to water condensation into ice crystals at negative temperatures. Secondly, it encompasses the maximum static friction between the contact surfaces at the critical state of shear damage. Lastly, it includes the cohesive force resulting from the presence of soil particles and the contact surface. Consequently, the factors influencing the ice cementation force, maximum static friction between contact surfaces, and cohesion also impact the magnitude of freezing strength.

In this study, we primarily analyzed the influence of fine-grained soil content on freezing strength concerning water content, normal pressure, ice cementation force, and friction force between the soil and interface. We disregarded the effect of the friction coefficient on freezing strength as the test aims to maintain uniform surface roughness to the greatest extent possible.

The freezing strength is determined by the combination of ice cementation, friction, and cohesion forces acting between the soil and the contact surface. Each of these forces can be characterized by shear strength parameters, and the Moore-Cullen strength criterion effectively captures the influence of interfacial shear strength parameters on shear strength. This criterion can be expressed in terms of interfacial cohesion and interfacial internal friction angle, which can be defined using the following equations [15]:

$$\tau_f = \sigma_N \tan\varphi + c \qquad (1)$$

Where $\boldsymbol{\tau_f}$ denotes the shear strength in kPa; $\boldsymbol{\sigma_N}$ denotes the normal pressure in kPa; $\boldsymbol{\varphi}$ denotes the interfacial friction angle in °; and c denotes the interfacial cohesion in kPa.

Tables 2 & 3 present the interfacial cohesion at -8°C and 19°C for various fine-grained soil contents. As shown in **Table 4**, the interfacial cohesion exhibited a consistent pattern of change with variations in water content and fine-grained soil content. Specifically, at -8°C and the same fine-grained soil content, the interfacial cohesion increased with higher water content. This is due to the increased ice content in the soil resulting from higher water content, thereby enhancing the ice cementation force and subsequently strengthening the adhesion between the soil and the interface. For instance, when the initial water content was 10%, the interfacial cohesion displayed a small amplitude change of approximately 2 kPa as the fine-grained soil content ranged from 25% to 65%. Similar patterns were observed under the other water content conditions.

Table 3 reveals that there was no clear pattern in the variation of interfacial cohesion with water content at room temperature. However, under the condition of 10% initial water content, the interfacial cohesion increased from 0.629 kPa to 10.844 kPa with the increase in fine-grained soil, showing an amplitude of around 10 kPa. This increase can be attributed to the viscous nature of fine-grained soil, where the rise in fine-grained soil content enhanced the cohesion between the soil and the interface. In permafrost, the interfacial cohesion consists of both the ice cementation force and the cohesion of soil particles with the structural surface. Specifically, in frozen soil, interfacial cohesion is a combination of ice cementation and cohesion between soil particles and the structural surface. Notably, the interfacial cohesion at room temperature does not include ice cementation. Furthermore, the increase in interfacial cohesion at 19°C was significantly greater than that at -8°C, indicating a reduction in ice cementation at -8°C as the fine-grained soil content increased from 25% to 65%. This reduction is attributed to the rapid decrease in free water content inside the soil with the increase in fine particle content at the same water content, leading to a decrease in ice content within the soil. It is noteworthy that while the decrease in ice cementation force was smaller than the increase in cohesion force resulting from the addition of powder particles at the same water content, the overall effect manifested as a slight increase in the interfacial cohesion force at a macroscopic level.

Table 4 illustrates that under the same initial water content, the interfacial friction angle gradually increased with the rise in fine-grained soil content. This phenomenon occurs because the contact area between soil particles expands with the continuous addition of fine particles. Simultaneously, the reduction in free water within the soil results in lower internal ice content, thereby increasing the contact area between the particles and subsequently enlarging the friction angle. Conversely, when the fine-grained soil content remains constant, the interfacial friction angle shows a slight decrease with the increase in water content.

Table 2. Interfacial cohesion with different particle content at -8°C

Temperature (°C)	Water content (%)	Interfacial cohesion (kPa)			
		25%	40%	50%	65%
-8	10	13.532	13.816	14.727	15.64
	11.5	16.034	17.405	18.06	18.78
	13	18.621	19.595	20.377	20.011

Table 3. Interfacial cohesion with different particle content at 19°C

Temperature (°C)	Water content (%)	Interfacial cohesion (kPa)			
		25%	40%	50%	65%
19	10	0.629	2.534	6.273	10.844
	11.5	0.748	2.863	6.792	11.038
	13	0.601	1.95	6.057	10.738

Table 4. Interfacial friction angle of different particle content

Temperature (°C)	Water content (%)	Interfacial cohesion (kPa)			
		25%	40%	50%	65%
-8	10	32.76	34.621	36.592	40.99
	11.5	32.305	34.054	36.037	39.946
	13	31.007	33.712	35.922	38.543

4. Discussion

Through the above study, it is evident that the freezing strength between soil and structure primarily relies on internal friction and ice cementation force. The study revealed a clear positive linear correlation between fine-grained soil content and freezing strength. In other words, an increase in soil content leads to an overall increase in freezing strength. However, as the content of fine-grained soil increases, the ice cementation force at the interface decreases while the interfacial friction continues to grow. This observation indicates that the growth in strength provided by interfacial friction and the increase in cohesion due to the addition of fine-grained soil content outweigh the decrease in ice cementation force, resulting in an overall increase in freezing strength from a macroscopic perspective.

5. Conclusion

After conducting a series of direct shear tests and freezing temperature experiments, this paper investigates the impact of varying fine-grained soil content on the freezing strength of the contact surface. It also considers the influence of initial water content and normal pressure, analyzing the reasons for changes in freezing strength due to the addition of fine-grained particles. The following conclusions are drawn:

(1) The Moore-Cullen strength theory is utilized to describe the interface freezing strength. The test data indicates that interfacial cohesion experiences a slight increase with the addition of fine-grained particles. Furthermore, the cohesion between the soil and structural surfaces demonstrates an increasing trend, with its growth surpassing that of interfacial cohesion. This finding validates the reasonableness and accuracy of the volumetric ice content parameter. Additionally, the interfacial friction angle continues to increase throughout this process, contributing significantly to the interfacial freezing strength.

(2) From a macroscopic perspective, the observed phenomenon of fine-grained content enhancing freezing strength is attributed to its ability to increase the friction between the sand and the contact surface.

References

[1] Ma W, Wang D, 2014, Mechanics of Frozen Soil, Science Press, Beijing, 286–302.

[2] Chen Yong, Huang Yinghao, Wang Shuo, et al. Experimental Study on the Influence of Freeze-Thaw Cycles on Mechanical Properties of Expansive Soils with Different Compactable Degrees. Chinese Journal of Rock Mechanics and Engineering, 2023(S2): 4299–4309.

[3] Yue Y, Zhang W, Liu H, 2013, Study of Calculation Methods for Interactional Force Between Drag Anchor and Installation Cable, 34(2): 503–512.

[4] Jiang S, Wu Y, Pan G, et al., 2017, Research and Application of Pile Test Device for Thermal Effect of Groundwater. Railway Standard Design, 61(5): 105–108.

[5] Yasushi U, Moriuchi K, Ohrai T, 2004, Influence of Normal Stress on the Adfreeze Interface on Adfreeze Shear Strength of Frozen Soil. Journal of the Japanese Society of Snow and Ice. 66(2): 197–205. https://www.doi.org/10.5331/seppyo.66.197

[6] Sun T, Gao X, Liao Y, et al., 2020, Experimental Study on Adfreezing Strength of Silt-Concrete Contact Surface. Chinese Journal of Rock Mechanics and Engineering, 39(05): 1032–1039.

[7] Shi Q, Yang P, Wang G, 2016, Experimental Study on Freezing Strength Of Artificially Frozen Sand And Structural Contact Surface. Chinese Journal of Rock Mechanics and Engineering, 35(10): 2142–2151.

[8] He P, Ma W, Mu Y, et al., 2020, Experimental Study On The Effect Of Freeze-Thaw Cycles On The Freezing Strength of Frozen Earth-Concrete Interface. Chinese Journal of Geotechnical Engineering, 42(2): 104011.

[9] Wang X, Cao W, Zhang D, et al., 2020, Study on Mechanism of Influence of Particle Size and Content of Gangue on Strength of Cement Base with High Sand and Foam. Journal of Mining and Safety Engineering, 37(2): 376–384.

[10] Liu H, Yang X, Chen Y, 2021, Experimental Study on the Effect of Mica Content in Machine-Made Sand on the Properties of Cement-Based Materials. Journal of North China Institute of Water Resources and Hydropower, 2021(6): 42.

[11] Ding X, Li X, Yang B, 2023, Experimental Study on Effect of Ultrafine Mineral Admixtures on Mechanical Properties of Cement Mortar. Progress in Materials Science in China, 2(1): 1–7.

[12] Chang L, Wang H, Cao J, et al., 2023, Experimental Study on the Influence of Sand Content on the Strength Characteristics of Sand-Silt Mixture. Journal of Yangtze River Scientific Research Institute, 40(10): 96–102.

[13] Wu Y, Cui J, Li C, et al., 2022, Experimental Study on the Effect of Fine Particle Content on the Maximum Dynamic Shear Modulus of Coral Sand From Reef Reclamation. Chinese Journal of Rock Mechanics and Engineering, 41(1): 12.

[14] Zhang J, Song Y, Yang H, et al., 2022, Effect of Load and Fine Soil Content on Frost Heave and Melt Settlement of Saturated Sand and Gravel. Rock and Soil Mechanics, 43(S01): 213–221.

[15] Gao Q, Wen Z, Wang D, et al., 2018, Instability Process of Frozen Soil Slope Based on Direct Shear Test at Freeze-Thaw Interface. Rock and Soil Mechanics, 39(8): 2814–2822.