Experimental study on the shear characteristics of frozen soil-concrete interface under the constant normal stiffness

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Abstract

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Abstract: The interaction between the structure and soil is the key factor for infrastructure stabilization in permafrost engineering. In this study, the shear mechanical behavior of the interface between concrete and permafrost under different normal stiffness, temperature and water content is investigated by using the interface direct shear test under temperature-controlled conditions. The results show that with the increase of temperature and water content, the initial shear stiffness of the interface shear stress-shear displacement curve gradually increases, and the interface shear strength gradually increases. Different normal stiffnesses have a small effect on the morphology of the interfacial shear stress-shear displacement curve, but have a significant effect on the peak shear strength. The peak shear strength increases significantly with the increase of normal stiffness, and this trend is more obvious with the decrease of temperature. The corresponding interfacial cohesion and friction angle also increase with the increase of normal stiffness.

Keywords: constant normal stiffness; frozen soil; interfacial shear strength; shear; boundary condition

1 INTRODUCTION

Frozen soil is a complex geo-material composed of solid particles, liquid water, gas inclusions and ice crystals. Currently, the widely accepted definition of frozen soil is soil and rock that have a temperature equal to or below 0 and contain ice. The area of frozen soil in the world accounts for about 25% of the total land area of the earth[1-2]. The physical and mechanical properties of frozen soil are closely related to changes in temperature, moisture, and loading. Under different conditions, complex physical processes occur within the soil mass, resulting in changes such as water and heat movement, phase transition, and stress redistribution, which further lead to frost heave and thaw settlement deformation of the soil[3-8]. Therefore, when conducting engineering construction in frozen soil regions, it is necessary to conduct a thorough analysis of the changes in the mechanical properties of frozen soil during construction and usage, as well as the patterns of interaction between frozen soil and structures. Concrete is currently one of the main materials used in building structures, and its application is indispensable in large-scale infrastructure projects such as high-speed railways, canal slopes, high-rise buildings, and transmission pile foundations constructed in frozen soil regions. Due to the differences in the physical and mechanical properties of soil and concrete materials, the soil-concrete interface has become one of the key factors that affect the stability of structures[9-14]. Especially in frozen soil regions, the reciprocating changes in water, heat, and force conditions alter the physical and mechanical properties of the soil mass, and the frost heave and thaw settlement deformations of the soil can significantly affect the stress state and stability of the interface between the soil and structures. In severe cases, this can even lead to instability and failure of engineering structures. Therefore, the study of the interaction mechanism between frozen soil and concrete interfaces has received widespread attention.

The study of soil-concrete interface shear characteristics is one of the important topics in the field of geotechnical engineering. Conducting a thorough investigation into the shear mechanical behavior of the interface, as well as the evolution mechanism and influencing factors of the shear zone, holds significant theoretical and practical guiding significance for addressing practical engineering problems such as foundation settlement and slope failure[15-17]. Direct shear test, as an economical and efficient experimental method for studying interface shear behavior, can conveniently obtain the stress-displacement curve relationship, shear strength, and strength parameters of the interface. It has been widely used in the study of soil-concrete interface shear characteristics[18-20]. A series of direct shear test studies have shown that factors such as the grading of soil particles, the roughness of the structural surface, environmental conditions, and boundary conditions can all influence the shear mechanical behavior of the interface[21-23]. Under negative temperature conditions, the dynamic changes between ice and water, as well as the formation of cemented ice particles within the soil at the interface, complicate the interfacial shear mechanism. The interfacial shear strength not only comprises the cohesion between soil particles and the friction between soil and concrete, but also includes the cementing force generated by the cemented ice. Liu et al. by combining the methods of nuclear magnetic resonance (NMR) layered testing, direct shear testing, and fractal theory analysis, the degradation mechanism of the soil-rock mixture-concrete interface strength in cold regions under freeze-thaw cycles is revealed[24-27]. Sun et al carried out a series of direct shear tests on frozen soil-concrete interfaces to investigate the characteristics and formation mechanisms of the freezing strength at the frozen soil-concrete interface. By decomposing the peak strength, the formation mechanism of the freezing strength at the frozen soil-concrete interface was explained[28]. Wang et al. conducted a series of indoor direct shear tests on silty clay-concrete binary system under freeze-thaw cycles. Based on the indoor test results, they combined macroscopic and microscopic observations to obtain the changing patterns of interfacial shear strength, shear strength parameters, and shear strength damage degree[29-30]. Wan et al. explored the relationship between shear stress and displacement at the contact surface as well as the variation of shear strength through a combination of indoor experiments and mathematical modeling. They revealed the mechanical properties of the contact interface between saline frozen soil and concrete under the influence of multiple factors. Furthermore, through grey correlation analysis, they determined the significance ranking of various influencing factors[31]. Xie et al. conducted dynamic shear tests on the interface between frozen clay and concrete pile foundation under different influencing factors using a temperature-controlled dynamic direct shear system[32].

The aforementioned studies have conducted an analysis of the interfacial strength characteristics, providing a thorough elucidation of the features and formation mechanisms of interfacial freezing strength. For structures such as pile foundations buried underground at a certain depth, the normal boundary condition at the interface between the soil and the structure is a condition of constant normal stiffness[33]. Based on the characteristic changes in the volume of soil surrounding the structure during the shearing process (shear dilation or shear contraction), the restraining effect of the surrounding soil on the structure can be simplified as a series of springs with certain stiffness, which is referred to as the constant normal stiffness boundary condition[34]. In tests with constant normal stiffness, the effect of normal stiffness on the interfacial shear strength depends on the volume response of the interface during the test. Research indicates that under shear dilation conditions, an increase in normal stress during tests with constant normal stiffness leads to an increase in shear stress. On the other hand, the change in shear stress under shear contraction conditions is opposite. Some studies have shown that under conditions of constant normal stiffness, the friction angle remains unchanged during the variation of interfacial shear strength[35-37].

However, for structures such as pile foundations in frozen soil regions, research on the shear characteristics of the soil-structure interface under constant normal stiffness conditions is still not systematic. Therefore, this paper utilizes a two-stage temperature-controlled direct shear test to investigate the effects of different normal stiffnesses, temperatures, and moisture contents on the shear characteristics of the frozen soil-concrete interface. It analyzes the variation patterns of stress-displacement curves, shear strength, cohesion, and internal friction angle under different conditions. The research results can provide scientific references for the design, operation, and maintenance of structures such as pile foundations in frozen soil engineering.

2 EXPERIMENTAL MATERIALS AND METHODS

2.1 Soil

The soil used in the experiment was taken from a slope in Lanzhou City, Gansu Province. It appears as a light-yellow color, with uniform and continuous texture, and without large particulate impurities. The basic physical properties of the soil are shown in Table 1. The soil particle size distribution curve is presented in Figure 1. According to the soil classification standards (ASTM D2487/Standard for Soil Test Method GB/T50123-2019), it is classified as silty clay.∘ **TABLE 1** Basic physical properties of silty clay

Soil Classification	Optimal Moisture Content(%)	Liquid Limit (%)	Plastic Limit (%)	Maximum Dry Density(g/cm^{-3}
Silty Clay	13.3	28.5	14.7	1.93

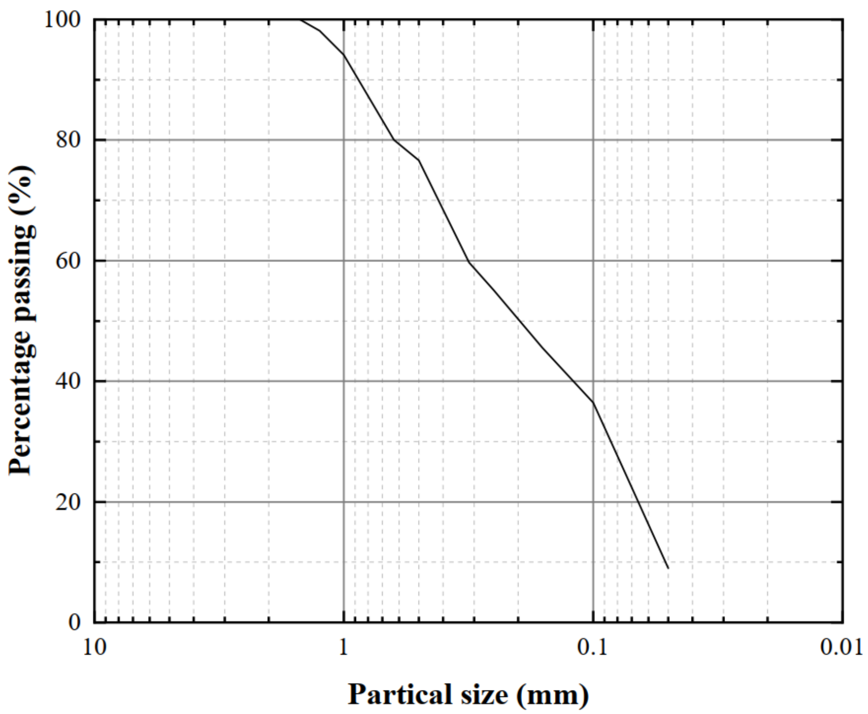


FIGURE 1 Particle size grading curve

2.2 Concrete Block

In this experiment, the mortar cubes were prepared with a ratio of cement, sand, and water of 1:3:0.65 (by weight). Due to the relatively small size of the samples, larger particles in the sand were removed to ensure the uniformity of the mortar cube samples. During the sample preparation process, Vaseline was first applied around the iron mold (with a height of 25 mm). The concrete mortar was then evenly poured into the mold, and vibrated and smoothed to ensure that the thickness of the concrete sample was the same as the height of the mold. Subsequently, a standard curing procedure was followed, involving natural curing through watering every 8 hours at a temperature of 25°C to achieve hydration. After 28 days of curing, the mold was removed. Finally, samples with a height of 25 mm and uniform surface roughness were selected for further measurements as the final mortar cube samples. The process of preparing the mortar cubes is shown in Figure 2.

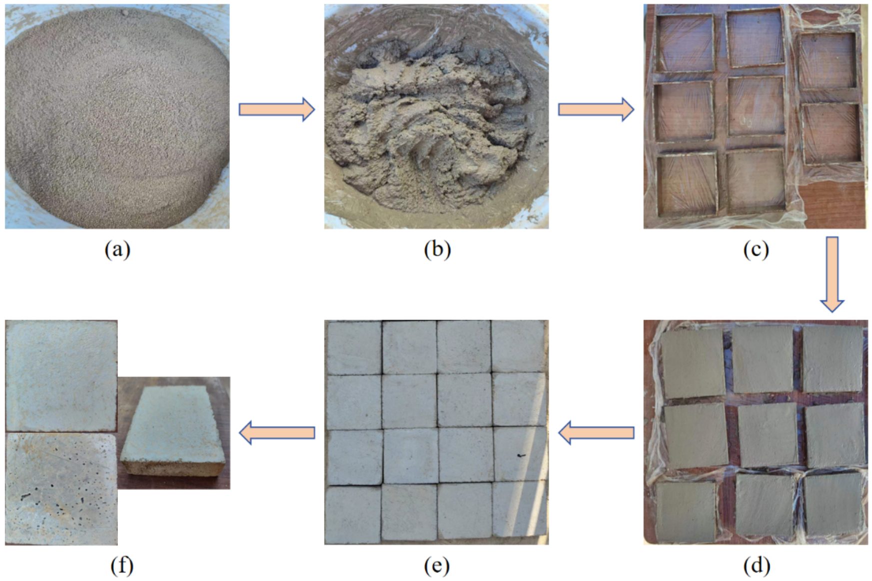


FIGURE 2 Mortar block sample preparation process (a) Material preparation, (b) Mixing, (c) Pouring into the mold and vibrating/smoothing, (d) Curing, (e) Demolding, (f) Measuring dimensions

2.3 Interfacial sample

After naturally air-drying the soil samples collected on site and passing them through a 2mm sieve, they were thoroughly mixed to ensure homogeneity. The initial water content was determined using the oven-drying method, and then a certain amount of water was added to achieve wet soil samples with water contents of 10%, 13%, and 16%. These samples were placed in sealed bags and allowed to stand for 24 hours to ensure uniform water content distribution. A mortar block was placed on the lower side of the sample mold, and wet soil with a compaction of 95% was weighed and compacted in three layers into the mold until level with the top edge of the mold box. The size of the test sample was 100mm×100mm×50mm (Figure 3a). The test sample consisted of two layers, with the mortar block being 25mm tall, and the soil layer on top and the mortar block below. This configuration placed the shearing interface exactly in the middle and aligned with the upper and lower shear box interfaces of the direct shear apparatus, enabling better study of the mechanical properties of the interface during the shearing process. After preparing the direct shear samples, they were wrapped in plastic wrap, and the bottom and sides were further wrapped with insulating material and placed in a constant temperature chamber (Figure 3b). The temperature of the chamber was adjusted to the target test temperature and maintained for 24 hours to complete the freezing of the direct shear samples.

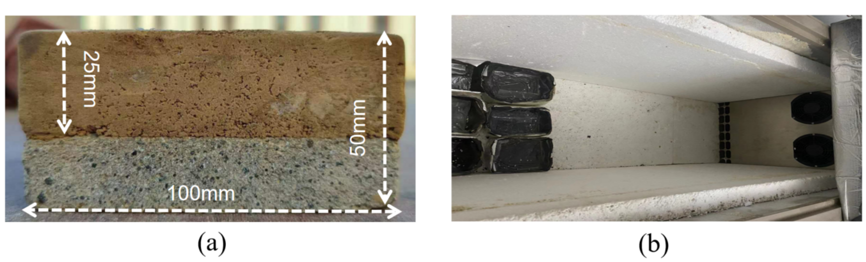


FIGURE 3 Sample preparation and size (a) Interfacial sample, (b) Constant temperature process

2.4 Testing Device

Due to the strong water-heat sensitivity of frozen soil, a constant normal stiffness direct shear apparatus (Figure 4) was used to conduct interfacial characteristics research in order to better control the experimental temperature. The direct shear apparatus was first installed in a thermostat with a temperature control accuracy of ±0.2, and then the thermostat was placed in a freezer with a temperature control accuracy of +-0.5. This two-level temperature control system achieved good temperature control accuracy.

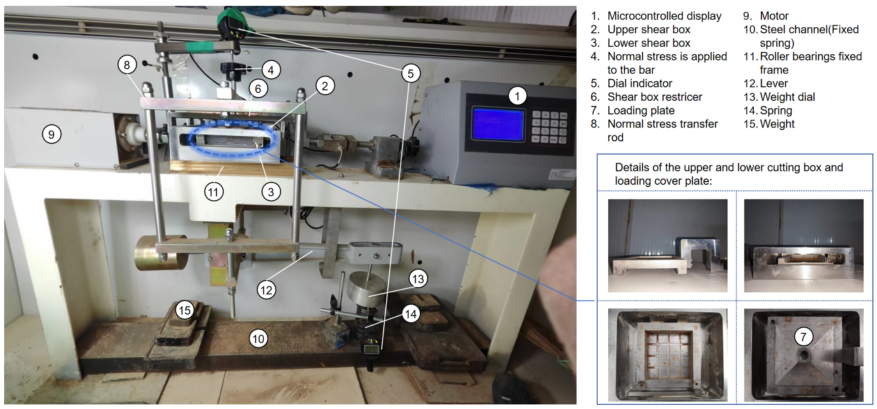
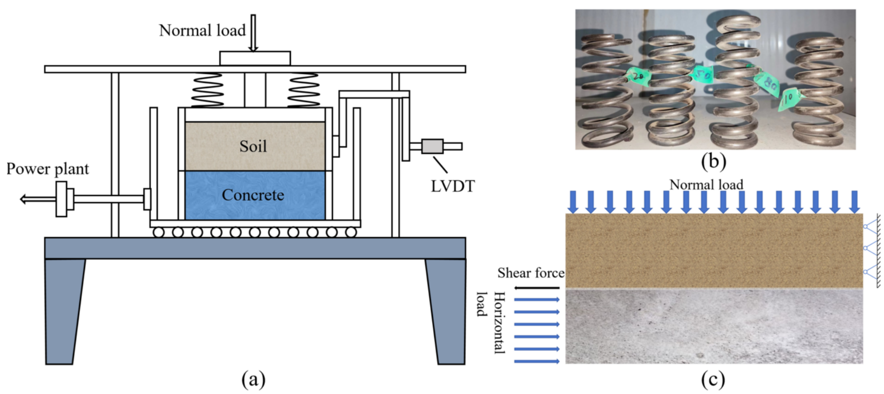


FIGURE 4 Constant normal stiffness direct shear instrument



The normal stress of the constant normal stiffness direct shear apparatus is applied by weights through a lever, and the normal stiffness is controlled by a normal spring connected to the lever. Different normal stiffness boundary conditions can be achieved by replacing springs with different stiffnesses. During shearing, the shear stress at the interface is controlled by a micro-motor in the system, with a maximum shear stress of 10kN. The measurement and control system can simultaneously measure and output the interfacial shear displacement and normal displacement in real-time. Data can be directly collected to the control computer through the data acquisition system. The working principle of the direct shear apparatus during the shearing process is shown in Figure 5a. By measuring the stiffness of soils with different properties as required by the experiment, different stiffness values can be controlled for the experiment. The maximum and minimum stiffness values obtained are 1100kPa/mm and 200kPa/mm, respectively. Two intermediate values are then selected, and all springs are uniformly processed using 65Mn carbon steel (Figure 5b). The internal effective dimensions of the shear box are 100mm × 100mm × 50mm, with both the upper and lower shear boxes having a height of 25mm. The sample consists of a 100mm × 100mm × 25mm soil layer on top and a 100mm × 100mm × 25mm mortar cube below. The sample is tightly attached to the shear box to reduce shear stress errors during preloading. A schematic diagram of the force applied to the sample is shown in Figure 5c.。

FIGURE 5 (a) Direct shear instrument (b) Spring selection (c) Specimen stress diagram

2.5 Testing Process

Boundary conditions are crucial factors that influence the mechanical response of soil. During the shearing process, changes in the normal stress applied to the interface due to volume changes in the shear zone can lead to alterations in shear stress. Existing research has shown that constant normal stiffness (CNS) conditions are closer to actual engineering conditions compared to constant normal stress conditions[38]. Under constant normal stiffness conditions, the change in normal stress at the interface is denoted as,and the change in normal displacement at the interface is denoted as , the normal stiffness at this time is represented by k =constant.

The process of interfacial shear testing includes the following steps: (1) Calculate the weight of the soil sample required for a compaction rate of 95%. Install the prepared mortar block into the mold, and then fill the soil sample into the mold evenly in three layers. Fabricate the interfacial shear sample using the layered compaction method and wrap it in plastic film to prevent moisture loss during the freezing process. (2) Place the interfacial shear sample in a -20 freezer for rapid freezing for 12 hours to prevent moisture migration during the freezing process. (3) After rapid freezing, remove the mold from the solidified sample, wrap it in a new plastic film, and transfer it to a constant temperature freezer. Maintain the sample at the target experimental temperature for 24 hours. (4) Adjust the environmental temperature and instruments for the test, ensure the sealing of the freezer to minimize any potential errors, install the sample on the shear apparatus, and begin the interfacial shear test. (5) After the shear test is completed, take photos of the sheared interface and record the test details.

The experiment was conducted using a rapid shear mode with a shear rate of 0.8mm/min. The shearing duration was set to 15 minutes, resulting in a shear displacement of 12mm. The experimental conditions considered during the test included various normal stiffnesses (200kPa/mm、500 kPa/mm、800kPa/mm、1100 kPa/mm),normal stress(40kPa、80kPa、120kPa、160kPa),water content of soil(10%、13%、16%)and testing temperature(20、-2、-4、-6).

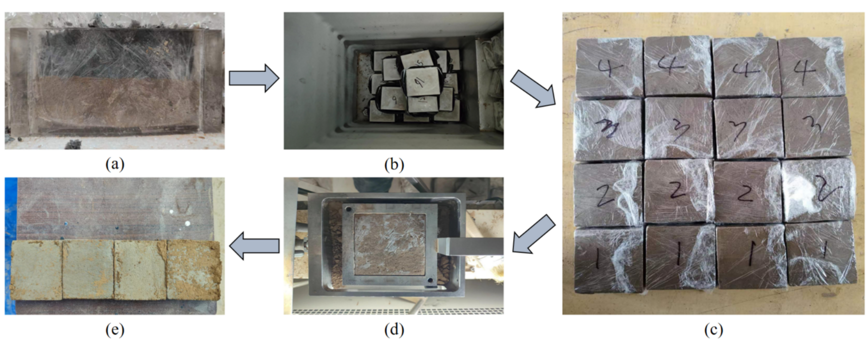


FIGURE 6 Flow chart of interface direct shear experiment (a)Sample preparation, (b) Unifirectional freezing, (c) Constant temperature maintenance, (d) Shearing, (e) Photography

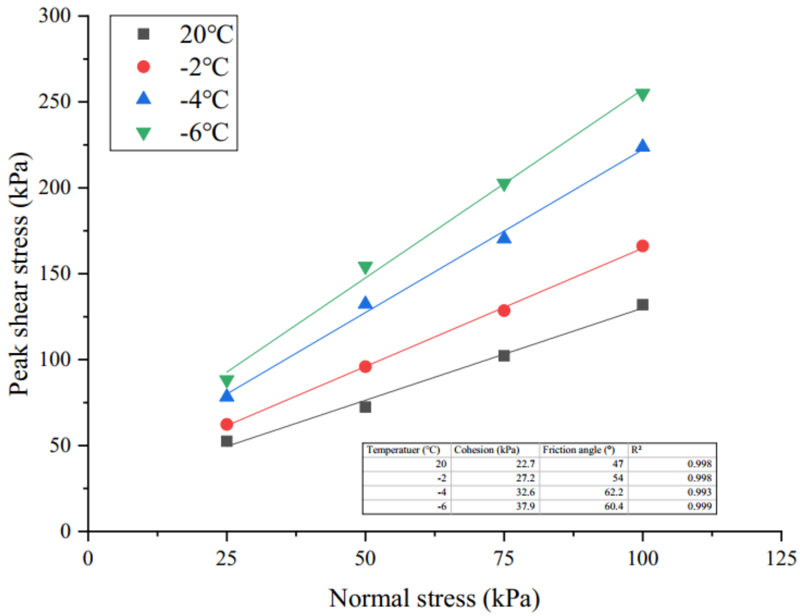


FIGURE 10 Effect of temperature on the peak shear strength(k =1100kPa/mm,w =13%)

Figure 11 demonstrates the influence of water content on the interfacial shear strength at temperatures of 20 and -4. As shown in Figure 11(a) for room temperature conditions, with the increase in water content, the interfacial shear strength initially increases and then decreases, reaching a maximum at the optimal water content (w =13%). Correspondingly, the interfacial cohesion and friction angle also peak at the optimal water content. This is because when the soil water content is low, strongly bound water dominates around soil particles, forming a common bound water film between adjacent soil particles. The binding effect of the bound water enhances the interaction force between the soil, as well as between the soil and the concrete interface. As the water content increases, this interaction force gradually increases, leading to a corresponding increase in the interfacial shear strength. However, as the water content in the soil further increases, the weakly bound water film around the soil particles gradually becomes thicker. The binding effect of the weakly bound water is weaker, resulting in a gradual decrease in the strength of the soil and the interface. Additionally, as the water content gradually increases, the bound water film in the soil gradually forms, thickens, and even free water appears. In this process, the water in the soil acts as a lubricant, making the movement of soil particles relatively easier. Therefore, the interfacial shear strength exhibits a pattern of first increasing and then decreasing with the increase in water content [35,38].

Figure 11(b) illustrates the variation of interfacial shear strength at -4. It can be observed that the strength gradually increases with the increase in water content, and the increase is more significant under high normal pressure. Both the interfacial cohesion and friction angle also increase with the increase in water content.

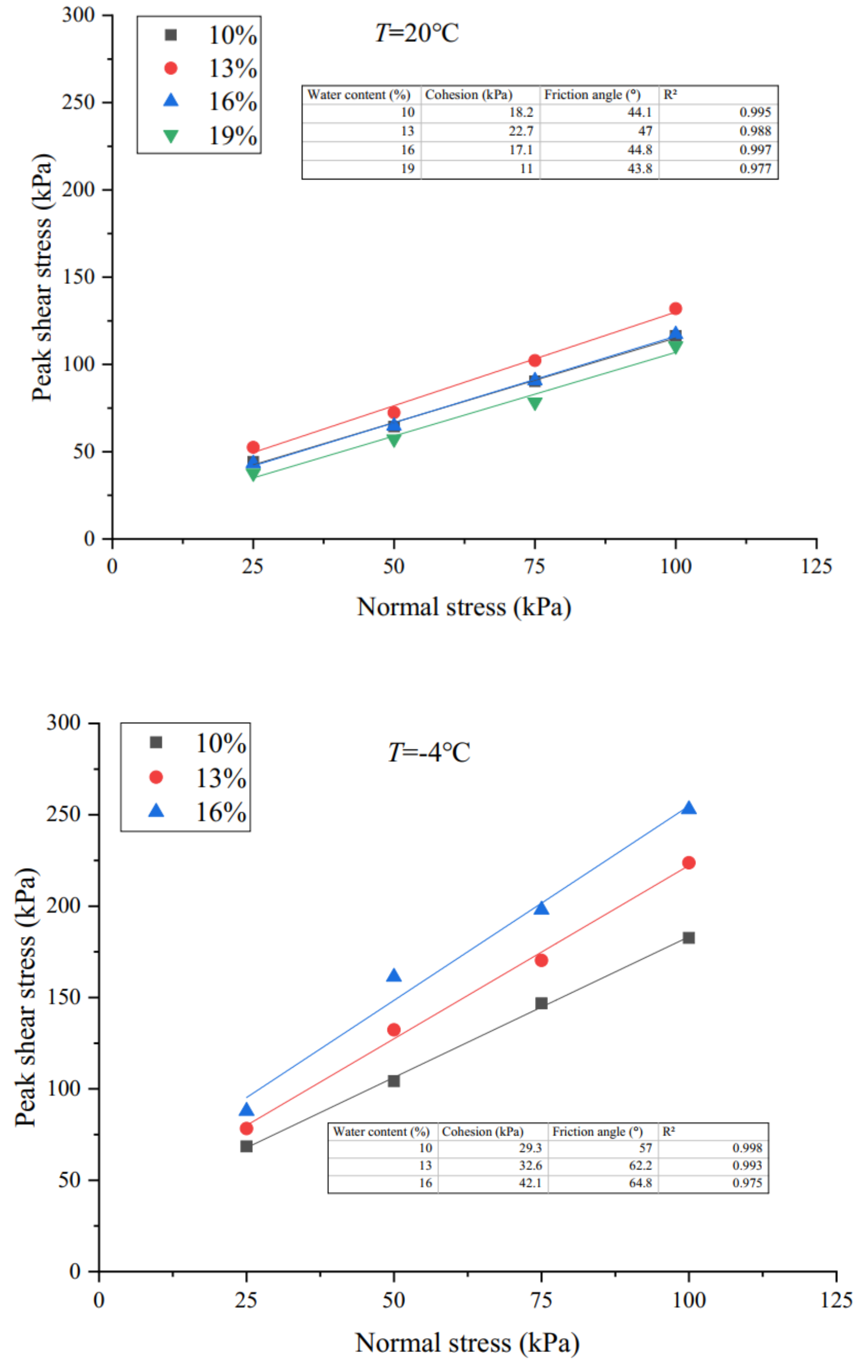
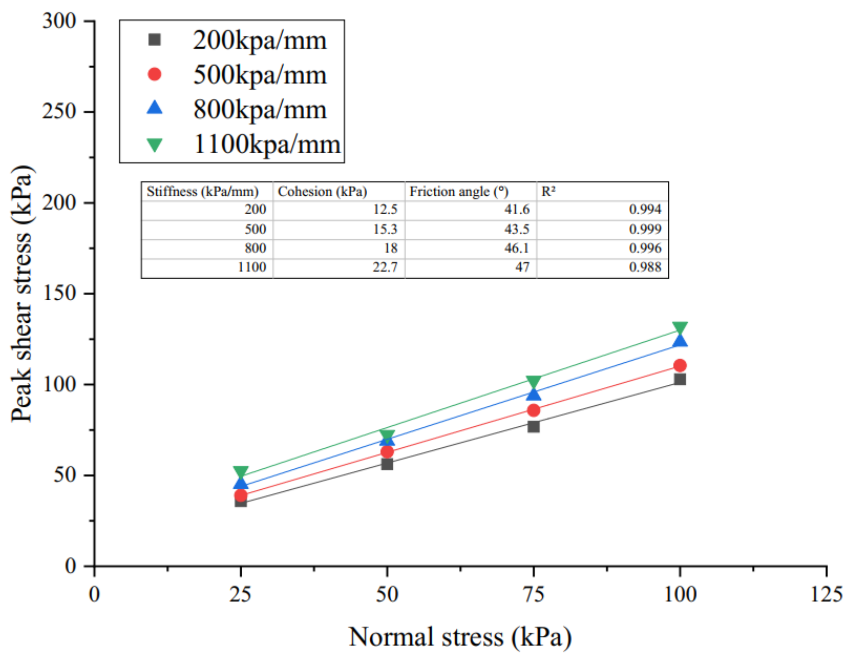


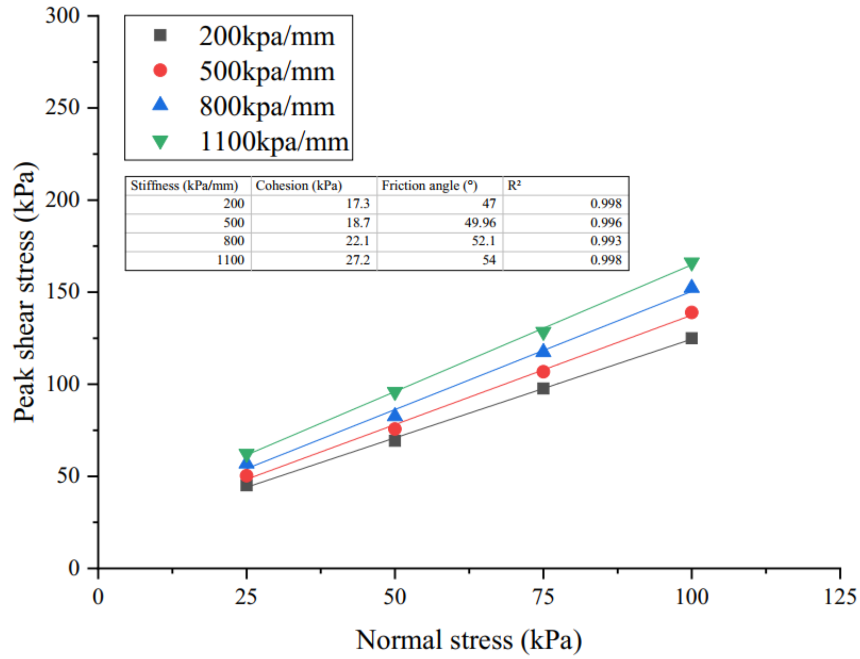
FIGURE 11 Effect of water content on the peak shear strength with temperature of 20 and -4(k =1100kPa/mm)

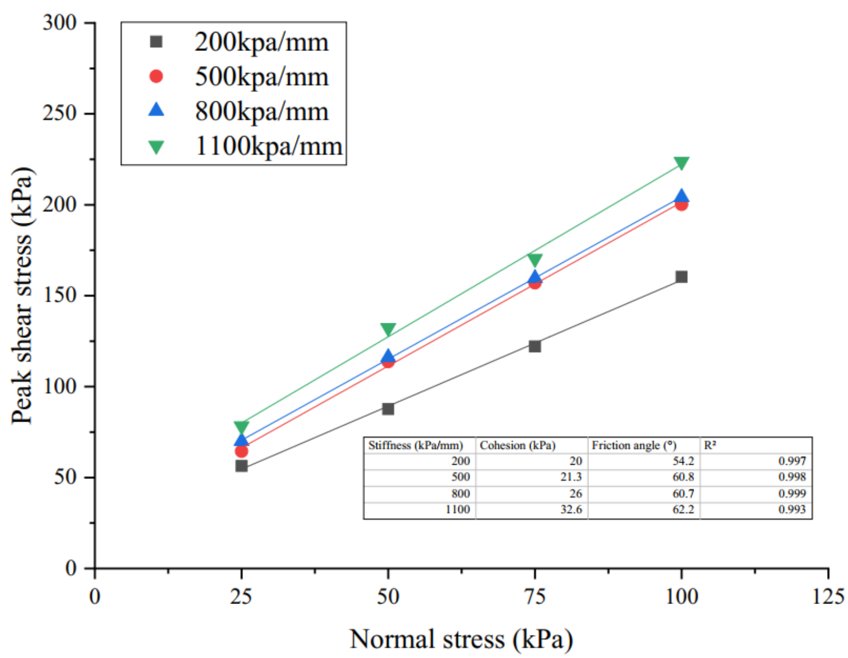
Figure 12 illustrates the influence of different temperatures and normal stiffnesses on the peak interfacial shear strength at a water content of 13%. Overall, as the normal stiffness increases, the interfacial shear strength also increases. Figure 12(a) shows the effect of various normal stiffnesses on the interfacial shear strength under room temperature conditions. It can be observed that under different normal pressures, the trend of the peak interfacial shear strength increasing with the increase in normal stiffness is consistent, exhibiting a gradual increase. This trend becomes more pronounced as the normal stress increases. This is because as the stiffness increases, greater normal stress is generated during the expansion of the specimen during shearing, thereby making the change in peak interfacial shear strength more significant. Under the same normal stiffness, the peak shear stress increases linearly with the increase in normal stress.

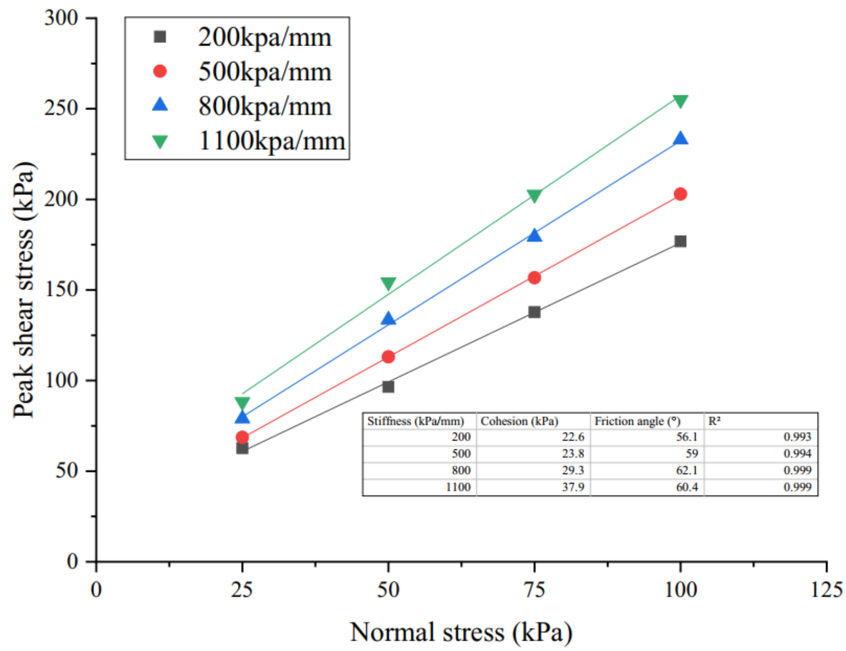
Figures 12(b-d) present the variation patterns under negative temperature conditions. The trends of stiffness and normal stress on peak shear strength are similar to those observed under room temperature conditions. However, under the same stiffness conditions, both cohesion and friction angles increase significantly. This is primarily due to the formation of ice cementation at the interface under negative temperature conditions, making the interfacial bonding tighter. As the temperature decreases, the peak shear strength gradually increases, and the cohesion also increases with the change in stiffness. Comparing stiffnesses of 200 and 1100, the increases are 9.9kpa, 12.6kpa, and 15.3kpa, respectively, showing a gradually increasing trend. This is because as the temperature decreases, the content of ice cementation between soil particles increases, allowing for a tighter bonding. As the stiffness of the soil gradually increases, it can exert a more concentrated force on the shear interface during sample expansion, resulting in a larger peak shear strength, thereby enhancing the influence of normal stiffness on cohesion.

As the temperature decreases, the internal friction angles of the interface with a normal stiffness of 1100 increase by 14.9%, 14.7%, and 7.7% compared to those with a normal stiffness of 200, showing a gradually decreasing trend. This is due to the increasing content of ice cementation at the interface. Since samples with high normal stiffness undergo greater shear strengths during shearing due to expansion and contraction, the ice cementation experiences brittle fracture. Consequently, the change in internal friction angle gradually slows down. This also explains why the internal friction angle at a normal stiffness of 1100 is slightly larger than that at a normal stiffness of 800 at -6.




200kpa/mm
500kpa/mm
800kpa/mm
1100kpa/mm
Stiffness (kPa/mm) | Cohesion (kPa) | Friction angle (°) | R²
200 | 17.3 | 47 | 0.998
500 | 18.7 | 49.96 | 0.996
800 | 22.1 | 52.1 | 0.993
1100 | 27.2 | 54 | 0.998
Peak shear stress (kPa)
Normal stress (kPa)


200kpa/mm
500kpa/mm
800kpa/mm
1100kpa/mm
Stiffness (kPa/mm) | Cohesion (kPa) | Friction angle (°) | R²
200 | 20 | 54.2 | 0.997
500 | 21.3 | 60.8 | 0.998
800 | 26 | 60.7 | 0.999
1100 | 32.6 | 62.2 | 0.993
Peak shear stress (kPa)
Normal stress (kPa)



Stiffness (kPa/mm)	Cohesion (kPa)	Friction angle (°)	R^2
200	22.6	56.1	0.993
500	23.8	59	0.994
800	29.3	62.1	0.999
1100	37.9	60.4	0.999

4 CONCLUSIONS

Through a controlled-temperature direct shear test system, this paper systematically investigates the shear characteristics of the interface between frozen soil and concrete under constant normal stiffness conditions, and arrives at the following conclusions: (1) With the increase in temperature and water content, the interfacial curve gradually transitions from a strongly hardening type to a weakly hardening type. The initial shear stiffness of the interfacial shear stress-shear displacement curve gradually increases, and the interfacial shear strength also gradually increases. (2) In the thawed state, there is no significant change in the curve morphology as the normal stiffness increases, all exhibiting strong strain hardening with a relatively small elastic deformation stage. In the frozen state, as the normal stiffness increases, the curve morphology transitions from a strongly hardening type to a weakly hardening type. The initial elastic stage of shearing is more pronounced, corresponding to a larger displacement. In the residual stage, the increment of shear stress decreases as the shear displacement increases. (3) Under normal temperature conditions, the peak interfacial shear strength gradually increases with the increase in normal stiffness, and this trend becomes more pronounced as the normal stress increases. Under negative temperature conditions, the peak shear strength significantly increases with the increase in normal stiffness, and this trend becomes more evident as the temperature decreases. Correspondingly, the interfacial cohesion and friction angle also increase with the increase in normal stiffness.

AUTHOR CONTRIBUTIONS

Shibin Yuan : methodology, validation, data curation, writing - review & editing. **Jiaming Cong** : investigation, resources, writing-origin draft. **Xuguang Fang** : funding acquisition, writing - review & editing. **Yue Wu** : investigation, formal analysis. **Huaichen Yu** : writing-origin draft, formal analysis.

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CONFLICT OF INTEREST

They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

Zhou Y W, Guo D X, Qiu G Q. *Geocryology in China* . Beijing: Scientific Press, 2000.

1. Zhou Z,Ma W,Zhang S, Mu Y, Li G. Effect of freeze-thaw cycles in mechanical behaviors of frozen loess. *Cold Regions Science and Technology* ,2018,146:9-18.
2. Li SY, Lai YM, Pei WS, Zhang S, Zhong H. Moisture-temperature changes and freeze-thaw hazards on a canal in seasonally frozen regions.*Nat. Hazards* ,2014, 72 (2), 287–308.
3. Özgan E, Serin S, Ertürk S, Vural I. Effects of freezing and thawing cycles on the engineering properties of soils. *Soil Mechanics and Foundation Engineering* , 2015, 52: 95-99.
4. Cui ZD, He PP, Yang WH. Mechanical properties of a silty clay subjected to freezing–thawing. *Cold Regions Science and Technology* , 2014, 98: 26-34..
5. Lai Y, Pei W, Zhang M, Zhou J. Study on theory model of hydro-thermal–mechanical interaction process in saturated freezing silty soil. *International Journal of Heat and Mass Transfer* , 2014, 78: 805-819.
6. Lu J, Zhang M, Zhang X, Pei W, Bi J. Experimental study on the freezing–thawing deformation of a silty clay. *Cold Regions Science and Technology* , 2018, 151: 19-27.
7. Zhou Z, Ma W, Zhang S, Mu L, Li G. Effect of freeze-thaw cycles in mechanical behaviors of frozen loess. *Cold Regions Science and Technology* , 2018, 146: 9-18.
8. He P, Mu Y, Yang Z, Ma W, Dong J, Huang Y. Freeze-thaw cycling impact on the shear behavior of frozen soil-concrete interface. *Cold Regions Science and Technology* , 2020, 173: 103024.
9. Hashemi A, Sutman M, Abuel-Naga H. Thermomechanical response of kaolin clay–concrete interface in the context of energy geostructures.*Canadian Geotechnical Journal* , 2022, 60(3): 380-396.
10. Ravera E, Sutman M, Laloui L. Cyclic thermomechanical response of fine-grained soil- concrete interface for energy piles applications.*Canadian Geotechnical Journal* , 2021, 58(8): 1216-1230.
11. Wang Y B, Zhao C, Wu Y. Study on the effects of grouting and roughness on the shear behavior of cohesive soil–concrete interfaces.*Materials* , 2020, 13(14): 3043.
12. Tan Z, Gou H, Li W, Bao Y. Effect of frost heave deformation of bridge foundation on operation safety of high-speed railway.*Structures* . Elsevier, 2023, 47: 2099-2112.
13. Wang T, Qu S, Liu J, Luo Q, Hu T. Frost jacking of piles in seasonally and perennially frozen ground. *Cold Regions Science and Technology* , 2022, 203: 103662.
14. Haeri H, Sarfarazi V, Zhu Z, Marji MF,Masoumi A. Investigation of shear behavior of soil-concrete interface. *Smart Structures and Systems* , 2019, 23(1): 81-90.
15. Yavari N, Tang A M, Pereira J M, Hassen G. Effect of temperature on the shear strength of soils and the soil–structure interface.*Canadian Geotechnical Journal* , 2016, 53(7): 1186-1194.
16. Fang R, Wang B, Pan J, Liu J, Wang Z, Wang Q, Ling X. Effect of concrete surface roughness on shear strength of frozen soil–concrete interface based on 3D printing technology. *Construction and Building Materials* , 2023, 366: 130158.
17. Liu J W, Cui L, Zhu N, Han B, Liu J. Investigation of cyclic pile-sand interface weakening mechanism based on large-scale CNS cyclic direct shear tests. *Ocean Engineering* , 2019, 194: 106650.
18. Di DA, Ferrari A, Laloui L. Experimental investigations of the soil–concrete interface: physical mechanisms, cyclic mobilization, and behaviour at different temperatures. *Canadian Geotechnical Journal* . 2016;53(4):659-72.
19. Liu SW, Zhang QQ, Ma B, Li S, Yin W, Luo Q. Study on surface roughness effect on shear behavior of concrete-soil interface. *Engineering Failure Analysis* . 2023, Mar 1;145:107050..
20. Li Y, Chai J, Li Y, Wang R, Qin Y, Cao Z . Experimental investigation of the interfacial bonding

properties between polyurethane mortar and concrete under different influencing factors. *Construction and Building Materials* , 2023, 408, 133800..

21. Pan J, Wang B, Wang Q, Ling X, Fang R, Liu J, Wang Z. An adhesion–ploughing friction model of the interface between concrete and silty clay. *Construction and Building Materials* , 2023, 376: 131039.
22. Hu G, Xia Y, Ruan X, Zheng M. Parameter analysis of coupling characteristics and load-sharing law of arch-chord coupled anti-sliding structure. *Engineering Reports* , 2023, 5 (2): e12568.
23. Liu J, Lv P, Cui Y, Liu J. Experimental study on direct shear behavior of frozen soil–concrete interface. *Cold regions science and technology* , 2014, 104: 1-6.
24. Tang L, Du Y, Liu L, Yang L, Yu Y. Experimental study of the frozen soil–structure interface shear strength deterioration mechanism during thawing. *Arabian Journal of Geosciences* , 2021, 14: 1-11.
25. He Pengfei, Ma Wei, Mu Yanhu, Dong Jianhua, Huang Yongting. Study on freezing strength characteristics and formation mechanism of frozen soil-concrete interface. *Transactions of the Chinese Society of Agricultural Engineering* ,2018,34(23):127-133.
26. Tang L, Huang T, Wang W, Jin L, Sun Q. Experimental study on shear characteristics and pore structure evolution characteristics of soil-rock mixture-concrete interface during freeze-thaw cycles.*Journal of Central South University(Science and Technology)* , 2023, 54(5): 1954-1969.
27. Sun T,Gao X,Yue Z,Li X, Sun X. Experimental study on the adfreezing strength of the interface between silt and concrete. *Chinese Journal of Rock Mechanics and Engineering* ,2020, 39(5): 1032-1039.
28. Wang B,Gao Y,Wang Q,Liu J. Effect of Freeze-Thaw Cycles on Shear Properties of Jilin Seasonal Frozen Silty Clay-Concrete Interface. *Journal of Jilin University (Earth Science Edition)* ,2023,53(6):1-11.
29. Wang B, Liu J, Wang Q, Lin X. Study of meso-damage and macroscopic shear performance of silty clay-concrete interface under freeze-thaw cycles. *Chinese Journal of Rock Mechanics and Engineering* ,2023,42(S01):3792-3800.
30. Zhang S, Liu F, Ying M, Zeng W. Test and prediction for the shear behavior of the sand–irregular concrete interface under constant and dynamic normal loading. *Soil Dynamics and Earthquake Engineering* , 2024,180, 108620.
31. Xie Y, Chen T, Wang J, Gu S, Zhu F. Study on dynamic shear characteristics of frozen clay-concrete interface. *Journal of Railway Science and Engineering* , 2022,19(9):2637-2646.
32. Maghsoodi S, Cuisinier O, Masrouri F. Thermal effects on mechanical behaviour of soil–structure interface. *Canadian Geotechnical Journal* , 2020, 57(1): 32-47.
33. Wernick E. Skin friction of cylindrical anchors in noncohesive soils.*Symp. on Soil Reinforcing and Stabilising Techniques* . 1978: 201-219.
34. Yin K, Fauchille A L, Di Filippo E, Kotronis P, Sciarra G. A review of sand–clay mixture and soil–structure interface direct shear test.*Geotechnics* , 2021, 1(2): 260-306.
35. Wang P, Yin Z Y. Effect of particle breakage on the behavior of soil-structure interface under constant normal stiffness condition with DEM. *Computers and Geotechnics* , 2022, 147: 104766.
36. Hashemi A, Sutman M, Medero G M. A review on the thermo-hydro-mechanical response of soil–structure interface for energy geostructures applications. *Geomechanics for Energy and the Environment* , 2023, 33: 100439.
37. Xu J, Liu J, Shi X, Ji F, Zeng Y. DEM investigation of the effect of coarse content and size ratio on the local shear behavior at gap-graded soil-structure interface. *Powder Technology* , 2024, 433, 119281..