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Impact of Climate Change on the Performance of Permafrost Highway Subgrade Reinforced by Concrete Piles

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Abstract: Climate change has a detrimental impact on permafrost soil in cold regions, resulting in the thawing of permafrost and causing instability and security issues in infrastructure, as well as settlement problems in pavement engineering. To address these challenges, concrete pipe pile foundations have emerged as a viable solution for reinforcing the subgrade and mitigating settlement in isolated permafrost areas. However, the effectiveness of these foundations depends greatly on the mechanical properties of the interface between the permafrost soil and the pipe, which are strongly influenced by varying thawing conditions. While previous studies have primarily focused on the interface under frozen conditions, this paper specifically investigates the interface under thawing conditions. In this study, direct shear tests were conducted to examine the damage characteristics and shear mechanical properties of the soil-pile interface with a water content of 26% at temperatures of −3 °C, −2 °C, −1 °C, −0.5 °C, and 8 °C. The influence of different degrees of melting on the stress–strain characteristics of the soil-pile interface was also analyzed. The findings reveal that as the temperature increases, the shear strength of the interface decreases. The shear stress-displacement curve of the soil-pile interface in the thawing state exhibits a strain-softening trend and can be divided into three stages: the pre-peak shear stress growth stage, the post-peak shear stress steep drop stage, and the post-peak shear stress reconstruction stage. In contrast, the stress curve in the thawed state demonstrates a strain-hardening trend. The study further highlights that violent phase changes in the ice crystal structure have a significant impact on the peak freezing strength and residual freezing strength at the soil-pile interface, with these strengths decreasing as the temperature rises. Additionally, the cohesion and internal friction angle at the soil-pile interface decrease with increasing temperature. It can be concluded that the mechanical strength of the soil-pile interface, crucial for subgrade reinforcement in permafrost areas within transportation engineering, is greatly influenced by temperature-induced changes in the ice crystal structure.

Keywords: transportation and pavement engineering; highway subgrade reinforcement; freeze–thaw cycles; soil-pile interface; permafrost thawing; climate change

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1. Introduction

Global warming has emerged as one of the most significant challenges of the 21st century. The impact of climate change has resulted in a rise in the average annual ground temperature in cold regions, leading to a reduction in permafrost thickness and an increase in the thickness of the active layer [1,2]. The freeze–thaw cycles have caused various issues such as uneven heaving, settlement, rutting, and cracking of pavements, as well as landslides and mudflows. These problems severely compromise the stability and serviceability of infrastructure in transportation engineering [3,4].

To address the range of issues arising from subgrade degradation of permafrost areas affected by climate change, the primary solution to combating deformation resulting from the thawing and freezing of railway foundations is to utilize materials or structures that enhance thermal resistance, reduce heat, cool the permafrost layer, and maintain the stability of the foundation. Traditional construction methods, such as soil replacement with gravel and the installation of thermosyphons, insulation layers, and ventilation pipes, have been proposed and implemented in practice over the past few decades. However, these methods often lead to long-term subgrade settlement and incur high costs for highway maintenance. An alternative approach to subgrade treatment for highways constructed on permafrost or weak soils is the use of rigid pile composite foundations. These foundations are designed to bear external loads and transfer them downward through soil-pile interaction. As the soil surrounding the pile undergoes the thawing process, changes in the unfrozen water content at the soil-pile interface can impact the mechanical properties. To prevent subgrade settlement, even during the thawing process, it is essential to investigate the mechanical properties of the soil-pile interface under varying temperature conditions.

Studies on the mechanical properties of the soil-pile interface under ambient conditions have been conducted since the 1960s. Potyondy et al. [5,6] used direct shear tests to investigate the mechanical properties of a variety of soil-structure contact surfaces and showed that the rate of increase in shear stress was greater in the initial phase of shear. By conducting large direct shear tests on concrete slab-soil bodies with different roughness, Xiong et al. [7] found that the maximum shear stress and the shear expansibility of the specimens increased with the interface roughness; the stress-displacement curves had significant strain softening characteristics. Lv et al. [8] used direct shear apparatus to conduct rapid shear tests on a modified loess-concrete interface. They analyzed the shear properties of the interface under the influence of moisture content, dry density, and normal stress and investigated variations in interface shear strength, tangential stiffness, cohesion, and internal friction angle. Wang et al. [9] investigated the effect of super-pore water pressure on the shear strength parameters of the pile-soil interface by analyzing the super-pore water pressure at the concrete-soil interface. Huck and Saxena [10] investigated the mechanical properties of soil-structure contact surfaces using torsional shear. They successfully implemented the shearing process on both contact surfaces by substituting the upper and lower base plates of sandy soil specimens with concrete plates. Consequently, factors such as the normal stress, surface roughness of the structure, moisture content of the soil, and its mechanical properties play a significant role in determining the shear properties of the interface.

Regarding the interaction between soil and piles on frozen ground, research has indicated that the tangential freezing expansion force at the soil-pile interface is determined by the freezing strength [11]. The freezing strength between the frozen soil and pile interface plays an important role in foundation stability, especially in group pile foundations. Biggar [12] studied the effects of temperature, salt, and other factors on the shear properties of the concrete-grouted pile-soil interface. Shi [13] presented results from cryogenic direct shear tests and an elastoplastic model based on damage at the ice-frozen soil interface. The variation pattern of the shear stress profile with temperature was obtained, and it was observed that the volume deformation initially contracts and then expands with increasing shear displacement. Shi et al. [14] performed shear tests on the permafrost-structure interface under different influencing conditions using a multifunctional large-scale direct shear instrument. They investigated the relationship between peak freezing strength, sub-peak freezing strength, normal stress, temperature, and roughness. Chen [15] conducted a large-scale direct shear test within a low-temperature environmental chamber and analyzed the relationship between the shear strength of the frozen soil and the freezing strength of the interface. He et al. [16] investigated the impact of freeze–thaw cycling on the shear behavior of a frozen soil-concrete interface through direct shear tests. They examined the effects of freeze–thaw cycling on shear displacement and strength parameters and provided key parameters for simulating the shear behavior of the interface. Wang et al. [17,18] investigated the effects of roughness, temperature, water content, vertical stress, and salt content conditions on the frozen soil-structure interface and summarized the degree of influence of each factor on the mechanical properties of the interface. Currently, research has demonstrated that moisture content and normal stress are key factors influencing the shear properties of the soil-pile interface, with temperature being another crucial factor. However, the existing studies on interface properties primarily concentrate on normal soil, permafrost, and freeze-thaw soil, while there is a lack of research on the thawing soil-pile interface.

In this paper, the mechanism of temperature influence on the shear properties of the pile-soil interface is investigated through direct shear tests, with a focus on the shear characteristics of the pile-frozen soil interface of composite foundations. Particularly, the damage characteristics, stress–strain curve characteristics, evolution of peak shear strength, and residual shear strength of both the thawing soil-pile and thawed soil-pile surfaces are obtained and analyzed. In addition, the effect of temperature on the mechanical response of the soil-pile interface is studied, and the evolution of the shear properties of the soil-pile interface from the frozen to the thawed state is characterized. The findings of this research hold significant importance in understanding the mechanism of soil-pile interaction in permafrost areas, revealing the influence of permafrost degradation on the load-bearing capacity of composite foundations, and providing guidance for the design and construction of road foundations in permafrost areas.

2. Materials and Methods

2.1. Materials and Equipment

2.1.1. Soil Samples

The soil samples studied in this experiment are typical of the studied area in Qinghai, Tibet Plateau, China, and their basic physical property indices are shown in Table 1 [19]. The soil sample grading curve is shown in Figure 1. The content of the fine-grained group in the soil sample is 94.94%, and the plasticity index is 12.81, indicating that the soil sample used in the test is pulverized clay.

Table 1. Basic physical indicators of the soil sample.

Optimum Moisture Content/%	Maximum Dry Density/g·cm^{-3}	Plasticity Index	Plastic Limit/%	Liquid Limit/%	Specific Gravity
14%	1.86	12.81	17.69	30.5	2.72

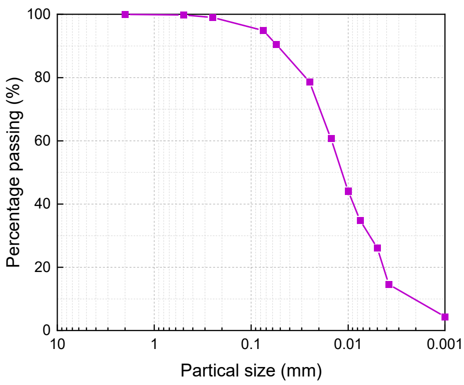


Figure 1. Gradation curve of the soil sample.

This paper focuses on the mechanical properties of ice-rich, frozen soils. According to the classification of perennially frozen soils according to the volumetric ice content in the Specifications for Design of Highway Subgrades JTG D30-2015 [20], and the formula: $w_p + 4\% < w < w_p + 15\%$, where w_p is the plastic limit, the water content of this ice-rich frozen soil is taken as 26%.

2.1.2. Concrete Specimens

The concrete specimens were prepared by mixing ordinary silicate cement (PO42.5) with fine sand and gravel (particle size less than 5 mm) in a ratio of cement:sand:gravel:water = 1:1.5:2.4:0.4. The ring knife was used as a concrete specimen mold with dimensions of 6.18 cm × 2 cm (diameter × height), filled with the mixed cement mortar, which is maintained for 28 days [21], following standard procedure (Figure 2). During the shear tests, the cured concrete specimens exhibited minimal particle crushing or peeling on the surface, allowing the permafrost–concrete interface to be approximated for direct shear tests.

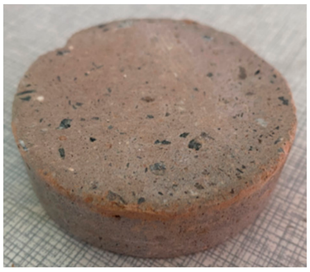
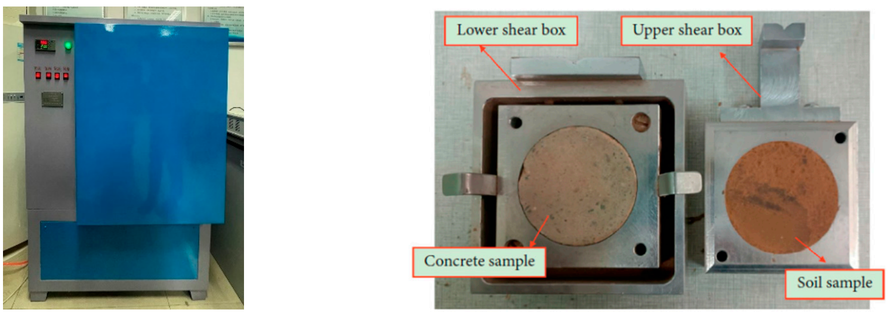


Figure 2. Concrete specimens.

2.1.3. Testing Equipments

The temperature control range of the test conditions in this study is −3~8 °C, and the equipments used in tests mainly include temperature control equipment and shear test equipment.

A constant-temperature environmental chamber was utilized to simulate a changing environment of high and low temperatures and humidity (as shown in Figure 3a). The equipment consists of a box, a heating and cooling system, and a control system (including a temperature controller, a sensor, safety protection measures, and a user operation panel), among other components. For the shear test of the powdered clay-concrete interface in the thawing process, a strain-controlled straight shear apparatus was employed (as shown in Figure 3b). The upper and lower shear boxes of the straight shear instrument had dimensions of 6.18 cm × 2 cm (diameter × height). It was imperative that the permafrost-concrete interface and the upper and lower shear box interfaces were perfectly aligned, and the shear rate was maintained at 0.8 mm/min.



(**a**) (**b**)

Figure 3. Testing equipments: (**a**) constant temperature environmental chamber; (**b**) direct shear test.

2.2. Methodology

Due to the significant impact of varying unfrozen water content on the engineering properties of the soil-pile interface within permafrost soil, it becomes essential to investigate the characteristics of shear behavior during the thawing process. To achieve this, different shear temperatures under thawing conditions were designed, ranging from molding temperatures −8 °C to −3 °C, −2 °C, −1 °C, −0.5 °C and 8 °C for the direct shear test. The soil-pile interface during the freeze–thaw process can be categorized into two groups:

the thawing frozen soil-pile interface and the thawed soil-pile interface. The soil moisture content was set at 26%, and the normal stresses were designed to be 200 kPa.

For the shear test preparation, once the materials were filled into the upper and lower shear boxes, they were placed into the temperature chamber. After completion of the filling process, they were left to stabilize for 12 h until the interface reached the specified temperature of −8 °C. Subsequently, all frozen specimens were transferred to an ambient temperature environment to allow them to thaw to the desired shear temperature (−3 °C, −2 °C, −1 °C, −0.5 °C, and 8 °C). The specimens were then placed on a thermostat set to the corresponding shear temperature for the direct shear test. The testing procedure can be seen in Figure 4.

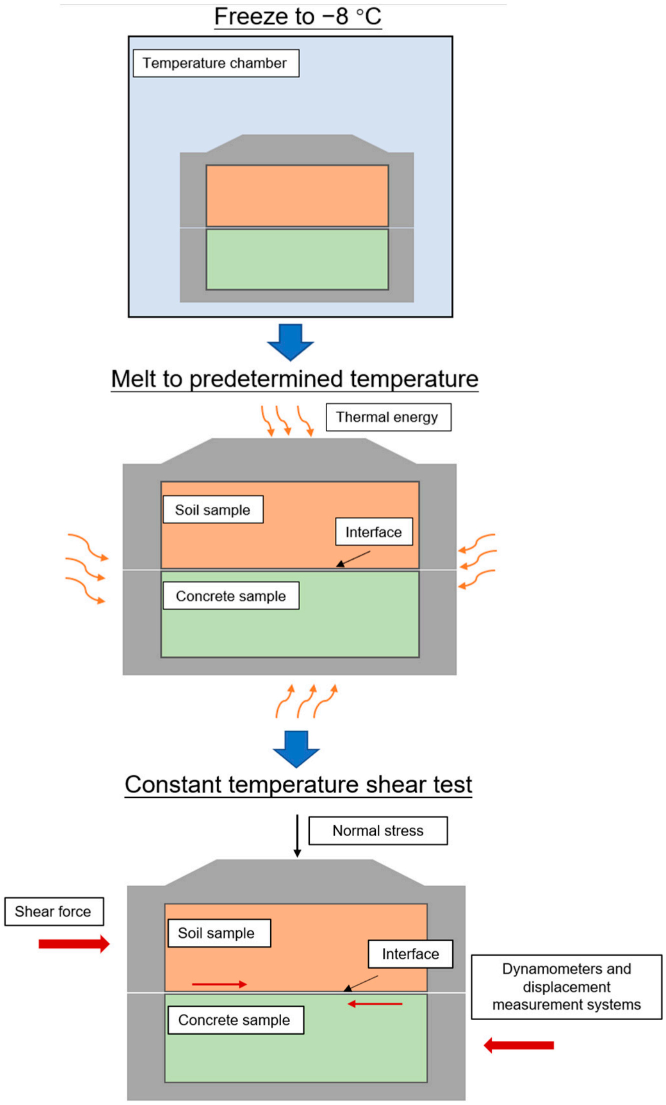


Figure 4. Schematic diagram of the shear test process.

3. Influence of Temperature on Stress–Strain Characteristics

Figure 5 illustrates the shear stress–strain curves of the permafrost soil-concrete pile with a moisture content of 26% under different shear temperatures (−3 °C, −2 °C, −1 °C, −0.5 °C, and 8 °C) during the freeze–thaw process. It was found that the stress–strain curves exhibited a steep drop in shear stress and brittle damage characteristics under the shear test. After the soil is completely thawed at a temperature of 8 °C, the stress–strain curve shows a weak strain-hardening trend. Additionally, it can also be seen in the thawing process that, as the temperature increases, both the initial stiffness and the shear strength decrease.

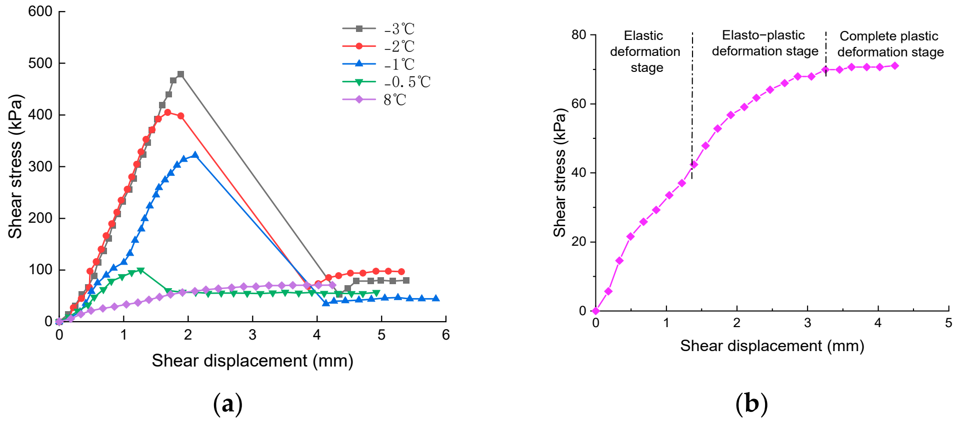


Figure 5. Shear stress−displacement curves at the soil−concrete pile interface at different shear temperatures: (**a**) overall diagram; (**b**) 8 °C shear temperature.

The shear stress-displacement curves of the frozen soil-concrete pile interface are divided into three phases, namely, the pre-peak shear stress growth phase, the post-peak shear steep drop phase, and the post-peak shear stress reconstruction phase. When the shear temperatures are −3 °C, −2 °C, and −1 °C, the curves of the pre-peak shear stress growth phase exhibit an "S" shape. In the initial phase of the shear test, the curves demonstrate exponential growth. As the test progresses, the slope of the curves increases until they become nearly straight lines, indicating that shear stress increases proportionally with shear displacement. Subsequently, the growth of shear stress gradually slows down as shear displacement increases until peak shear stresses are reached. Overall, as the shear temperature decreases, the peak shear stress at the interface gets larger. This can be attributed to the rapid shearing of the interface, the destruction of ice crystals, and the transition from maximum static friction to sliding friction [22]. Consequently, shear stress starts to decay rapidly. The destruction of ice crystals alters their direction towards reduced resistance during recrystallization, thus causing a significant decay of shear stress. With increasing shear temperature, the degree of shear stress release decreases gradually, with values of 88.98%, 82.95%, 79.18%, and 39.85%. This indicates that under the influence of normal stress and shear stress, the ice crystal structure of the interface is destroyed, and the unfrozen water content increases. Higher shear temperatures lead to increased unfrozen water content, resulting in a greater lubrication effect and a larger degree of shear stress release.

The shear stress-displacement curve of the soil-concrete pile interface under the thawed temperature condition (8 °C) is shown in Figure 5b. The stress–strain displacement curve can be divided into three stages: (i) elastic deformation stage, in which the shear strength of the soil-structure interface increases approximately linearly with the shear displacement; (ii) elastic-plastic deformation stage, in which the stress–strain relationship is curved and, with the increase of shear displacement, the slope of interface shear strength gradually decreases; (iii) fully plastic deformation stage, in which the interface shear strength tends to stabilize with the increase of shear displacement.

In summary, the different phases observed in the thawing process of the soil-pile interface provide insights into the changing behavior of interface strength and bond. The pre-peak phase demonstrates strengthening, indicating an initial increase in shear strength. The post-peak phase signifies weakening or failure, suggesting a decrease in shear strength. The post-peak reconstruction phase indicates some level of recovery or reestablishment of strength. These observations are crucial for comprehending and analyzing the behavior and stability of soil-pile systems under thawing conditions. They contribute to our understanding of how the interface between soil and pile evolves and adapts during the thawing process, providing valuable insights for designing and managing such systems in frozen ground environments.

4. Damage Characteristics of the Soil-Concrete Pile Interface

Figure 6 shows the characteristics of the frozen soil-concrete pile interface in the thawing process at 26% water content. It can be seen that when the temperature of the contact surface is −3~−1 °C, there is no unfrozen water accumulation at the interface; when the interface temperature increases to −0.5 °C, a large amount of unfrozen water accumulates at the interface.

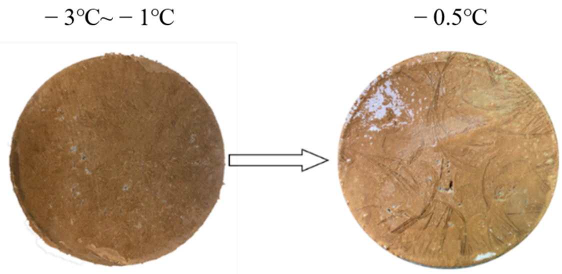


Figure 6. Shear surface characteristics of thawing frozen soil-concrete at different temperatures.

The presence of increased unfrozen water content within the ice crystal structure and the disturbed hydrothermal equilibrium at the soil-pile interface during the shear-slip process are factors that significantly influence the mechanical properties of the interface. The unfrozen water acts as a lubricant, leading to changes in the interface's behavior. This phenomenon holds particular significance in ice-rich permafrost areas, where the mechanical properties of the soil-pile interface are heavily influenced by the presence of unfrozen water.

5. Effect of Temperature on the Shear Mechanical Properties of Soil-Pile Interface

5.1. Peak Freezing Strength

The freezing strength refers to the maximum shear stress that the interface between frozen soil and other structures can withstand when they are frozen together. By examining the shear stress-displacement curves of the soil-concrete pile interface, the peak shear stress before the decay of shear stress in the thawing state is considered the peak freezing strength of the contact surface. Similarly, the shear strength of the interface in the thawed state is regarded as the peak freezing strength. The effect of temperature on the peak freezing strength of the soil-pile interface is shown in Figure 7.

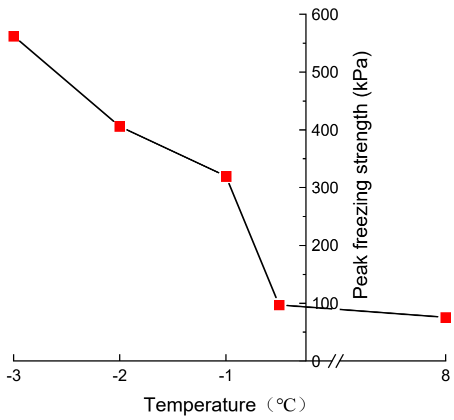


Figure 7. Peak freezing strength of thawing frozen soil-pile interface at different temperatures.

The peak freezing intensity of the interface tends to decrease as the temperature increases. This is mainly attributed to the variation in the unfrozen water content of the contact surface. When the interface is thawed to −3 °C, the unfrozen water content of the interface is low, and most of the water exists in the form of ice crystals, resulting in a higher cementation strength of the interface shear stress. As the temperature rises but does not reach the thawed state, the unfrozen water content of the interface also rises, leading to a reduction in the cementation strength of the ice crystals. It can also be seen that the peak freezing strength has a drastic drop when the shear temperature rises to −0.5 °C, due to the disturbed thermal equilibrium at the interface in the shear process, where part of the ice crystals experience phase change, resulting in higher unfrozen water content and enhanced "lubrication" effects.

The variation in peak freezing strength highlights the significance of lower temperatures in promoting the development of freezing strength, which plays a crucial role in ensuring foundation stability. Furthermore, in ice-rich island permafrost zones, group pile composite foundations face unfavorable conditions due to the relatively high ground temperature, typically ranging from −1 to 0 °C. Consequently, it is advisable to avoid utilizing the perennial permafrost layer as a subgrade in the island permafrost zone, and instead, bedrock is recommended as a more suitable subgrade option.

5.2. Residual Freezing Strength

In the thawing process of the soil-pile interface, the last stage of the stress-displacement curves exhibits a slight increase in shear stress after shear slip at the interface, eventually reaching a stable peak value known as the residual freezing strength. The post-peak shear stress reconstruction phase can be further divided into a shear stress growth phase and a shear stress stabilization phase (Figure 5). During the shear stress growth phase, the previously damaged interface experiences a regain of shear stress due to the ability of ice crystals to form secondary cementation in a lower temperature environment. Subsequently, the shear stress stabilization phase contributes to the development of residual freezing strength. Therefore, the residual freezing strength primarily comprises three components: (i) the strength of secondary cementation formed by ice crystals at the interface; (ii) the cohesion between soil particles and the concrete surface; and (iii) the friction between soil particles and the concrete surface.

Figure 8 illustrates the curve depicting the residual freezing strength under different temperatures while maintaining a constant normal stress of 200 kPa and a consistent moisture content of 26%. It can be observed that the overall residual freezing strength of the interface tends to decrease with increasing temperature. The presence of higher water content in the soil leads to a more pronounced development of ice crystals during the freezing process. However, as the temperature rises, the ice crystals begin to melt, resulting in an increase in the unfrozen water content at the interface. Unfrozen water at the interface shows lubricating effects, diminishing the secondary cementation strength of ice crystals and reducing the friction between soil particles and the concrete interface.

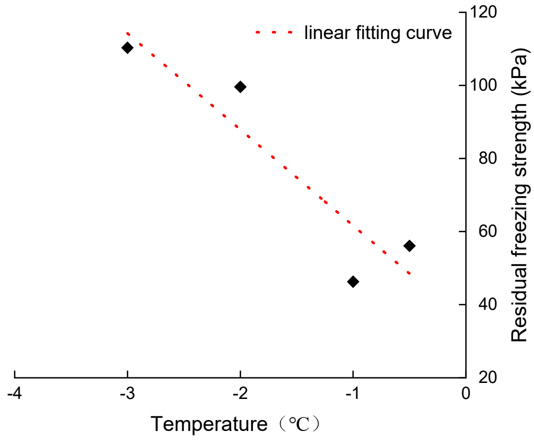
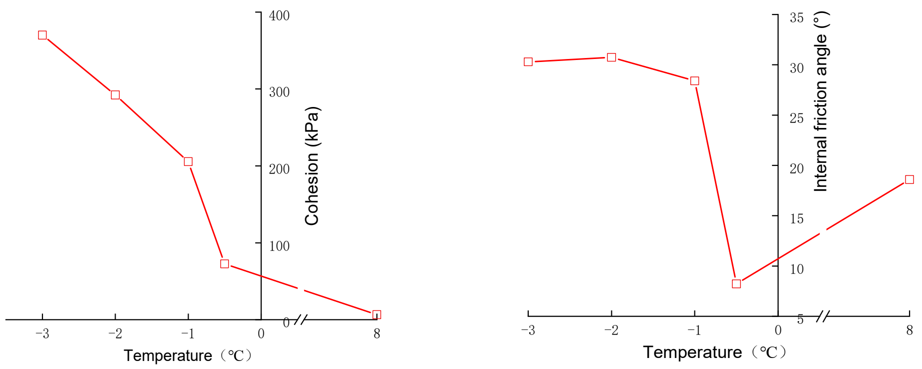


Figure 8. Residual freezing strength of thawing frozen soil-pile interface at different temperatures.

5.3. Characteristics of Shear Strength Parameters

The presence of normal stresses causes the structure surface and the frozen soil to squeeze each other, increasing the contact friction between the frozen soil and the structure surface. The Mohr–Coulomb strength criterion is widely used to describe the shear strength characteristics of the frozen soil-pile interface with the parameters of interfacial cohesion and internal friction angle.

The cohesion of the thawing frozen soil-concrete pile interface consists of the structural cementation strength of ice crystals and the cohesion between the soil particles and the concrete surface [17]. In general, as the temperature increases, the cohesion at the interface tends to decrease. This decrease is more significant when the temperature reaches −0.5 °C (Figure 9a). When the cementation strength of the ice crystal structure decreases sharply due to the increase of unfrozen water content at the contact surface, resulting in a sudden drop of the cohesive force.



(**a**) (**b**)

Figure 9. Temperature dependence of mechanical parameters of thawing frozen soil-concrete pile interface: (**a**) change in cohesion; (**b**) change in the internal friction angle.

Figure 9b shows that the internal friction angle decreases with the increase in temperature, with a sharp drop at −0.5 °C, and then it starts to increase at a temperature of 8 °C. This observation indicates that the increased unfrozen water content plays a role in lubricating the interface and reducing the internal friction angle in the early stages of the thawing process. However, in the later stage of the thawing process, the friction between soil particles and concrete begins to recover, leading to an increase in the internal friction angle. This change in the internal friction angle can be attributed to the alteration of the ice crystal structure and the redistribution of unfrozen water content at the contact surface. As water accumulates on the interface, the frictional effect is weakened.

6. Conclusions

Climate change is causing a rise in temperatures, which accelerates the degradation of permafrost used as a subgrade in pavement and transportation engineering. To combat this issue, concrete piles are being used as an alternative solution to prevent subgrade settlement and permafrost degradation. The differences between the frozen and thawed soil surrounding the pile are evident not only in the soil's phase but also in the composition of the soil-pile interface. In the frozen state, the interface comprises soil particles, ice crystals, unfrozen water, and the structure's surface. In contrast, the contact surface in the thawed state primarily consists of soil particles, water, and the structure's surface. The presence of ice crystals provides ice cementation, which helps resist lateral and shear deformation at the interface.

In this paper, the shear properties of the soil-concrete pile interface were studied through direct shear tests in the thawing state and the thawed state, and the conclusions are summarized below.

(1) In the thawing state (−3 °C, −2 °C, −1 °C, −0.5 °C), the soil-pile interface undergoes brittle damage, resulting in a strain softening trend observed in the shear stress-displacement curve. The curve can be divided into three stages: the pre-peak shear stress growth stage, the post-peak shear stress steep drop stage, and the post-peak shear stress reconstruction stage. In the thawed state (8 °C), the shear stress-displacement curve shows a strain hardening trend, and the curve can be divided into three stages: the elastic deformation stage, the elastic-plastic deformation stage, and the fully plastic deformation stage. This transition from strain-softening to strain-hardening behavior occurs as the frozen soil around the concrete pile transforms into thawed soil due to the increase in temperature. As the shear temperature increases, the shear strength of the interface gradually decreases and approaches that of the thawed state.
(2) The peak freezing strength of the permafrost-pile interface decreases as the temperature increases, with a sharp drop occurring at −0.5 °C. Similarly, the cohesion and internal friction angle of the permafrost soil-pile interface exhibit a decreasing trend with increasing temperature, and a sharp drop is observed at −0.5 °C. This indicates that near the thawing state, the ice crystal structure of the interface undergoes a significant phase change and enters a state of ice-water coexistence, leading to a rapid decay in the mechanical properties of the interface. The residual freezing strength of the thawing frozen soil-concrete pile interface at different temperatures demonstrates an overall decreasing trend as the temperature increases.
(3) In the frozen state, the cohesion of the soil-pile interface is primarily governed by the adhesive force of the ice crystal structure formed at the interface. This adhesive strength is influenced by the temperature. However, in the thawing state, the cohesion is determined by the adsorption force between the soil particles and the surface of the structure. As the temperature increases, the cementation force provided by the ice crystals gradually transitions to the adsorption force, resulting in a gradual decrease in cohesion. On the other hand, the change in the internal friction angle over the temperature rise follows a decreasing trend initially, followed by an increase as it approaches the thawed state.

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