DOI: https://doi.org/10.14256/JCE.4437.2025

Građevinar 5/2026

Primljen / Received: 17.10.2025.
Ispravljen / Corrected: 13.4.2026.
Prihvaćen / Accepted: 7.5.2026.
Dostupno online / Available online: 10.6.2026.

Adfreezing and freeze-thaw effects on the shear strength of the Güngören clay-concrete interface

Authors:

Assist.Prof. **Aysenur Aslan Fidan**, PhD. CE
Dicle University, Turkey
Department of Engineering
aysenur.aslan@dicle.edu.tr
aysenur.asln@gmail.com
Corresponding author

Assist.Prof. **Murat Gulen**, PhD. CE
Siirt University, Turkey
Department of Engineering
murat.gulen@siirt.edu.tr

Prof. **Suat Akbulut**, PhD. CE
Yildiz Technical University, Turkey
Department of Engineering
sakbulut@yildiz.edu.tr

Original research paper

Aysenur Aslan Fidan, Murat Gulen, Suat Akbulut

Adfreezing and freeze-thaw effects on the shear strength of the Güngören clay-concrete interface

The interaction between soil and structures is significantly affected by freeze-thaw (F-T) cycles, which alter soil strength and deformation behaviour. This study investigates the effects of F-T cycles on the shear strength, adhesion, and interface friction angle of the Güngören clay-concrete interface under varying water content. Samples were prepared at 5 % below and 5 % above the optimum water content and subjected to 0, 3, 7, and 10 F-T cycles between -20 °C and +20 °C. Direct shear tests were conducted under both freezing and thawing conditions. The results indicate that adfreezing, ice bonding at the interface, significantly enhanced the strength of frozen samples with shear strength increasing by 1.6-2.7 times in frozen wet-side samples and 1.05-1.19 times in dry-side samples. After thawing, dry-side samples exhibited strain-softening and reduction in strength 0.80-0.95 times the initial value, whereas wet-side samples largely preserved their strength. Adhesion increased slightly in dry-side frozen samples, whereas in wet-side samples, it increased nearly threefold after the third cycle and then stabilised. The interface friction angle exhibits different trends depending on the moisture content and thermal state. These variations are attributed to the combined effects of ice cementation, unfrozen water, particle interactions, and moisture redistribution at the interface.

Key words:
adfreezing, clay-concrete interface, freeze-thaw cycles, Güngören clay, shear strength

Izvorni znanstveni rad

Aysenur Aslan Fidan, Murat Gulen, Suat Akbulut

Učinci adhezijskog smrzavanja i F-T ciklusa na posmičnu čvrstoću sučelja između Güngören gline i betona

Ciklusi smrzavanja i odmrzavanja (F-T ciklusi) znatno utječu na interakciju tla i konstrukcije jer mogu promijeniti čvrstoću tla i njegovo deformacijsko ponašanje. U ovom se istraživanju analiziraju učinci F-T ciklusa na posmičnu čvrstoću, adheziju i kut trenja na sučelju između Güngören gline i betona pri različitim udjelima vode. Uzorci su pripremljeni s udjelima vode 5 % nižim i 5 % višim od optimalnog udjela te su podvrgnuti 0, 3, 7 i 10 F-T ciklusa u temperaturnome rasponu od -20 °C do +20 °C. Pokusi izravnog smicanja provedeni su u smrznutome stanju i nakon odmrzavanja. Rezultati pokazuju da je adhezijsko smrzavanje, odnosno vezivanje ledom na sučelju, znatno povećalo čvrstoću smrznutih uzoraka. Posmična čvrstoća povećala se od 1,6 do 2,7 puta kod smrznutih uzoraka s većim udjelom vode te od 1,05 do 1,19 puta kod uzoraka s manjim udjelom vode. Nakon odmrzavanja uzorci s manjim udjelom vode pokazali su deformacijsko omekšavanje i smanjenje čvrstoće na 0,80 do 0,95 početne vrijednosti, dok su uzorci s većim udjelom vode uglavnom zadržali svoju čvrstoću. Adhezija se blago povećala kod smrznutih uzoraka s manjim udjelom vode, dok se kod uzoraka s većim udjelom vode nakon trećeg ciklusa povećala gotovo trostruko, a zatim stabilizirala. Kut trenja na sučelju pokazao je različite trendove ovisno o udjelu vode i toplinskome stanju uzorka. Navedene se promjene mogu pripisati zajedničkome djelovanju cementacije ledom, nesmrznute vode, međudjelovanja čestica i preraspodjele vlage na sučelju.

Ključne riječi:
adhezijsko smrzavanje, sučelje glina-beton, ciklusi smrzavanja i odmrzavanja, Güngören glina, posmična čvrstoća

1. Introduction

In cold regions, the interaction between the soil and structures is highly influenced by the F-T cycles. The freezing of water within soil pores leads to significant changes in the soil strength and deformation characteristics [1, 2]. In addition, the shear resistance developed at the interface between frozen soil and structural surfaces, known as adfreezing, plays a critical role in the stability of the infrastructure embedded in or supported by soil [3, 4].

Repeated F-T cycles can change the mechanical properties of both the soil and the soil-structure interface, resulting in variations in the shear strength [5, 6]. These variations create challenges in maintaining the long-term performance and stability of structures subjected to such environmental conditions. Therefore, understanding soil-structure interactions under freezing and thawing conditions is essential for the safe and cost-effective design of geotechnical systems such as friction piles, retaining walls, anchors, highways, embankments, shallow foundations, and compacted layers [7, 8]. Most engineering problems in frozen soil mechanics are related to predicting the behaviour of soil under coupled mechanical and thermal effects [9, 10].

The F-T cycle has four stages: prefreezing, freezing, thawing, and consolidation. In the pre-freezing stage, the soil was compact and exhibited high shear strength. During freezing, ice formation causes separation of soil particles, leading to a more dispersed structure. During the thawing stage, the soil exhibited a higher void ratio and lower shear strength. Finally, after consolidation, the soil gradually regains strength as it settles under load, with a reduced void ratio compared to the thawed condition, although it remains higher than that in the prefreezing state [11, 12].

The shear behaviour of the interface between the frozen soil and structural materials is critical for evaluating the performance of geotechnical systems in cold regions. The effect of adfreezing on the interface shear strength has been extensively investigated using different soil types, including silt [4], clay [13, 14], sand [15], and sandstone [16], in combination with structural materials such as steel [4, 17, 18], concrete [19-21] or ice [13]. These studies were conducted using temperature-controlled standard tests [13, 21], large shear tests [14, 19, 22] and low-temperature chambers [4] at different temperatures.

At a constant temperature, an increase in the initial water content resulted in a higher interface shear strength. Conversely, at a constant water content, decreasing the temperature results in an increase in shear strength, which has a more pronounced effect on adhesion [13, 19]. As the temperature decreased, the failure mode transitioned from strain hardening to strain softening, primarily because of the increase in ice content. As ice behaves as a brittle material, it significantly influences the observed failure behaviour [14, 23].

Furthermore, the higher thermal conductivity of concrete compared to that of soil promotes the migration of unfrozen water toward the interface. This process leads to the formation of an ice film at the contact surface between the frozen soil and concrete. Such moisture migration and ice film formation significantly affect the mechanical behaviour of the soil-concrete interface [20, 24-26].

According to meteorological data from the Turkish State Meteorological Service (MGM) for the period 2000-2022, although Istanbul generally exhibits a mild climate, minimum air temperatures during winter months-particularly in December, January, and February-frequently fall below 0 °C and can occasionally reach as low as −8 °C. These conditions led to repeated F-T cycles in the near-surface layers. Therefore, understanding the effects of such thermal conditions on the mechanical behaviour of Güngören clay is critical for ensuring the long-term stability of structures found on or interacting with this soil. A significant portion of Istanbul's infrastructure, including major roads, Atatürk Airport, railway lines, and shallow building foundations, has been constructed using Güngören clay [27, 28].

This study investigates the shear behaviour of the Güngören clay-concrete interface under frozen and thawed conditions, considering the effects of F-T cycles, normal stresses, and water content. The objective of this study is to evaluate the effects of freezing and thawing processes on the interface shear strength and to provide insights for improving the safety and resilience of urban infrastructure.

2. Materials and methods

2.1. Geotechnical properties of Güngören clay

In this study, the soil samples were collected from a site near the Yildiz Technical University campus and belonging to a locally known unit referred to as "Güngören clay". This high-plasticity green clay is a constituent of the widely distributed Güngören Formation. Along with the Gürpınar Formation, it is considered one of the most problematic soil units in Istanbul because of its high plasticity and pronounced sensitivity to environmental conditions [29]. The Güngören Formation is extensively distributed across Istanbul and is particularly prominent in areas such as Yedikule, Kazlıçeşme, Osmaniye, Şirinevler, Yenibosna, and Halkalı, with thicknesses ranging from approximately 9 to 22 meters [28]. Figure 1 illustrates the spatial distribution of this formation on the European side of Istanbul and highlights its geological prevalence across the urban districts.

These clays underlie critical infrastructure, including major transportation corridors, airports, and densely populated residential zones [27, 28], making their behaviour under thermal conditions particularly important to consider.

X-ray diffraction (XRD) analysis was conducted in the laboratory of the Yildiz Technical University to determine the mineralogical composition of the sample. The results indicate that montmorillonite was the dominant mineral, exhibiting the highest peak intensity. Other identified minerals included illite-muscovite, kaolinite, and quartz, which were observed at varying intensities. In addition, the coexistence of illite and montmorillonite was confirmed by the multiple characteristic peaks in the XRD pattern (Figure 2).

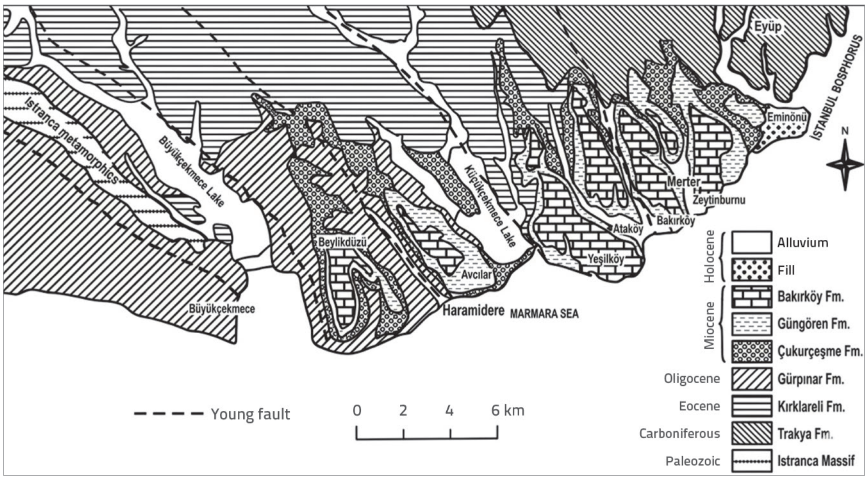

Figure 1. Geology map of the European part of Istanbul [30]

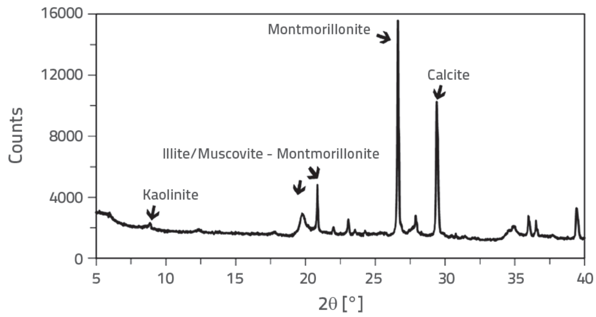

Figure 2. XRD result of Güngören clay

Laboratory tests were conducted on samples obtained from the site to determine the engineering properties of the Güngören clay. These tests include sieve analysis [31, 32], consistency limits [33], specific gravity [34] and compaction tests [35]. Figure 3 shows the location of the Güngören clay on the Casagrande plasticity chart, and Table 1 presents its index properties.

Table 1. Properties of Güngören clay

Property	Value
Specific gravity (Gs)	2.63
Liquid limit, LL [%]	81.50
Plastic limit, PL [%]	35.30
Plasticity index, PI [%]	46.20
Activity, A	0.71

The soil consisted of approximately 95 % fine-grained material with a clay fraction of 65 % based on sieve and hydrometer analyses. Sieve analysis was applied only to the coarse fraction retained on sieve no. 200, whereas the fine particle fraction was characterised using hydrometer analysis. The liquid limit (LL), plastic limit (PL) and plasticity index (PI) were 81.5 %, 35.3 %, and 46.2 %, respectively. According to ASTM D2487-17 [36], the soil was classified as high-plasticity clay (CH).

According to ASTM D4546 [37], clays with a PI > 40 % exhibit a very high swelling potential. Accordingly, Güngören clay is characterised by a high swelling potential, swelling pressure, and water retention capacity. These properties are largely governed by the mineral composition, specific surface area, and cation exchange capacity [38]. Montmorillonite-rich clays exhibit the highest swelling and water-retention capacities [39].

Mineral composition also influences the response of clay to freeze-thaw cycles. The expansion of montmorillonite during water absorption can induce structural degradation during freeze-thaw cycles and lead to softening of the soil upon thawing [40]. The results presented in Figure 2 and 3 further confirm the freeze-thaw cycles of Güngören clay.

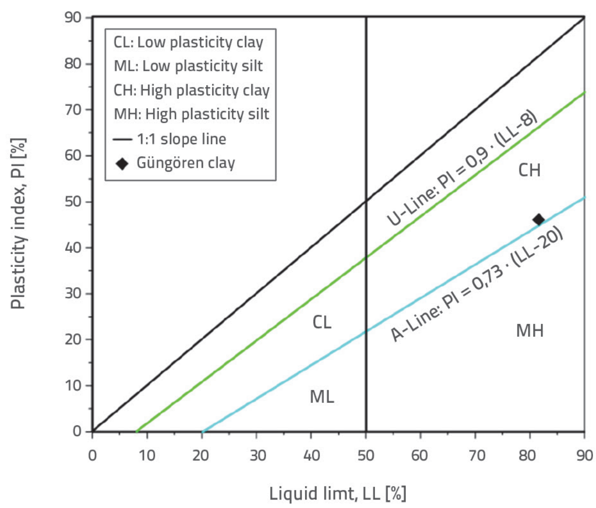

Figure 3. Location of Güngören clay on the Casagrande plasticity chart

All direct shear tests were conducted on soil samples compacted on both the dry and wet-sides of the optimum water content (wopt). The soil compaction curve is shown in Figure 4. The maximum dry density was 1.378 g/cm^3 and the optimum water content (wopt) was 28.3 %. The degree of soil saturation was approximately 60 % on the dry-side and 85 % on the wet-side.

A freezing-point depression test was conducted on compacted samples representing both the dry-side (w = 23.3 %) and wet-side (w = 33.3 %) of the compaction curve. The temperature-characteristic curves of the samples, shown in Figure 5, indicate that the freezing point (FP) is –1.1 °C for the dry-side sample and –0.4 °C for the wet-side sample.

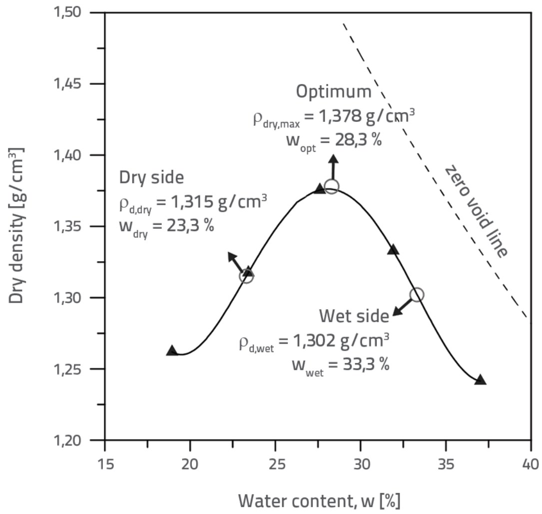

Figure 4. Standard compaction curve of Güngören clay

Previous studies have shown that the FP of soils is influenced by factors such as soil type, consistency limits, water content, salt composition and concentration, loading conditions, confining pressure, and vibrations [5, 41–44]. A lower initial water content leads to faster freezing and greater freezing-point depression due to changes in pore water pressure, whereas a higher water content delays freezing and slightly increases FP, particularly near saturation [16, 45, 46].

In addition, a higher water content resulted in a more pronounced delay in the advancement of the freezing front, whereas a lower moisture content led to a faster freezing rate and shorter stabilization time [45]. The FP of soil samples increased nonlinearly with increasing water content, approaching that of pure water (0 °C) at high saturation levels [16]. These effects are attributed to the presence of loosely bound water, which freezes at a much lower temperature, and to the increased water potential in soils with a higher moisture content [46].

2.2. Concrete blocks preparation and surface roughness characterization

The surface texture and hardness of construction materials at the contact interface play critical roles in governing the interface behaviour, with increased surface roughness generally leading to enhanced shear strength [48-50]. Although some studies have investigated smooth soil - concrete interfaces using plywood or steel moulds [51, 52], others have examined a range of surface roughness conditions to better represent field applications [53-55].

The concrete samples used to investigate the clay-concrete interfacial interactions were cast in specially designed plywood moulds. A water-cement-sand mixture (2:5:15 by mass) consisting of sand with particle sizes smaller than 4 mm was poured into the moulds, compacted, and cured by immersion in water (Figure 6a). During casting, vibration was applied to ensure adequate compaction and eliminate air voids, which could affect strength and uniformity.

After casting, the moulds were covered with plastic sheets to prevent the loss of moisture. Once the concrete had set (approximately 18-24 hours), the samples were demolded and subsequently cured in water under a moist cloth for 28 days to achieve full strength. The 28-day compressive strength of the cubic specimens (15 × 15 × 15 cm) prepared and cured under the same conditions was determined to be 51 MPa.

To evaluate surface roughness, the samples were analysed using an AEP Nanomap 1000WLI optical profilometer, which generates three-dimensional surface profiles by capturing variations in reflected light. Measurements were performed at multiple locations using both optical and stylus profilometry to ensure accuracy and repeatability (Figure 6.b).

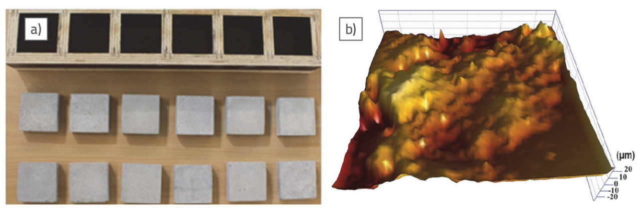

Figure 6. Details of concrete blocks: a) concrete samples and plywood molds b) surface roughness measurement sample

Various methodological approaches for quantifying surface roughness have been reported [56-58]. Among these, height-based parameters such as the normalised roughness index () are commonly used. The normalised roughness index (R_n) is

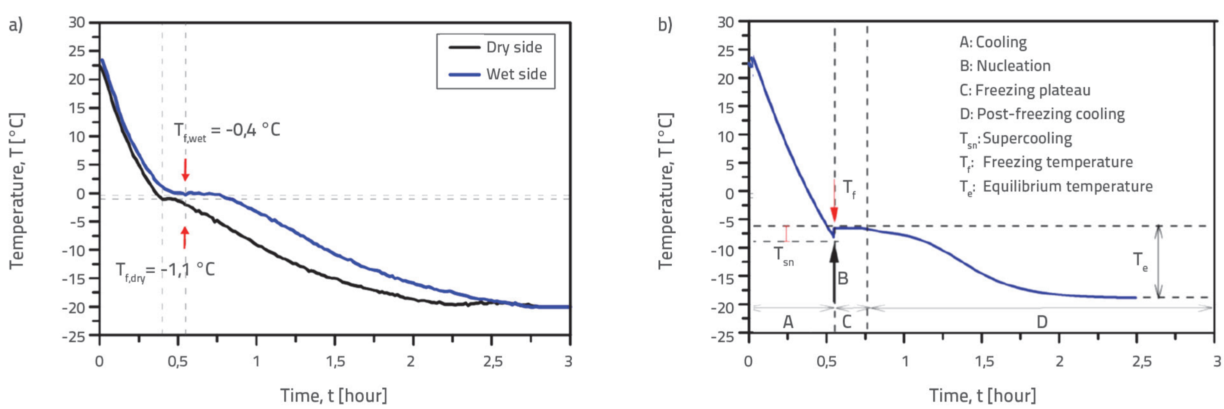

Figure 5. Temperature-time curves of: a) Güngören clay (experimental); b) typical freezing behaviour, according to [47]

commonly defined as the ratio of the maximum asperity height (R_{max}) to the mean particle size (D_{50}), as expressed in Equation (1): The corresponding R_n value for the clay used in this study was approximately 10.3, based on D_{50} = 0.0028 mm and R_{max} = 0.026 mm.

$$R_n = \frac{R_{max}}{D_{50}} \quad (1)$$

It is important to note that Equation (1) was primarily developed for granular soils, where the mechanical response is governed by the interaction between particle size and surface roughness. For fine-grained soils, such as clay-silt mixtures, where the representative particle size is significantly smaller, this parameter becomes less applicable and cannot be used to make a meaningful physical interpretation. In this study, instead of using approaches based on a single characteristic roughness height, an area-based formulation is adopted to account for the contribution of the entire surface texture along the interface. This formulation provides a more representative characterisation of surfaces with irregular roughness that do not exhibit consistent depth, spacing, or distribution.

In this formulation, the roughness parameter represents the ratio of the actual surface area to the projected planar area and provides a quantitative measure of the surface irregularity. Higher values indicate a rougher surface with more pronounced asperities, which may enhance mechanical interlocking at the interface. Based on this calculation method, the average roughness parameter (R_{av}) of the concrete blocks used in this study was determined to be 1.27.

$$R_{av} = \frac{A_r}{A_0} \quad (2)$$

2.3. Test procedure

For the freeze-thaw tests, the samples were compacted in a shear box ring, considering the density and water content for both the dry and wet-sides of the wopt determined from the compaction curve. The soil-water mixture was initially prepared and allowed to rest in a plastic mould for 24 h to ensure uniformity. The mixture was compacted into shear boxes directly onto the concrete surface, securely wrapped with a stretch film, and placed in a desiccator to ensure homogeneous moisture distribution after compaction. After compaction, the samples were arranged in boxes, placed in a cabinet in an orderly manner, and subjected to F-T cycles (Figure 7).

Figure 7. Stages in sample preparation shown in photos: a) prepared samples b) placing samples in a desiccator c) arranging sample in boxes d) placing samples in the freeze-thaw cabinet

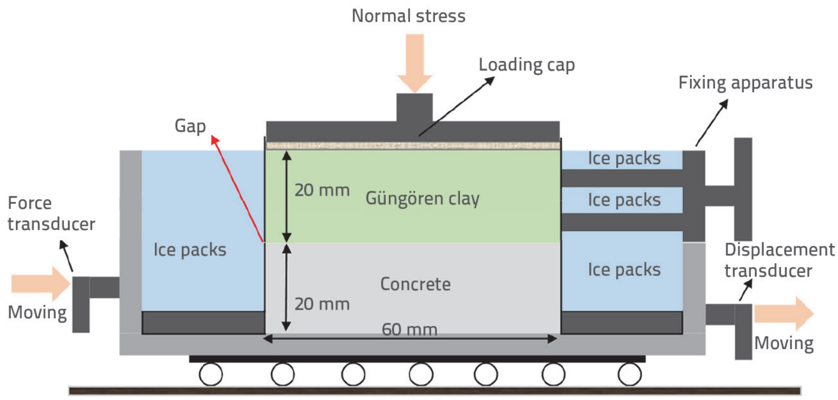

Figure 8. Schematic representation of the direct shear test apparatus

The compacted samples were then subjected to 0, 3, 7, and 10 F-T cycles. During the freezing stage, the samples were frozen at -20 °C and subsequently thawed at 20 °C. To prevent moisture loss, ambient humidity was maintained at 80 % throughout the thawing stage. The selected temperature range ensures complete freezing and thawing of the pore water, thereby eliminating partial phase change effects and reducing experimental variability.

The direct shear test, which is a well-established method for evaluating the shear behaviour of soils and soil-structure interfaces [13, 51, 59, 60], was employed in this study. The clay-concrete interface samples were tested using a shear box apparatus with dimensions of 6 cm × 6 cm under both freezing and thawing conditions. The tests were performed in accordance with ASTM D3080 [61] by applying normal stresses of 50, 100, and 200 kPa at a constant shear rate of 1.0 mm/min (Figure 8). This methodology is consistent with numerous studies on soil-structure interfaces under frozen and freeze-thaw conditions, including silt-concrete [4], clay-concrete [14, 62, 63], silty soil-steel [17], sand-steel [18], ice-frozen clay [13], clay-geotextile [64], and soil-geogrid interfaces [65]. Most studies used shear rates between 0.8 to 1.2 mm/min, consistent with the 1.0 mm/min applied in this study [4, 17, 20, 63, 64, 66]. Therefore, the experimental parameters, including the test method [13, 51, 59, 60], temperature [20, 63], shear rate [4, 17, 20, 63, 64, 66], and applied normal stress [4,13, 14,17] were consistent with those reported in the cited studies, supporting the validity and comparability of the results.

The samples were labelled according to the number of F-T cycles and thermal conditions applied during shearing. For instance, a "3-cycles (frozen)" sample refers to a specimen tested in a frozen

Table 2. Testing programme

Test material	Water ratio [%]	Freezing [°C]	Thawing [°C]	Cycles	σ [kPa]	Condition
Clay-concrete	23.3	–20	+20	0, 3, 7, 10	50, 100, 200	Frozen / Thawed
Clay-concrete	33.3	–20	+20	0, 3, 7, 10	50, 100, 200	Frozen / Thawed

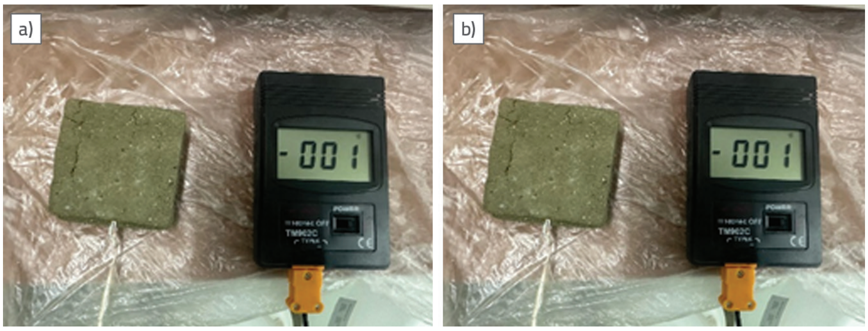

Figure 9. Temperature measurements of soil samples: a) before and b) after the direct shear test

state after three F-T cycles, whereas a "3-cycles (thawed)" sample denotes one tested in the thawed state after the same number of cycles (Table 2).

Control tests were conducted prior to the experimental program to assess repeatability. Under identical conditions, the variation in the measured shear stress was found to be limited, reaching approximately 3-4 % at 50 kPa, 2-3 % at 100 and 200 kPa for frozen tests, whereas for thawed tests, it remained at approximately 2 % for all normal stress levels. Following the verification, a planned test program was conducted. In addition, at least one test was repeated for each experimental condition under normal stresses of 50, 100, and 200 kPa.

Prior to the shear test, the metal ring of the shear box was cooled to prevent melting, and insulation was maintained during the experiment using ice packs and plastic covers (Figure 8). The temperatures of the soil samples measured before and after the test indicated an increase in temperature during shear testing (Figure 9). However, comparison with the freezing point indicated that the soil temperature remained close to it after testing.

In fine-grained soils, a portion of pore water remains unfrozen even at 0°C [67-70]. Even at very low temperatures, such as -20°C, considerable amounts of unfrozen water can persist, forming thin films around soil particles [70, 71]. According to Konrad [69], the amount of unfrozen water is strongly influenced by soil structure; open soil structures contain less capillary unfrozen water below -2°C, whereas soils subjected to higher loading retain larger amounts under the same temperature conditions.

The presence of this unfrozen water film affects the soil behaviour, as ice forms adjacent to the adsorbed layer rather than in direct contact with the soil particles [12, 72]. Therefore, the results of the tests on frozen on clay and clay-concrete samples should be interpreted by considering the combined presence of ice and unfrozen water. The tested samples represent compacted soil conditions rather than natural soil structures. Therefore, the distribution of unfrozen water and its influence on the mechanical behaviour may differ from in situ conditions, where the soil structure plays a more significant role.

3. Results and discussion

3.1. Visual observation of ice film formation at the interface

Frozen samples prepared on the wet-side with the optimum water content were subjected to direct shear testing and visually examined (Figure 10). A smooth and glossy interface was observed, indicating the formation of an ice layer with ice crystals present within the soil voids and along the contact surface. This behaviour is attributed to the thermal gradient across the interface during freeze-thaw cycling. As reported by He et al. [20], this thermal gradient drives the migration of unfrozen water from the surrounding soil toward the interface, leading to the formation of ice films at the contact surface. This mechanism is supported by previous studies [24-26, 73].

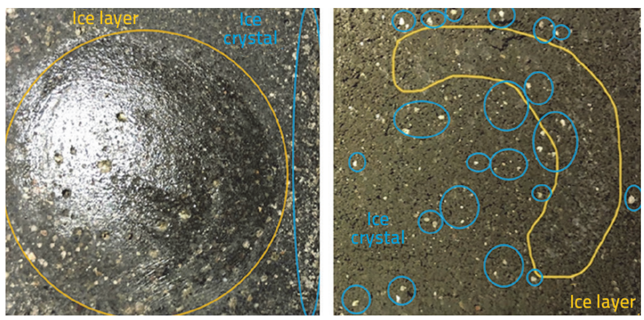

Figure 10. Ice layer and ice crystals observed on the soil and concrete surfaces after the 7th freezing cycle

3.2. Adfreezing and F-T cycles effect on stress-strain curve

In this study, the stress-strain curve of frozen clay-concrete samples compacted on the dry-side of the optimum water content closely aligns with the multi-stage deformation process described by Liu et al. [19] for frozen soil-concrete interfaces (Figure 11). Using large-scale direct shear tests, Liu et al. [19] identified the curve stages as elastic deformation (a-b), plastic deformation onset (b-c), sliding failure with shear stress reduction (c-d), strain hardening owing to progressive deformation (d-e), and residual shear strength (e-f). In our study, which was conducted using direct shear tests, the samples exhibited similar stages up to strain hardening (d-e), but did not reach the residual shear strength stage (e-f), likely because of the limitations of the smaller shear apparatus. As noted by Goughnour and Andersland [74], the ice matrix under typical pressure and temperature conditions is significantly more rigid than the soil skeleton, reaching its peak strength at lower strains. They often exhibit two distinct yield points: one at approximately 1 % axial strain, and the other at approximately 10 % or higher. This dual-peak behaviour was also observed at the clay-concrete interface in our tests, indicating that such a response is not limited to frozen soils alone. No residual behaviour was observed after the second peak, and the peak strength showed a slight increase compared with the initial value. Moreover, this increase became more pronounced with the number of freeze-thaw cycles.

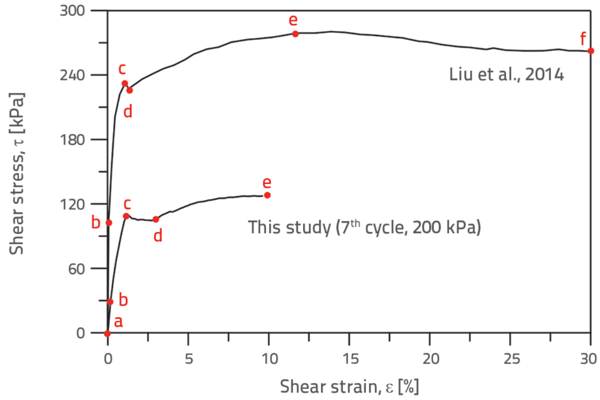

Figure 11. Stress-strain behaviour of frozen clay-concrete interface on the dry-side

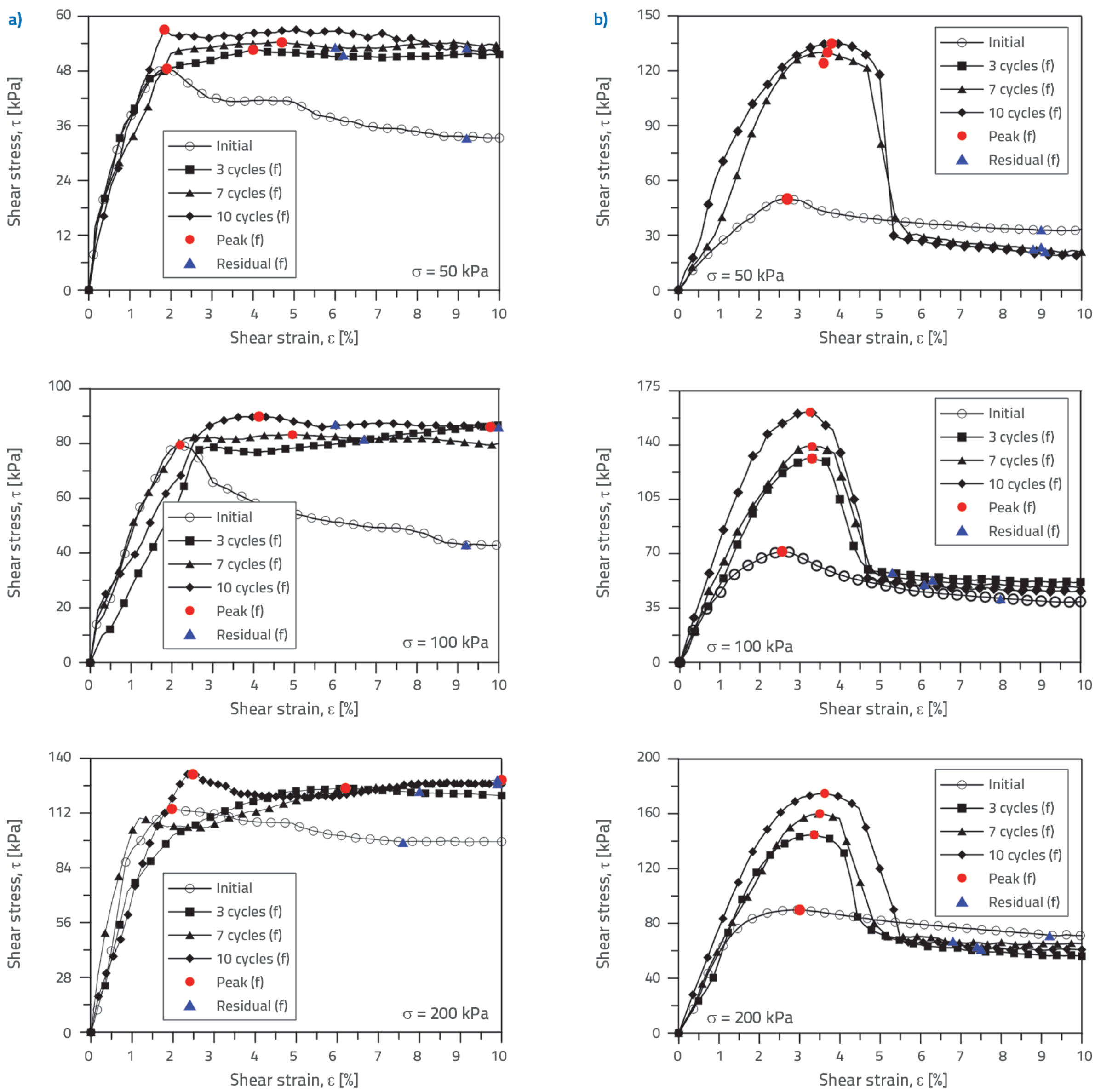

Figure 12. Stress-strain curves from direct shear tests for frozen clay-concrete samples with varying numbers of cycles: a) Frozen - Dry-side; b) Frozen - Wet-side

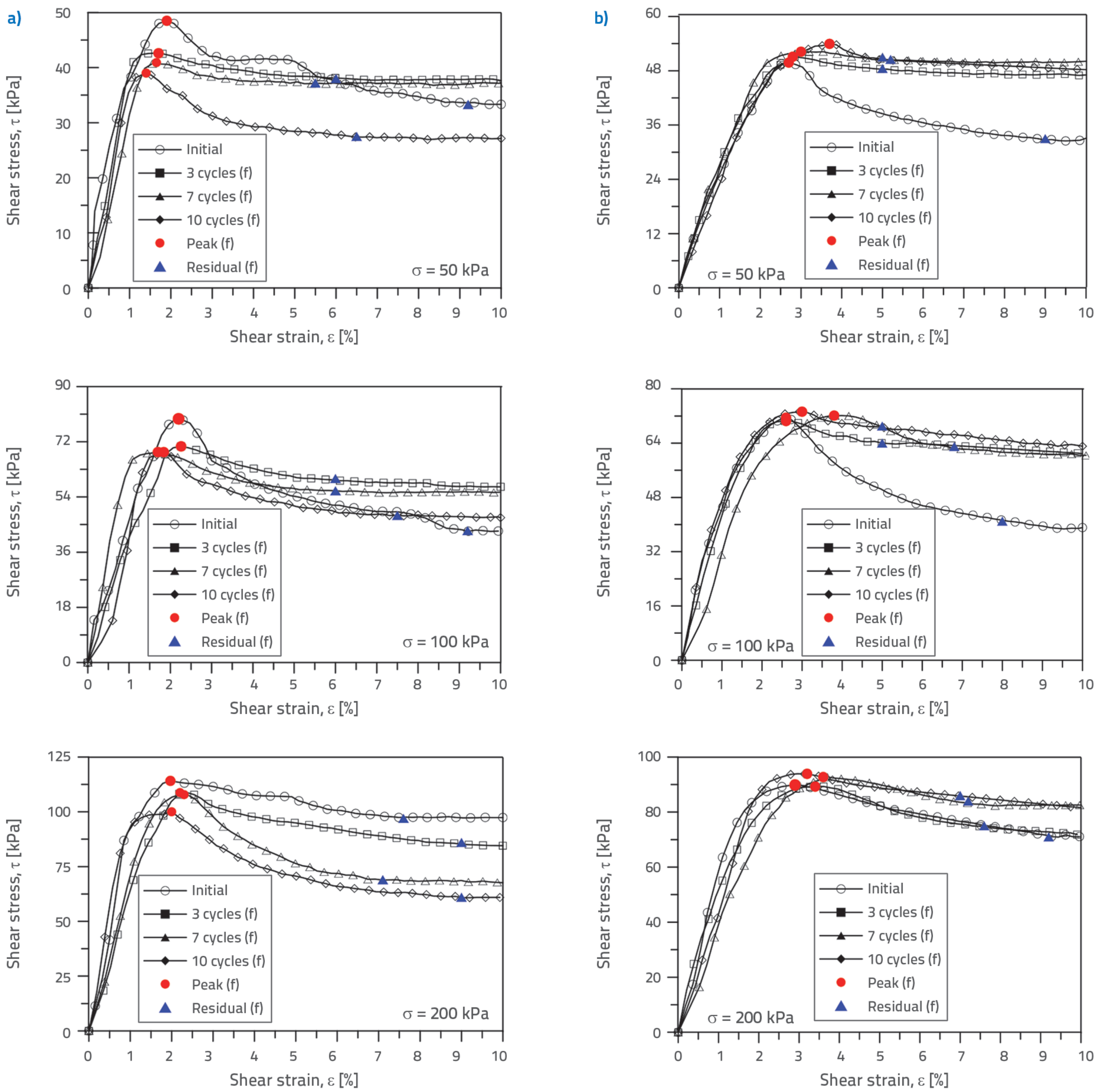

Figure 13. Stress-strain curves from direct shear tests for thawed clay-concrete samples with varying numbers of cycles: a) Thawed - Dry-side b) Thawed - Wet-side

The shear stress-strain curves of the frozen clay-concrete interface for the samples prepared on the dry and wet-sides of the optimum water content are presented in Figure 12.

For the wet-side samples, the failure mode shifted from strain hardening to strain softening. After reaching the peak shear stress, rapid stress reduction occurred owing to the breakdown of the cementing ice at the interface, followed by stabilisation at a residual level. This behaviour reflects a brittle response characterised by the disruption of the cementing ice at the interface.

The peak stress increased with the normal stress and number of F-T cycles, whereas the peak strain ranged between 3 to 4 %. Residual stress increased with normal stress but showed no clear dependence on freeze-thaw cycles, and residual strain remained within the range of 5 to 6 %.

The shear stress-strain curves obtained from the direct shear test results for the thawed clay-concrete interface with the initial water content on the dry and wet-sides of the optimum are presented in Figure 13.

For thawed samples on the dry-side, the stress-strain curve showed a strain-softening behaviour. Compared to the frozen condition, the curve shifted from a dual-peak shape to a single-peak shape. The peak strain ranges between 1.5-2.5 %, and the peak stress increased with the normal stress. However, the peak stress is lower than the initial state and decreases with an increasing number of freeze-thaw cycles, indicating progressive strength loss, in contrast to the trend observed in the frozen samples. The residual strain varies between 4-6 %, increasing with normal stress but showing no clear dependence on the number of cycles.

For samples thawed on the wet-side, strain-softening behaviour was also observed. The peak strain, which ranged from 2.5 % to 3.5 %, was higher than that on the dry-side. Peak stress slightly increased with normal stress and showed limited recovery with increasing cycles compared to the initial stage, but it remained significantly lower at approximately half of that of the frozen samples. Residual strain remained within 4-6 %, while residual stress increases with both normal stress and the number of freeze-thaw cycles.

The effects of freeze-thaw cycling on the interface behaviour are mainly related to moisture migration, ice formation, and the accumulation of ice films at the interface [20]. Ice layers play a key role in adfreezing strength because the shear resistance at low temperatures is largely controlled by ice cementation at the interface [75]. Higher initial moisture content increases the amount of water available for freezing, resulting in stronger ice bonding [4]. This enhances the shear strength under frozen conditions, but also promotes brittle failure owing to interfacial ice bonding. Previous studies [14, 19, 66, 76] have shown that increasing the water content shifts the behaviour from plastic to brittle. Similarly, the water content (or ice content under frozen conditions) significantly affects the stiffness and failure modes of frozen soils [13, 77, 78].

During thawing, the degradation of ice bonds reduces interface shear strength, particularly peak strength [20, 21]. In contrast, the residual strength remains relatively stable and is largely independent of the moisture content [17] and freeze-thaw cycles [20]. The influence of temperature on the residual strength was also limited, as shown by Zhang et al. [41].

Peak displacement increases with initial moisture content but is not strongly affected by freeze-thaw cycles, temperature, or normal stress. Similarly, the residual displacement showed little dependence on these factors [20].

In agreement with these findings, the results indicate that the residual shear strength varies only slightly under different moisture and freeze-thaw conditions. It increases with the normal stress but shows no systematic trend with the number of cycles. Studies have shown that the residual shear stress is less sensitive to changes in water content than the peak shear strength [14, 19].

Unlike the peak strength, which is highly sensitive to thermal conditions and moisture content, the residual behaviour remains relatively stable. It is also less affected by F-T cycles [20]. This suggests that the residual shear strength is mainly governed by frictional mechanisms at the interface, with limited influence from ice bonding or freeze-thaw cycling.

3.3. Adfreezing and F-T cycles effect on peak strength

The peak shear stress, defined as shear strength, demonstrated a strong correlation with the normal stress (Figure 14). This relationship followed a linear fitting function for both frozen and thawed samples prepared on the wet and dry-sides of the optimum water content (Table 3).

In the frozen dry-side samples, the interface strength exhibited an adfreezing effect. However, the increase was limited compared with the initial unfrozen strength. The peak strength increased with the normal stress.

The effect of the F-T cycles became more noticeable as the number of cycles increased. This is particularly evident after 10 cycles. The highest value was obtained at 200 kPa during the 10th cycle. The strength increases from 114.15 kPa (unfrozen) to 131.85 kPa, which is 1.16 times the initial value. Overall, the peak strength ranges between 1.05 to 1.19 times the initial strength. This indicates that repeated F-T cycles gradually increase the adfreezing strength owing to ice cementation at the interface.

The opposite trend was observed for the thawed dry-side samples. After 10 cycles, the peak strength decreases to 73.95 kPa at 200 kPa normal stress. This is 0.65 times the initial strength and 0.56 times the frozen strength. The lowest value occurred after 10 cycles, and the strength gradually decreased as the number of cycles increased. After thawing, it dropped to 0.80-0.95 times the initial strength, depending on the normal stress level. This result highlights the detrimental impact of repeated F-T cycles on the structural integrity of the thawed dry-side samples.

In frozen wet-side samples, shear strength increases 1.6 to 2.7 times depending on normal stress and the cycle number, primarily due to ice cementation at the interface driven by water migration caused by thermal gradients between clay and concrete. The peak strength increased with the normal stress, and the effect of the cycles was again most visible at 10 cycles. At 200 kPa, strength increases from 89.82 kPa to 174.79 kPa, corresponding to 1.95 times the initial value.

After three cycles, the peak shear strength reaching 1.61 times the initial value (144.67 kPa), 1.78 times after seven cycles (160.01 kPa), and 1.95 times after 10 cycles (174.79 kPa).

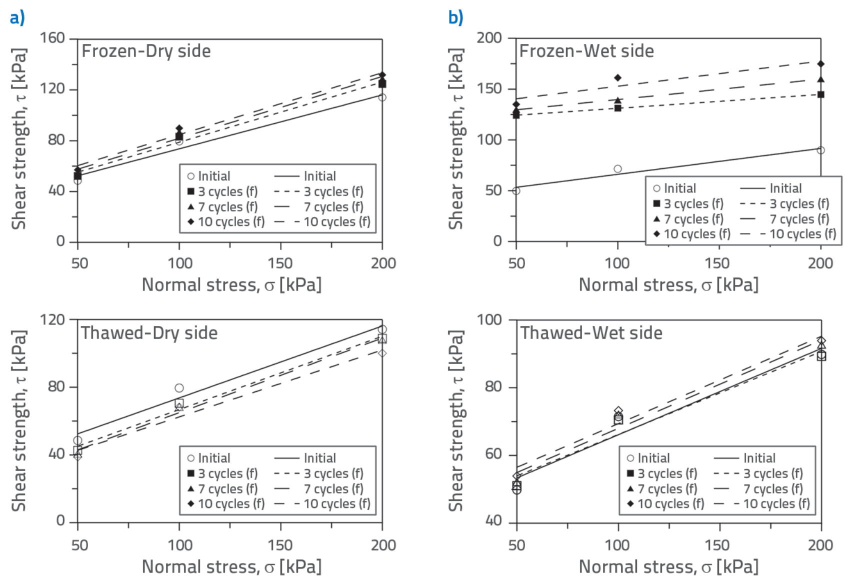

Figure 14. Change in shear strength of frozen and thawed clay-concrete samples with respect to normal stress and number of cycles for a) Dry-side b) Wet-side

Table 3. Shear strength fitting equations for frozen and thawed samples on the wet and dry-sides

Condition	Wet-side sample		Dry-side sample	
	Equation	R^2	Equation	R^2
Initial	$\tau = 0.255\sigma + 40.638$	0.944	$\tau = 0.425\sigma + 31.176$	0.975
3 cycle (frozen)	$\tau = 0.136\sigma + 117.516$	0.999	$\tau = 0.473\sigma + 31.544$	0.989
7 cycle (frozen)	$\tau = 0.201\sigma + 119.601$	0.999	$\tau = 0.487\sigma + 33.238$	0.986
10 cycle (frozen)	$\tau = 0.247\sigma + 128.109$	0.869	$\tau = 0.487\sigma + 36.030$	0.986
3 cycle (thawed)	$\tau = 0.245\sigma + 41.715$	0.961	$\tau = 0.433\sigma + 23.491$	0.990
7 cycle (thawed)	$\tau = 0.261\sigma + 41.916$	0.968	$\tau = 0.440\sigma + 20.957$	0.992
10 cycle (thawed)	$\tau = 0.258\sigma + 43.620$	0.971	$\tau = 0.395\sigma + 22.897$	0.972

This shows that repeated freezing enhances ice-bonding and increases strength. This effect was stronger in wet samples, highlighting the role of the initial water content.

After thawing, the wet samples exhibited a sharp decrease in strength. At 200 kPa and 10 cycles, strength drops from 174.79 kPa to 93.89 kPa. This is 0.54 times the frozen strength. However, compared with the initial unfrozen state, there was no significant decrease. However, only a slight increase was observed. Strength, increases from 89.82 kPa to 93.89 kPa which is 1.05 times the initial value.

The increase in the frozen strength was due to ice cementation at the interface. Water migrates toward the interface owing to the thermal gradient and freezes. After thawing, this led to a higher moisture content near the interface. The applied normal stress enhanced the contact surface between the soil and concrete. This reduced the weakening effects of the F-T cycles. Instead, the strength remained stable, or in some cases, increased slightly with repeated cycles.

When the temperature falls below freezing, ice adhesion at the interface increases the shear resistance. This was defined as the freezing strength [79]. This effect is related to the strength of ice and the increased adhesion between the frozen soil and concrete [14, 18, 19, 76]. Wang et al. [80] showed that the peak stress increases with moisture content under frozen conditions. This is due to water migration and ice layer formation [17]. Increased ice bonding may also change the behaviour from plastic to brittle as the moisture content increases [66]. The peak strength increased with normal stress, water content, and temperature [14]. After thawing, the softened soil can fill surface irregularities and increase contact [24].

3.4. Adfreezing and F-T cycles effect on adhesion and interface friction angle

The effects of freeze-thaw cycles and adfreezing on the adhesion (c_a) and interface friction angle (δ) between clay and concrete are clearly presented in Figure 15. The adhesion values in Figure 15a show clear differences between the wet- and dry-side samples under F-T cycles.

By the 3rd freezing cycle, the dry-side samples exhibited only a slight increase in adhesion. This increase continues gradually with additional cycles and reaches a total increase of 5.00 kPa after 10 cycles.

This limited increase was mainly related to the low availability of free water in the dry-side samples. The presence of air in the voids restricts water migration, and consequently, the extent of ice cementation at the interface.

After the third freezing cycle, the adhesion of the wet samples increased to three times its initial value. The subsequent increase was minimal, leading to stabilization at approximately 128.11 kPa by the 10th freeze cycle. However, despite this stabilisation,

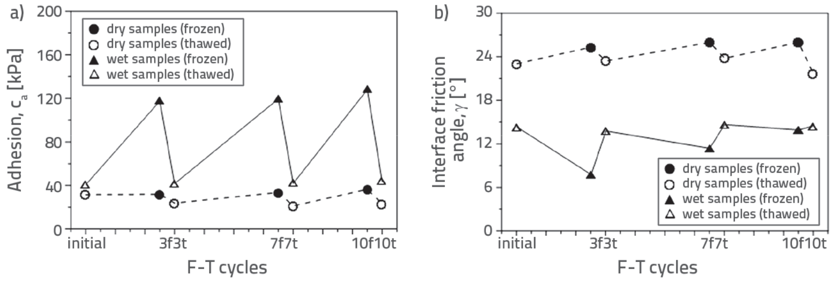

Figure 15. Shear strength parameters of the interface at dry-side and wet-side: a) adhesion; b) interface friction angle

each cycle still showed an increasing trend, with the adhesion gradually increasing as the number of cycles increased.

This suggests that although the initial impact of ice cementation is significant, its influence continues to contribute to a steady increase in adhesion with repeated freeze cycles. This behaviour was facilitated by the movement of free water toward the interface.

During the thawing cycles, the adfreezing effect on adhesion gradually weakened. In dry samples, adhesion shows a decreasing trend compared to the initial cycle, dropping from 31.18 kPa to 22.90 kPa by the 10th thawing cycle. This corresponds to 0.73 times the initial value and indicates that repeated thawing reduces the interfacial bond strength.

In contrast, the wet samples showed a slight recovery after thawing compared to the initial value. By the 10th thawing cycle, adhesion increases from 40.64 kPa to 43.62 kPa reaching 1.07 times the initial value. This recovery in the wet samples may be attributed to the free water migration toward the interface. This effect became more pronounced with repeated cycles, and the adhesion was slightly enhanced by increasing the moisture content near the interface.

When considering the interface friction angle of both the frozen and thawed samples, varied trends were observed. F-T cycles do not produce a consistent trend in interface friction, as both dry and wet samples show fluctuations, which are more pronounced in wet samples.

However, contrasting behaviours were observed between the dry- and wet-side samples in the frozen state. In dry samples, the interface friction angle in the frozen state shows a gradual increase with each freeze-thaw cycle, reaching its highest value at 10th cycle. This suggests that repeated freezing enhances interlocking or structural rearrangement at the interface, thereby improving shear resistance.

However, during thawing, the interface friction angle decreases by approximately 2°, falling below the initial value after 10 cycles, indicating that the degradation of interfacial bonding over successive thawing cycles weakened the shear resistance. Among the wet samples, the frozen samples initially experienced a sharp drop in the interface friction angle, which reduced it to nearly half of the initial value. However, after 3rd cycle, gradual recovery was observed. The values nearly returned to the initial level after multiple freeze-thaw cycles. This trend suggests that water migration and unfrozen water initially reduced the interfacial resistance owing to the lubricating effect. However, with an increasing number of cycles, higher ice cementation or better particle rearrangement may occur, leading to an improved shear resistance.

In the thawed state, the interface friction angle significantly decreased in the initial cycles and then stabilised. This behaviour was likely due to the redistribution of water at the interface.

The freeze bond strength at the interface consists of two components: ice adhesion to the concrete surface and friction between the soil grains at the interface, as described by He et al. [14] in their study. The influence of temperature on the interface shear strength is primarily reflected in changes in the cohesive forces. As the temperature decreased and the moisture content increased, the adhesion increased significantly, highlighting its crucial contribution to the shear strength under frozen conditions.

In contrast, the friction angle is generally considered insensitive to temperature variations. Sadovskiy [81] observed that freezing increases the soil cohesion, whereas the angle of shearing resistance remains virtually unchanged. Similarly, Wang et al. [80] reported that, although the cohesive force increases sharply with increasing moisture content, the internal friction angle tends to decrease under constant surface roughness [17]. However, under frozen conditions, the moisture content exerts a dual influence. It enhances the interface cementation through the formation of ice crystals, whereas unfrozen water acts as a lubricant. This reduces friction and lowers the friction angle, particularly at higher moisture levels [17, 75].

Regarding the effects of F-T cycles, He et al. [20] found no significant variation in the peak or residual friction angles before or after F-T cycling. This observation aligns with the findings of Ladanyi and Theriault [82], who also concluded that F-T cycling predominantly affects cohesion, whereas frictional resistance remains largely stable.

Based on the experimental findings presented above, the underlying physical mechanisms governing interface behaviour can be interpreted by integrating the observed responses with established knowledge of freezing and freeze-thaw processes, as illustrated schematically in Figure 16. The results indicate that the interface behaviour differs fundamentally between wet- and dry-side conditions. For the wet-side samples, a high degree of saturation promoted water migration towards the concrete surface during freezing owing to thermal gradients. This led to the formation of a continuous ice layer at the interface. This enhances adfreezing and results in a significant increase in the shear strength. Following thawing, the elevated

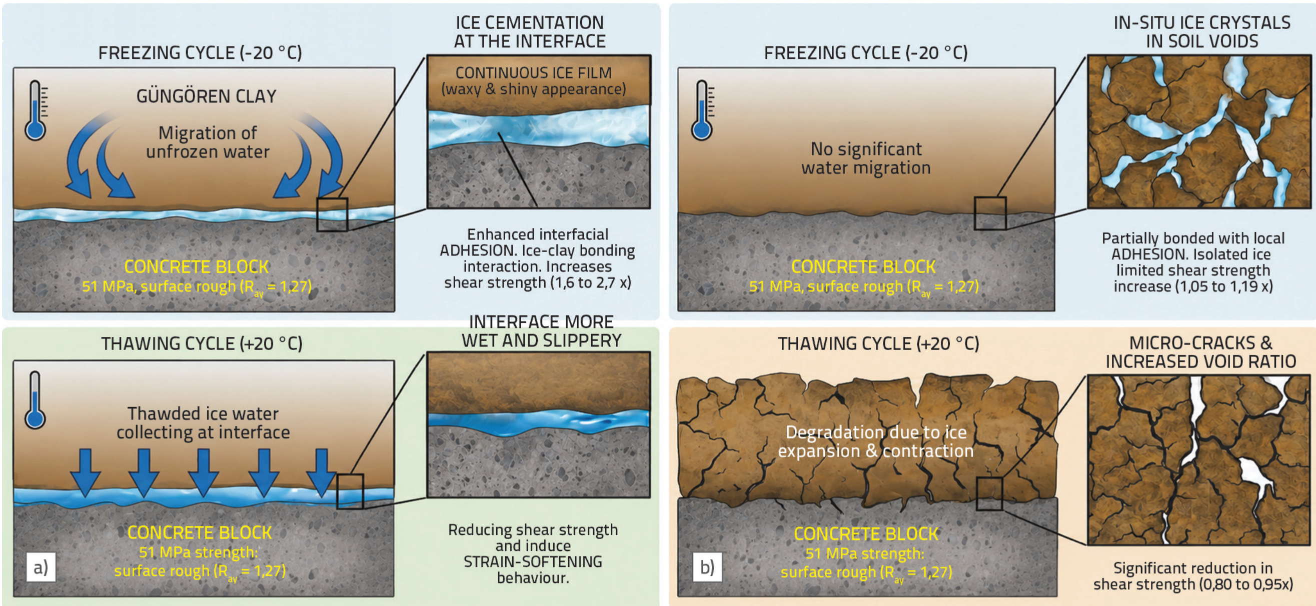

Figure 16. Mechanisms of clay-concrete interface behaviour under freeze-thaw cycles: a) wet-side mechanism; b) dry-side mechanism

moisture content improves particle contact under normal stress, enabling the interface to retain its shear strength. By contrast, the dry-side samples exhibited limited water mobility, which restricted the development of a continuous ice layer. As a result, freezing was primarily confined to the soil pores, leading to only a marginal increase in shear strength. During thawing, microstructural degradation and an increased void ratio weaken the interface, thereby reducing the shear strength.

4. Conclusion

This study examined the shear behaviour of the Güngören clay-concrete interface through direct shear tests, focusing on the effects of F-T cycling and adfreezing. The results obtained for the Güngören clay-concrete interface are as follows.

- During freezing, thermal gradients between clay and concrete induced water migration and adfreezing, as evidenced by visible ice crystal formation at the interface.
- Dry-side frozen samples showed double-peak, multi-stage deformation, whereas thawed samples exhibited strain softening. The frozen wet-side samples failed in a brittle manner, whereas the thawed samples exhibited gradual post-peak softening.
- In frozen wet-side samples, the shear strength increased by 1.6 to 2.7 times depending on the normal stress and the number of freeze-thaw cycles. The samples thawed on the wet-side retained their initial strength owing to water migration and an increased contact surface.
- In frozen dry-side samples, the shear strength increased 1.05 to 1.19 times due to limited water content and restricted ice cementation. After thawing, dry-side samples decreased to 0.80 to 0.95 times their initial values.
- Adhesion increased to ~5 kPa in the frozen dry-side samples after 10 freeze-thaw cycles and tripled in the wet-side samples after three cycles. After thawing, the adhesion slightly recovered in the wet-side samples, exceeding the initial value by approximately 3 kPa.
- The interface friction angle increased slightly under frozen conditions for dry-side samples but declined after thawing. In the wet-side samples, it initially decreased during freezing and then recovered and stabilised across cycles.

Limitations and recommendations

This study evaluated the shear strength under the adfreezing effect and F-T cycles, focusing on the macroscopic mechanical response. However, this study had several limitations.

First, microstructural observations, such as the visualisation of ice formation and crack development during thawing as well as the measurement and controlled variation of unfrozen water content, were not included, although these factors play a critical role in governing the interface behaviour. In addition, experiments were conducted on compacted soil samples, which do not fully represent the natural soil structure. Therefore, the distribution of unfrozen water and the associated mechanical behaviour may differ from in situ conditions, where the soil structure plays a more significant role. Second, the effects of strain rate and its interaction with temperature were not investigated, despite their importance in defining the mechanical response under different loading and thermal conditions. Third, the behaviour was examined only at fixed freezing and thawing temperatures, and the influence of different temperature levels across the freeze-thaw range was not considered.

It should be noted that these aspects require advanced and often specialized experimental setups. Therefore, each study presented a distinct and valuable research direction. Future studies addressing these factors would provide a more comprehensive understanding of the mechanisms governing the soil-structure interface behaviour under freeze-thaw conditions.

REFERENCES

[1] Qi, J., Vermeer, P.A., Cheng, G.: A review of the influence of freeze-thaw cycles on soil geotechnical properties, Permafrost and Periglacial Processes, 17 (2006) 3, pp. 245-252, https://doi.org/10.1002/ppp.559

[2] Hu, J., Zhang, H., Li, Z., Yang, S., Zhang, S., Li, H., Lu, M.: Study on pore-water pressure variation and deformation characteristics of warm frozen soils under confined dynamic loading, Cold Regions Science and Technology, 214 (2023), 103968, https://doi.org/10.1016/j.coldregions.2023.103968

[3] Ding, J., Han, L., Li, Y. et al.: Permafrost engineering characteristics and frozen soil engineering on Qinghai-Tibet railway, Journal of Railway Engineering Society, (2005) s1, pp. 327-332

[4] Sun, T., Gao, X., Liao, Y., Feng, W.: Experimental study on adfreezing strength at the interface between silt and concrete, Cold Regions Science and Technology, 190 (2021), 103346, https://doi.org/10.1016/j.coldregions.2021.103346

[5] Tang, L., Cong, S., Geng, L., Ling, X., Gan, F.: The effect of freeze-thaw cycling on the mechanical properties of expansive soils, Cold Regions Science and Technology, 145 (2018), pp. 197-207, https://doi.org/10.1016/j.coldregions.2017.10.004

[6] Hong, L., Li, M., Du, C. et al.: Bond behaviour of the interface between concrete and basalt fiber reinforced polymer bar after freeze-thaw cycles, Frontiers of Structural and Civil Engineering, 18 (2024), pp. 630-641, https://doi.org/10.1007/s11709-024-0989-y

[7] Tsinker, G.P.: Geotechnical aspects of soil-structure interaction design considerations, in: Handbook of Port and Harbor Engineering, Springer, 1997, https://doi.org/10.1007/978-1-4757-0863-9_4

[8] Pham, T.A., Nadimi, S., Sutman, M.: Critical review of physical-mechanical principles in geostructure-soil interface mechanics, Geotechnical and Geological Engineering, 42 (2024), pp. 6757-6808, https://doi.org/10.1007/s10706-024-02954-7

[9] Kadivar, M., Manahiloh, K.N.: Revisiting parameters that dictate the mechanical behaviour of frozen soils, Cold Regions Science and Technology, 163 (2019), pp. 34-43, https://doi.org/10.1016/j.coldregions.2019.04.005

[10] Shen, M., Zhou, Z., Zhang, S.: Effect of stress path on mechanical behaviours of frozen subgrade soil, Road Materials and Pavement Design, 23 (2021) 5, pp. 1061-1090, https://doi.org/10.1080/14680629.2020.1869583

[11] Sage, J.D., D'Andrea, R.D.: Long term mitigation of frost deterioration of existing roadways, Final Report, NSF Grant No. ECE 85 18813, Worcester, USA, 1988, pp. 1-105

[12] Czurda, K.A., Hohmann, M.: Freezing effect on shear strength of clayey soils, Applied Clay Science, 12 (1997), pp. 165-187, https://doi.org/10.1016/S0169-1317(97)00005-7

[13] Shi, S., Zhang, F., Feng, D., Xu, X.: Experimental investigation on shear characteristics of ice-frozen clay interface, Cold Regions Science and Technology, 176 (2020), 103090, https://doi.org/10.1016/j.coldregions.2020.103090

[14] He, P.F., Mu, Y.H., Ma, W., Huang, Y.T., Dong, J.H.: Testing and modeling of frozen clay-concrete interface behaviour based on large-scale shear tests, Advances in Climate Change Research, 12 (2021) 1, pp. 83-94, https://doi.org/10.1016/j.accre.2020.09.010

[15] Quanbin, S., Ping, Y., Guoliang, W.: Experimental research on adfreezing strength at the interface between frozen sand and structures, Scientia Iranica A, 25 (2018) 2, pp. 663-674, https://doi.org/10.24200/sci.2017.20005

[16] Wang, Q., Qi, J., Wang, S., Xu, J., Yang, Y.: Effect of freeze-thaw on freezing point of a saline loess, Cold Regions Science and Technology, 170 (2020), 102922, https://doi.org/10.1016/j.coldregions.2020.102922

[17] Wang, T.L., Wang, H.H., Hu, T.F., Song, H.F.: Experimental study on the mechanical properties of soil-structure interface under frozen conditions using an improved roughness algorithm, Cold Regions Science and Technology, 158 (2019), pp. 62-68, https://doi.org/10.1016/j.coldregions.2018.10.015

[18] Aldaeef, A.A., Rayhani, M.T.: Pile-soil interface characteristics in ice-poor frozen ground under varying exposure temperature, Cold Regions Science and Technology, 192 (2021), 103377, https://doi.org/10.1016/j.coldregions.2021.103377

[19] Liu, J., Lv, P., Cui, Y., Liu, J.: Experimental study on direct shear behaviour of frozen soil-concrete interface, Cold Regions Science and Technology, 104-105 (2014), pp. 1-6, https://doi.org/10.1016/j.coldregions.2014.04.007

[20] He, P., Mu, Y., Yang, Z., Ma, W., Dong, J., Huang, Y.: Freeze-thaw cycling impact on the shear behaviour of frozen soil-concrete interface, Cold Regions Science and Technology, 173 (2020), 103024, https://doi.org/10.1016/j.coldregions.2020.103024

[21] Zhao, Y., Mao, X., Wu, Q., Huang, W., Wan, Y.: Study on shear characteristics of the interface between frozen soil and pile during thawing process in permafrost area, Advances in Civil Engineering, 2022 (2022), 1755538, https://doi.org/10.1155/2022/1755538

[22] De Guzman, E.M.B., Stafford, D., Alfaro, M.C., Doré, G., Arenson, L.U.: Large-scale direct shear testing of compacted frozen soil under freezing and thawing conditions, Cold Regions Science and Technology, 151 (2018), pp. 138-147, https://doi.org/10.1016/j.coldregions.2018.03.011

[23] Zhao, L., Yang, P., Wang, J.G. et al.: Cyclic direct shear behaviours of frozen soil-structure interface under constant normal stiffness condition, Cold Regions Science and Technology, 102 (2014), pp. 52-62

[24] Volokhov, S.S.: Effect of freezing conditions on the shear strength of soils frozen together with materials, Soil Mechanics and Foundation Engineering, 40 (2003) 6, pp. 1-5, https://doi.org/10.1023/B:SMAF.0000017575.19213.67

[25] Kim, K.H., Jeon, S.E., Kim, J.K. et al.: An experimental study on thermal conductivity of concrete, Cement and Concrete Research, 33 (2003) 3, pp. 363-371, https://doi.org/10.1016/S0008-8846(02)00965-1

[26] Mu, R., Tian, W., Zhou, M.: Moisture migration in concrete exposed to freeze-thaw cycles, Journal of the Chinese Ceramic Society, 38 (2010) 9, pp. 1713-1717

[27] Istanbul Metropolitan Municipality Directorate of Earthquake and Ground Research: Geological-Geotechnical Study Report and Map for the Southern Region of Istanbul's European Side at a 1/5000 Scale for Zoning Plans, Istanbul, 2001

[28] Yılmaz, E.: Güngören formasyonu killerin mühendislik özellikleri ve mineralojik etkiler, Master's thesis, Istanbul University, Institute of Science, Department of Geological Engineering, Istanbul, 2005

[29] Mermutlu, E., Şans, G., Mahmutoğlu, Y.: İstanbul-Ambarlı heyelanının izlenmesi ve analizi, in: KAYAMEK'2011 - X. Bölgesel Kaya Mekaniği Sempozyumu / ROCMEC'2011 - Xth Regional Rock Mechanics Symposium, Ankara, Turkey, 2011

[30] Dalgıç, S.: Factors affecting the greater damage in the Avcılar area of Istanbul during the 17 August 1999 Izmit earthquake, Bulletin of Engineering Geology and the Environment, 63 (2004) 3, pp. 221-232, https://doi.org/10.1007/s10064-004-0234-9

[31] American Society for Testing and Materials (ASTM): ASTM D6913-18: Standard Test Method for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis, ASTM International, West Conshohocken, PA, USA, 2018

[32] American Society for Testing and Materials (ASTM): ASTM D7928-17: Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis, ASTM International, West Conshohocken, PA, USA, 2017

[33] American Society for Testing and Materials (ASTM): ASTM D4318-17: Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils, ASTM International, West Conshohocken, PA, USA, 2014

[34] American Society for Testing and Materials (ASTM): ASTM D854-14: Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer, ASTM International, West Conshohocken, PA, USA, 2014

[35] American Society for Testing and Materials (ASTM): ASTM D698-12: Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lb/ft^3), ASTM International, West Conshohocken, PA, USA, 2012

[36] American Society for Testing and Materials (ASTM): ASTM D2487-17(2025): Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System), ASTM International, West Conshohocken, PA, USA, 2025

[37] American Society for Testing and Materials (ASTM): ASTM D4546-14: Standard Test Methods for One-Dimensional Swell or Collapse of Soils, ASTM International, West Conshohocken, PA, USA, 2014

[38] Tiwari, B., Ajmera, B.: Consolidation and swelling behaviour of major clay minerals and their mixtures, Applied Clay Science, 54 (2011) 3-4, pp. 264-273, https://doi.org/10.1016/j.clay.2011.10.001

[39] Panda, G.P., Bahrami, A., Nagaraju, T.V., Isleem, H.F.: Response of high swelling montmorillonite clays with aqueous polymer, Minerals, 13 (2023) 7, 933, https://doi.org/10.3390/min13070933

[40] Li, X., Zhang, L., Zhang, Y.: Influence of montmorillonite on the freeze-thaw properties of expansive soils, Geotechnical Testing Journal, 34 (2011) 4, pp. 295-306

[41] Zhang, L., Ma, W., Yang, C., Dong, S.: A review and prospect of the thermodynamics of soil subjected to freezing and thawing, Journal of Glaciology and Geocryology, 35 (2013) 6, pp. 1505-1518

[42] Wang, C., Lai, Y., Yu, F., Li, S.: Estimating the freezing-thawing hysteresis of chloride saline soils based on the phase transition theory, Applied Thermal Engineering, 135 (2018), pp. 22-33, https://doi.org/10.1016/j.applthermaleng.2018.02.039

[43] Adorni, E., Ivanov, M., Revetria, R.: Review of the effects of the influence of external vibrations on the freezing point of water, MATEC Web of Conferences, 320 (2020), 00032, https://doi.org/10.1051/matecconf/202032000032

[44] Shah, R., Mir, B.A.: The freezing point of soils and the factors affecting its depression, in: Loon, L.Y., Subramaniyan, M., Gunasekaran, K. (eds): Advances in Construction Management, Lecture Notes in Civil Engineering, vol. 191, Springer, Singapore, 2022, https://doi.org/10.1007/978-981-16-5839-6_14

[45] Mo, C., Hanbing, C., Anyu, L.: Effect of freezing temperature and initial water content on hydrothermal migration of silty soil under freezing, Arabian Journal of Geosciences, 15 (2022) 2, https://doi.org/10.1007/s12517-022-09486-5

[46] Pennisi, S.V., Habteselassie, M.Y.: Laboratory-scale study on the effects of freezing in soils when subjected to different moisture content, Water, 14 (2022), 1892, https://doi.org/10.3390/w14121892

[47] Zhang, L., Yang, C., Wang, D., Zhang, P., Zhang, Y.: Freezing point depression of soil water depending on its non-uniform nature in pore water pressure, Geoderma, 412 (2022), 115724, https://doi.org/10.1016/j.geoderma.2022.115724

[48] Frost, J.D., De Jong, J.T., Recalde, M.: Shear failure behaviour of granular-continuum interfaces, Engineering Fracture Mechanics, 69 (2002), pp. 2029-2048

[49] Gómez, J.E., Filz, G.M., Ebeling, R.M., Dove, J.E.: Sand to concrete interface response to complex load paths in a large displacement shear box, Geotechnical Testing Journal, 31 (2008) 4, pp. 358-369

[50] Martinez, A., Frost, J.D.: The influence of surface roughness form on the strength of sand-structure interfaces, Géotechnique Letters, 7 (2017) 1, pp. 104-111

[51] Di Donna, A., Ferrari, A., Laloui, L.: Experimental investigations of the soil-concrete interface: physical mechanisms, cyclic mobilization, and behaviour at different temperatures, Canadian Geotechnical Journal, 53 (2015) 4, pp. 659-672

[52] Meier, A.L., Faro, V.P., Odebrecht, E.: Shear strength analysis of interfaces between granular soils and concrete cured under stress, Soils and Rocks, 46 (2023) 1, e2023004022

[53] Chang, W.R.: The effect of surface roughness on dynamic friction between neolite and quarry tile, Safety Science, 29 (1998) 2, pp. 89-105

[54] Tehrani, F.S., Han, F., Salgado, R., Prezzi, M., Tovar, R.D., Castro, A.G.: Effect of surface roughness on the shaft resistance of nondisplacement piles embedded in sand, Géotechnique, 66 (2016) 5, pp. 386-400, https://doi.org/10.1680/jgeot.15.P.007

[55] Nardelli, A., Cacciari, P.P., Futai, M.M.: Sand-concrete interface response: The role of surface texture and confinement conditions, Soils and Foundations, 59 (2019) 6, pp. 1675-1694, https://doi.org/10.1016/j.sandf.2019.10.004

[56] Uesugi, M., Kishida, H.: Influential factors of friction between steel and dry sands, Soils and Foundations, 26 (1986) 2, pp. 33-45, https://doi.org/10.3208/sandf1972.26.2_33

[57] Gokhale, M., Underwood, E.E.: A general method for estimation of fracture surface roughness, 1990

[58] ISO 25178-601: Geometrical product specifications (GPS) - Surface texture: Areal - Part 601: Nominal characteristics of contact (stylus) instruments, ISO, 2010

[59] Lemos, L.J.L., Vaughan, P.R.: Clay-interface shear resistance, Géotechnique, 50 (2000) 1, pp. 55-64

[60] Murphy, K.D., McCartney, J.S.: Thermal borehole shear device, Geotechnical Testing Journal, 37 (2014) 6, 20140009, https://doi.org/10.1520/GTJ20140009

[61] American Society for Testing and Materials (ASTM): ASTM D3080/D3080M-22: Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions, ASTM International, West Conshohocken, PA, USA, 2022

[62] Kou, H., Huang, J., Cheng, Y.: Friction characteristics between marine clay and construction materials, Journal of Ocean University of China, 23 (2024), pp. 427-437, https://doi.org/10.1007/s11802-024-5474-7

[63] Wang, B., Liu, J., Wang, Q., Ling, X., Pan, J., Fang, R., Bai, Z.: Influence of freeze-thaw cycles on the shear performance of silty clay-concrete interface, Cold Regions Science and Technology, 219 (2024), 104120

[64] He, P., Cao, H., Dong, J., Hou, G., Mu, Y., Zhang, J.: Effects of wet-dry-freeze-thaw cycles on the response of the frozen soil-composite geotextile interface in direct shear tests, Case Studies in Thermal Engineering, 63 (2024), 105217, https://doi.org/10.1016/j.csite.2024.105217

[65] Meng, Y., Xu, C., Yang, Y., Du, C., Jia, B., Zhao, C.: Study on the mechanism of freeze-thaw cycles on the shear strength of geogrid-sand interface, Cold Regions Science and Technology, 225 (2024), 104275, https://doi.org/10.1016/j.coldregions.2024.104275

[66] Zhang, K., Yan, J., Mu, Y., Zhu, X., Zhang, L.: Global and local shear behaviour of the frozen soil-concrete interface: Effects of temperature, water content, normal stress, and shear rate, Buildings, 14 (2024) 10, 3319, https://doi.org/10.3390/buildings14103319

[67] Bouyoucos, G.J.: The freezing point method as a new means of measuring the concentration of the soil solution directly in the soil, Michigan Agricultural College Experiment Station Technical Bulletin, 24 (1916), pp. 1-44

[68] Nersesova, Z.A., Tsytovich, A.: Unfrozen water in frozen soils, in: Proceedings of the 1st International Permafrost Conference, Purdue University, Lafayette, Indiana, 1963, pp. 230-234

[69] Konrad, J.M.: Unfrozen water as a function of void ratio in a clayey silt, Cold Regions Science and Technology, 18 (1990), pp. 49-55, https://doi.org/10.1016/0165-232X(90)90037-W

[70] Christ, M., Kim, Y.C.: Experimental study on the physical-mechanical properties of frozen silt, KSCE Journal of Civil Engineering, 13 (2009) 5, pp. 317-324, https://doi.org/10.1007/s12205-009-0317-z

[71] Andersland, O.B., Ladanyi, B.: An Introduction to Frozen Ground Engineering, ASCE & John Wiley & Sons, New York, 1994

[72] Williams, P.J., Smith, M.W.: The Frozen Earth: Fundamentals of Geocryology, Cambridge University Press, Cambridge, 1989, 306 pp.

[73] Ladanyi, B.: Frozen soil-structure interfaces, in: Selvadurai, A.P.S., Boulon, M.J. (eds): Studies in Applied Mechanics, vol. 42, Elsevier, 1995, pp. 3-33, https://doi.org/10.1016/S0922-5382(06)80004-8

[74] Goughnour, R.R., Andersland, O.B.: Mechanical properties of a sand-ice system, Proceedings of the American Society of Civil Engineers, 94 (1968) SM4, pp. 923-950

[75] Shi, Q., Yang, P., Wang, G.: Experimental study on adfreezing strength of the interface between artificial frozen sand and structure, Chinese Journal of Rock Mechanics and Engineering, 35 (2016) 10, pp. 2142-2151

[76] Wen, Z., Yu, Q., Ma, W. et al.: Experimental investigation on the effect of fiberglass reinforced plastic cover on adfreeze bond strength, Cold Regions Science and Technology, 131 (2016), pp. 108-115, https://doi.org/10.1016/j.coldregions.2016.07.009

[77] Xu, X.T., Dong, Y.H., Fan, C.: Laboratory investigation on energy dissipation and damage characteristics of frozen loess during deformation process, Cold Regions Science and Technology, 109 (2015), pp. 1-8, https://doi.org/10.1016/j.coldregions.2014.09.006

[78] Zhu, Z., Liu, Z., Xie, Q.: Dynamic mechanical experiments and microstructure constitutive model of frozen soil with different particle sizes, International Journal of Damage Mechanics, 26 (2017), 105678951770096, https://doi.org/10.1177/1056789517700967

[79] Parameswaran, V.R.: Adfreeze strength of frozen sand to model piles, Canadian Geotechnical Journal, 15 (1978), pp. 494-500

[80] Wang, W., Yang, X., Huang, S., Yin, D., Liu, G.: Experimental study on the shear behaviour of the bonding interface between sandstone and cement mortar under freeze-thaw, Rock Mechanics and Rock Engineering, 53 (2020), pp. 881-907, https://doi.org/10.1007/s00603-019-01951-0

[81] Sadovskiy, A.V.: Adfreeze between ground and foundation materials, in: Proceedings of the 2nd International Conference on Permafrost, Yakutsk, Northern American Volume, 1973, pp. 650-653

[82] Ladanyi, B., Theriault, A.: A study of some factors affecting the adfreeze bond of piles in permafrost, in: Proceedings of the Geotechnical Engineering Congress GSP 27 ASCE, vol. 1, 1990, pp. 213-224