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DOI

[10.1680/jgeen.16.00101](https://doi.org/10.1680/jgeen.16.00101)

Publication date

2017

Document Version

Accepted author manuscript

Published in

Proceedings of the Institution of Civil Engineers - Geotechnical Engineering

Citation (APA)

Steiner, A., Vardon, P., & Broere, W. (2017). The influence of freeze–thaw cycles on the shear strength of illite clay. *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering*, 171(2018)(1), 16-27. <https://doi.org/10.1680/jgeen.16.00101>

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The influence of freeze-thaw cycles on the shear strength of Illite clay

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Date written: June 2016, Revised February 2017, Re-revised May 2017

Number of words: 4034

Number of tables: 1

Number of figures: 12

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Abstract (192 words)

Geo-energy infrastructure, such as ground source heat systems (thermo-active structures), induce thermal cycles that can result in changes of the bearing capacity of soil by changing, for example, the void ratio, soil structure, unit weight and hydraulic conductivity. The influence of repeated freeze/thaw (FT) cycles and different freezing rates on the shear strength of a frost susceptible Illite clay was investigated. Samples were subjected to between 1 and 20 FT cycles, and the shear strength of the thawed material was determined using undrained unconsolidated triaxial tests. After the shear strength decrease due to the first FT cycle, a transitory shear strength recovery occurred between 1 and 3 freezing cycles, followed by a shear strength decrease between 3 and 7 FT cycles, which then approached an equilibrium value. CT scans showed ice lenses increased in size moving away from the freezing surface, and more uniform ice distribution with increasing FT cycles. Changing the freezing rate yielded differences in the formation and structure of ice lenses perpendicular to the freezing direction. The observed failure plane typically coincides with the plane of the largest ice lens due to formation of a slurry layer after thawing.

Keywords chosen from ICE Publishing list

Strength & testing of materials, Thermal effects, Geotechnical engineering

List of notation

- E elastic modulus (stiffness) of the thawed soil
- PI Plasticity Index of the soil
- PL Plastic Limit of the soil
- R thermal resistance
- T_{bf} applied freezing temperature at the bottom of the sample
- T_{bt} applied thawing temperature at the bottom of the sample
- e void ratio
- k hydraulic conductivity
- p pore pressure
- w water content of the soil by mass
- γ_d dry unit weight

64 **1. Introduction**

65 Geo-energy infrastructure, such as ground source heat systems (thermo-active structures), induce thermal cycles
66 that result in changes in bearing capacity by changing the void ratio, unit weight, hydraulic conductivity, and
67 soil structure (Andersland and Ladanyi, 1994). Changes in the shear strength due to seasonal freezing and
68 thawing (FT) cycles, as well as changes in thermal equilibrium of the soil due to construction, present
69 challenges when engineering in cold regions. Cyclic thermal loads can be transferred into the ground by energy
70 infrastructure, such as thermosiphons, energy piles, storage tanks, or pipelines, many of which can serve an
71 additional structural function in cold regions. The changes in the physical properties of a soil during freezing
72 and thawing alter the heat storage capacity of the soil, and design guidelines for thermal piles identify hydraulic
73 conductivity as a major design factor (GHSPA, 2012).

74 The temperature at the soil surface, the type/properties of the soil, and the confining pressure influence the speed
75 that the freezing front, defined as the boundary between frozen and unfrozen soils, penetrates the soil. Soil is
76 considered frozen when the temperature is below 0°C, even if the soil is dry and no ice is present (Talamucci,
77 2003).

78 When designing on clay, the undrained shear strength is often used as the primary design parameter, as it is the
79 worst-case scenario (Vardanega and Bolton, 2011). Current design practices for engineering in frost susceptible
80 soils focus on surface deformation caused by frost heaving, but changes in the soil structure due to repeated FT
81 cycles may be deserving of greater consideration, as they result in long-term changes to soil strength. The
82 freezing rate will influence the development of shear strength by altering the soil structure via formation of ice
83 lenses. Strength evolution over multiple freeze thaw cycles can be evaluated using mobilised shear strength,
84 defined as the shear stress in a medium which corresponds to the failure or deformation plane at a certain strain,
85 i.e. the strength that is used or 'mobilised' (Ching and Phoon, 2013). The critical strength is when the material is
86 in the unfrozen state, as the frozen pore water contributes considerably to shear strength (and stiffness).

87 FT cycles in clay have been observed to result in a reduction in shear strength, attributed to formation of large
88 cracks, destruction of the soil's microstructure due to volumetric expansion of water during freezing, and
89 formation of a saturated 'slurry' layer along the plane of the largest ice lens in the thawed material (Wang et al.,
90 2007). The formation of this slurry layer results in a temporary decrease in shear strength, known as thaw
91 weakening, until the water is able to redistribute back into the soil. Research has found that the largest change in
92 shear strength occurs within the first 7 FT cycles, after which the strength stabilises (Qi et al., 2006).

93 Ice lenses are formed by two contributing factors: (1) the expansion of water as it turns to ice, and (2) water
94 flowing towards horizontal ice layers, often through vertical cracks forming perpendicular to the freezing front.
95 This water flow is primarily caused by negative pore pressures in the soil caused by the interface tension
96 between ice and water in the region where the soil which is partially frozen, i.e. the frozen fringe, known as
97 cryogenic suction (Thomas et al., 2009). Cracks form when the soil reaches its tensile strength, driven by either
98 increases in pore pressure for the horizontal cracks for a vertical heat flow (Thomas et al., 2009), or by tensile
99 stresses driven by water leaving the matrix for the vertical cracks. The vertical cracks, therefore, form below the
100 horizontal lenses. With slower freezing rates, both vertical and horizontal cracks are larger, as water has longer
101 to flow before the freezing front moves down. At higher freezing rates, water has less time to move through the
102 soil and the resulting cracks are smaller. The development of temperature with depth, pore pressure distribution,
103 and cryogenic suction distribution are schematised in Figure 1 for a soil with a freezing/thawing surface at the
104 ground surface. In Figure 1(A), a soil profile is shown with the frozen zone shown in region (a), the frozen
105 fringe and ice lens formation, where both frozen and liquid water exist, shown in region (b), and the unfrozen
106 zone in region (c). In Figure 1(B), the temperature profile is schematised in a freezing condition, where the
107 highest gradient is shown in the frozen zone due to the applied temperature (not steady state conditions) and the
108 highest thermal conductivity. In Figure 1(C), the pore pressures are shown, with an ice lens forming at the
109 highest pore pressure (above the tensile strength of the material). Figure 1(D) shows the variation of cryogenic
110 suction, which occurs due to the interface stresses between the water and ice, therefore in the full frozen and
111 fully unfrozen zones, cryogenic suction is 0 and increases from the edge of the frozen fringe towards the frozen
112 zone.

113 This research evaluates the influence of different number of FT cycles and different freezing rates on the shear
114 strength development and ice lens formation in an Illite clay (Steiner, 2016).

115

116 **2. Methodology**

117 A physical model setup has been developed for this research, which aims to evaluate the ice lensing and shear
118 strength of undrained Illite clay subjected to one-dimensional freezing, in a closed system, where water cannot
119 enter or leave.

120

121 *Material and sample preparation*

122 Samples were prepared in batches by mixing Illite clay (WBB Vingerling k122, with plastic limit (PL) = 23%
123 and liquid limit (LL) = 57%, obtained from Deutschland (2016)) with water. The samples were prepared by
124 adding water to the clay and mixing by hand until reaching the target water content, w , of ~34% and a dry unit
125 weight, γ_d , of ~16.4 kN/m³, yielding a void ratio of 0.62. The dry unit weight, water content and void ratio were
126 determined for every prepared sample to ensure uniformity, with the details of the samples and the experiments
127 undertaken with them given in Table 1. Samples were cut into 50 mm by 100 mm cylinders and the unit weight
128 was measured for each sample. The samples were then placed into a water-tight membrane and secured to a
129 copper plug with gaskets at the bottom end to prevent moisture loss during freezing and thawing. The frost
130 susceptibility, which describes the tendency for ice segregation during freezing, of the clay was categorised as
131 F3, using the USACE Frost Susceptibility Criteria (Chamberlain, 1981) based on the plasticity index (PI) of the
132 soil (in this case PI = 34%, based on 3 tests). The samples were initially saturated, but became partially saturated
133 due to water movement during the freezing process.

134

135 *Experimental equipment and procedure*

136 The freezing apparatus used in this research was developed by van den Bosch (2015), and is shown in Figure 2.
137 The heat for freezing and thawing was provided via a Peltier element – a solid state thermo-electric device –
138 which allows the conversion of electricity to a temperature gradient across the element. A Peltier element was
139 used to allow fast and accurate temperature control. The base of the Peltier element was cooled (freezing) /
140 heated (thawing) using a liquid cooled heat sink and cooling fan. The copper plug at the bottom of the sample,
141 with an embedded temperature sensor that measures the temperature of the Peltier element, was used to transfer
142 heat from the Peltier element to the soil. Temperature readings are also taken at the top of the sample via the
143 temperature sensor at the top of the figure.

144 The samples were placed in an insulated container (Figure 3), placed directly onto the freezing/thawing
145 equipment, and subjected to FT cycles. The insulation consisted of a 194 mm x 194 mm x 120 mm (l x w x h)
146 box and a 60 mm x 50 mm (l x d) thick insert composed of URSA XPS insulation with a minimum thermal
147 resistance $R = 2.0$ (m²K)/W. The equipment was located in a temperature controlled laboratory, with the
148 temperature controlled at 14.5°C ±1°C and humidity controlled at 70%. The sample was sealed at the base so
149 water could not drain and the surrounding membrane extended at the top, so water could move to the top of the
150 sample, but not leave the sample casing. Evaporation at the top of the sample was limited due to the cool air
151 temperature and high humidity in the room, as well as the URSA XPS insulation insert placed above the sample.

152 The temperature was controlled at the base of the samples and fixed during freezing or thawing (T_{bf} during
153 freezing, T_{bt} during thawing). The samples were considered completely frozen when the temperature at the top
154 was below -2.5°C for at least 1 hour and completely thawed when the temperature at the top exceeded 3°C for 1
155 hour. The base temperature and number of cycles were controlled automatically via a computerised control
156 system.

157 After the specified number of FT cycles, the still-frozen samples were placed in a triaxial testing machine and
158 the loading piston was lowered (docked) and the triaxial cell was filled with 17°C water. The sample was
159 allowed to thaw for at least 6.5 hours, then the water was replaced by de-aired 14.5°C water. The triaxial setup
160 used is specifically calibrated for use on extremely soft samples and is based on a standard 50 kN GDS load
161 frame, a STALC9-1kN load cell and 3 MPa controllers, recalibrated for low stress. For test ranges below 600
162 kPa the accuracy of the setup is rated < 0.17 kPa for axial stress, < 0.5kPa for cell pressure and < 0.2% for axial
163 strain. Unconsolidated Undrained (UU) triaxial tests (strain controlled) in accordance with ASTM D2850-15:
164 Standard Test Method for Unconsolidated Undrained Triaxial Compression Test for Cohesive Soils (ASTM,

165 2015), were undertaken to determine the shear strength of the thawed samples at a confining pressure of 400 kPa
166 and a loading rate of 0.1 mm/min. In addition to the considerations given in the introduction of the critical
167 strength in unfrozen conditions, the laboratory setup has not been calibrated for the significantly higher stress
168 range that would be encountered in frozen samples, it was not considered appropriate to test frozen samples.
169 Macro-Computerised Tomography (CT) scans using a Siemens SOMATOM Definition macro-CT scanner,
170 were performed on some of the frozen samples to evaluate the changes in soil structure. UU triaxial tests (strain
171 controlled) were done on never-frozen samples from each batch to obtain a reference shear strength and verify
172 the initial variability of the material.

173

174 *Experimental series*

175 Two experimental series were undertaken:

- 176 • The first, to investigate the number of FT cycles, with 1, 3, 5, 7, 10, and 20 FT cycles with a $T_{bf} = -$
177 20°C and a $T_{bt} = 20^{\circ}\text{C}$.
- 178 • The second, to investigate the freezing rate, with a single FT cycle with applied freezing surface
179 temperatures T_{bf} of $-5, -10, -15, \text{ and } -20^{\circ}\text{C}$ (and $T_{bt} = 20^{\circ}\text{C}$).

180

181 **3. Results**

182 *Number of FT cycles*

183 The strength development with axial strain for samples subjected to different FT cycles is shown in Figure 4.
184 Test results were not corrected for membrane stiffness effects. Samples subjected to freezing all exhibited a
185 significant reduction in shear strength compared to samples that have never been frozen. After a single FT cycle,
186 the samples show a clear peak shear strength and subsequent softening behaviour. The samples also exhibit a
187 greater initial stiffness, almost double that of the intact, never-frozen, sample, which is in agreement with
188 existing literature. After the first FT cycle, the stiffness decreases at a diminishing rate, approaching an
189 equilibrium stiffness after many cycles. At 3 FT cycles the sample is about half as stiff as a never-frozen sample,
190 and exhibits strain hardening and shear strength recovery. At 7 to 10 FT cycles, similar behaviour is observed,
191 the samples are weaker in shear strength than 3 FT cycles, stronger than 1 FT cycle (at high axial strains), strain
192 harden and are less stiff than 1 or 3 FT cycles. After 7 FT cycles, the ice lens distribution through the sample
193 stabilised and the stiffness increased. At 20 FT cycles, the initial behaviour matches that of 10 FT cycles, but a
194 rapid transition to a residual shear strength occurs (similar to that from 1 FT cycle) with no softening or
195 hardening. From this single 20 FT cycle test, however, the possible variation in residual shear strength cannot be
196 reliably established. The soil stiffness decreased over the period where most of the structural changes within the
197 soil occurred.

198 The same results are plotted in Figure 5 in terms of shear strength against number of FT cycles. As many of the
199 samples strain harden, there is no peak shear strength to plot, therefore the mobilised shear strength at 2, 4, 6
200 and 10% axial strain have been shown. It is shown that after a substantial initial strength loss with a single FT
201 cycle, strength recovery occurs between 1 and 3 FT cycles, which again reduces until 7 FT cycles.

202 Figure 6 shows photographic and CT scan images of the samples with different FT cycles. All samples show ice
203 lenses which are primarily vertically oriented. The samples show a decrease in density and an increase in size of
204 the ice lenses with increasing distance from the freezing side (the base). This is likely due to a decreasing
205 thermal gradient due to temporal heat changes and lateral heat losses. As the number of FT cycles increases, the
206 size of the ice lenses decreases in all locations in the sample. At 7 FT cycles onwards there are no perceivable
207 differences between the samples. Moreover, with increasing cycles, the ice lens distribution becomes
208 increasingly uniform over the height of the sample.

209

210 *Freezing rate*

211 Figure 7 presents the mobilised shear strength against axial strain for the second results series, different freezing
212 rates, controlled by differing base freezing temperatures. Slower freezing rates, associated with warmer freezing

213 surface temperatures, resulted in lower shear strengths. A significant reduction in shear strength occurs between
214 $T_{bf} = -5^{\circ}\text{C}$ and -10°C . The difference in shear strength and stiffness between -10°C and -15°C is much smaller.

215 The photographic and CT scan images with different freezing rates for this experimental series are presented in
216 Figure 8. Horizontal ice lenses are visible for all samples frozen with $T_{bf} < -20^{\circ}\text{C}$. Samples with slower freezing
217 rates exhibited larger cracks and lensing in both horizontal and vertical directions. With faster freezing rates,
218 smaller cracks/lenses were observed. Again, both vertical and horizontal cracking increased in size and
219 decreased in amount moving away from the freezing side for all freezing rates. With decreasing T_{bf} , the ice lens
220 distribution became more uniform. This was attributed to pore water freezing in place before water was able to
221 flow due to cryogenic suction, thus preventing formation of bulk ice and reducing macro structural
222 rearrangement.

223 With slow freezing rates (e.g., $T_{bf} = -5^{\circ}\text{C}$), consolidation occurred at the top of the sample (furthest from the
224 freezing side). This can be observed from the gap between the sample casing and sample (e.g., Figure 8a) above
225 the large ice lens. The sample frozen with $T_{bf} = -5^{\circ}\text{C}$ exhibits almost no lensing in the top 25 mm of the sample.
226 This was due to water movement towards the freezing front causing the soil to reach its shrinkage limit.

227 The location of the largest ice lens and failure plane for a subset of the samples are shown in Figure 9. The
228 failure planes are seen to generally coincide with the plane of the largest ice lens. The thicker ice lenses at
229 warmer freezing surface temperatures resulted in lower shear strength. This is attributed to the formation of the
230 slurry layer when the sample is completely thawed and cannot drain or redistribute through the soil.

231

232 **4. Analysis and discussion**

233 **4.1 Strength Behaviour**

234 The intermediate strength recovery seen between 1 and 3 FT cycles (in the first experimental series) was not
235 identified in existing literature. An almost continuous slurry layer along the plane of a horizontal ice lens
236 occurred after 1 FT cycle. This lens is substantially smaller than observed in e.g. Figure 8a, and cannot be
237 easily observed in Figure 6a but is identified in Figure 9d, alongside the failure plane on the failed sample. At 3
238 cycles, no continuous horizontal ice lens is visible, and therefore no slurry layer formed, resulting in a higher
239 mobilised shear strength. After the first FT cycle, the space between the soil particles reduced during thawing,
240 resulting in slight consolidation. The lack of a continuous horizontal ice lens at 3 FT cycles explains the strength
241 recovery between the first and third FT cycles. The presence of strain hardening and residual strain for samples
242 subjected to more than 1 FT cycle indicates the material can carry larger loads before failing in the range of
243 strength measured. Strain softening was only seen after 1 freezing cycle, and was not identified as a phenomena
244 in existing literature. The strain softening after 1 FT cycle suggests a significant amount of damage occurs
245 during the first freezing cycle, and can be attributed to the onset of clay fragmentation that occurs as the sample
246 cracked during freezing.

247 Thicker ice lenses resulted in lower shear strengths, due to continuous ice lenses, and after thawing, porewater is
248 unable to redistribute in to the soil due to very low gradients and decreased permeability due to consolidation of
249 the clay. Lower freezing gradients (in this case, from warmer fixed freezing temperatures) approaching 0°C
250 result in larger ice lenses and therefore weaker soils. Based on these results, locally freezing clay as a
251 stabilisation measure in construction would be best done using a colder freezing temperature for more rapid
252 freezing.

253 An attempt was made to investigate the repeatability and variability of the impact of freeze thaw cycles by
254 repeating tests with all the same conditions. Freezing and consequential cracking added additional variability
255 into the samples as the crack patterns are strongly influenced by local imperfections. However, the repeatability
256 is significant, as seen in Figure 4, although differences are clear between samples. Therefore, the local
257 variabilities observed are not significant at the element level in terms of describing the qualitative processes and
258 behaviour. Overall, the never-frozen samples had a maximum variability from the mean of approximately 16%
259 (10 samples), while the variation from the mean of thawed samples was approximately 13% (15 samples).
260 Given the heterogeneous nature of soil, this indicates that the sample preparation and testing was sufficiently
261 consistent. The true reliability of the results is difficult to determine, as there are insufficient data points to
262 assess the error and develop a standard deviation. More tests are needed to draw conclusions about the reliability

263 and variation within the samples, especially between 1 and 3 FT cycles, where the results were not as expected
264 based on the literature review and models. Test results were also not corrected for membrane stiffness effects,
265 which would affect the quantitative values reported, but not the qualitative trends.
266

267 **4.2. Ice lens formation**

268 It can be seen in Figures 8 and 9 that slower freezing rates result in larger ice lenses, which allows formation of
269 slurry layers and a consequential weak plane in the soil. This discontinuity results in decreased shear strength
270 and reduced stiffness compared to the never-frozen material. Samples frozen with $T_{bf} = -5^{\circ}\text{C}$ exhibited almost
271 no lensing in the top 25 mm of the sample, but had a very large ice lens. The lack of ice lensing in the upper
272 portion of the sample is attributed to movement of pore water towards the freezing front and active ice lens via
273 cryogenic suction until the 'unfrozen' soil reached its shrinkage limit. At this point, the soil could desaturate and
274 any remaining water could mostly freeze within the pore space, therefore not causing any significant fracturing
275 or cracking of the soil. The pore water in the thawed sample along the plane of the slurry layer will try to
276 redistribute through the sample, due to excess pore pressures derived from the consolidated material above, but,
277 due to the sealed nature of the samples drainage out of the sample was not possible. Moreover, the soil
278 fragments will have become consolidated, and will not swell to the same initial volume, therefore it is likely that
279 there will be some free water/slurry in the sample.

280 Formation of many, small ice lenses destroys the soil microstructure and results in a reduction of shear strength.
281 The presence of larger ice lenses with slower freezing rates results in significant weakening under undrained
282 conditions due to formation of a saturated zone that acts as a failure plane. The equilibrium shear strength
283 reached when $T_{bf} < -10^{\circ}\text{C}$ coincides with fewer changes in the soil structure. The difference in ice lens
284 formation between $T_{bf} = -15^{\circ}\text{C}$ and $T_{bf} = -20^{\circ}\text{C}$ is significantly less than the difference between $T_{bf} = -5^{\circ}\text{C}$ and
285 $T_{bf} = -10^{\circ}\text{C}$. The increasingly uniform ice lens distribution with increasing freezing rate is caused by pore water
286 freezing rapidly and a reduced influence of cryogenic suction. Similarly, changes in ice lens distribution
287 decrease dramatically between 1 and 3 FT cycles, and are more similar between 5 and 7 cycles. After 7 cycles,
288 the ice lens distribution stabilised, along with the shear strength. This is in agreement with research by Ghazavi
289 and Roustaei (2013), Arenson et al. (2008), and Konrad (1998).

290

291 **4.3. Stiffness**

292 The development of soil stiffness with increasing FT cycles is given in Figure 10. The stiffness after 1 FT cycle
293 at $T_{bf} = -20^{\circ}\text{C}$ is almost double that of never-frozen soil. Hypothetically, continuing to increase the freezing rate
294 by lowering the surface freezing temperature could result in greater stiffness. This increased stiffness after 1 FT
295 cycle may be due to the soil fragments consolidating locally during the first freezing cycle. This phenomenon
296 has been documented by Volokhov (2003), Ghazavi and Roustaei (2013), Qi et al. (2008) and Simonsen and
297 Isacsson (2001). With increasing FT cycles, the microstructure is rapidly destroyed, resulting in decreasing
298 stiffness, for example at 3 FT cycles the stiffness is about a half of the original. The decrease in stiffness mainly
299 occurs in the first few cycles. At low freezing rates, any local consolidation after the first freezing cycle is offset
300 by the formation of large ice lenses that act as failure planes. The development of stiffness and mobilised shear
301 strength with different freezing rates at 1 FT cycle is shown in Figure 11. For $T_{bf} > -20^{\circ}\text{C}$, the stiffness is lower
302 than that of a never-frozen sample.

303 The decreasing stiffness with decreasing freezing rate, seen in Figure 11, supports the considerations suggested
304 by GHSPA (2012) for design of energy piles. This change in stiffness can be attributed to the fragmentation and
305 destructuring of the clay, a faster freezing rate yields a less fragmented material thus structure and stiffness is
306 maintained. The relationship between a softer (less stiff) soil and lower shear strength with decreasing freezing
307 rates is not in agreement with the findings of Ghazavi and Roustaei (2013), who found an increase in stiffness
308 approaching 0°C . This difference is attributed in part to the low confining pressures used in their research
309 (between 30 and 90 kPa), as both stiffness and shear strength are known to increase with confining pressures.
310 From Volokhov (2003), Simonsen and Isacsson (2001), and Qi et al. (2008), soil stiffness increases after the
311 first freezing cycle, regardless of freezing rate, was expected to be larger than that of the never-frozen material.
312 Instead, lower shear strengths seen with slower freezing rates correspond to lower stiffness. This was attributed

313 to the influence of the slurry layers that form along the plane of the largest ice lens and associated reduction in
314 shear strength.

315 The development of mobilised shear strength with increasing FT cycles is shown in Figure 12. Between 3 and 7
316 FT cycles, both the shear strength and stiffness decrease. There is an increase in stiffness at 10 FT cycles that
317 coincides with the equilibrium shear strength. The shear strength at 1 and after 10 FT cycles is approximately
318 the same when the variability of the system is taken in to account.

319

320 **4.4. Void Ratios**

321 While the initial void ratio of the samples is uniform between samples and within the samples (Table 1), the
322 void ratio is highly non-uniform in each sample after freezing (Figures 6 and 8). This means that the void ratio
323 of the fragments would be significantly lower than as prepared, with the areas between these fragments having a
324 very low void ratio. Due to the very small nature of these fragments, these have not been quantifiably measured.
325 Based on the results of the CT scans, the void ratio of the intact fragments decreases as the soil microstructure
326 degrades, and cracks appear. As the samples are frozen and porewater migration occurs, local consolidation
327 occurs on the thawed side of the freezing front due to cryogenic suction, resulting in a smaller void ratio in the
328 fragments. Samples exposed to more freezing cycles have increasingly more and smaller cracks, regaining
329 therefore a more uniform void ratio as the microstructure degrades, and the changes in void ratio can be
330 correlated to changes in soil strength and stiffness.

331

332 **4.5. Scale effects**

333 The tests done for this research are not true element tests and are therefore subject to scale effects. As seen in
334 the CT scans and literature, formation of ice lenses is highly depth dependent and is a function of the
335 temperature gradient, water availability and soil properties (e.g., compressibility, hydraulic conductivity). To
336 capture the structural changes and ice distribution, large samples are needed. The time required for the entire
337 sample to freeze or temperature at the top of sample to stabilise varied with applied surface temperature. The
338 sample size used in this research was designed to be small enough that the freezing front would penetrate the
339 entire sample and freeze all the pore water. An external water supply (excess water placed on top of the sample)
340 would keep the material fully saturated and encourage more extensive ice lens formation. The lack of external
341 water supply resulted in some of the soil exhibiting no ice lensing (e.g., Figure 9a at the top of the sample). The
342 rate of freezing also varies with depth, due to the transience of the temperature boundary and heat losses from
343 the sample edges (in the laboratory).

344 The strength recovery between 1 and 3 FT cycles, attributed to changes in ice lens formation and formation of a
345 slurry layer, suggests that in cold regions, foundation elements are best constructed and allowed to experience at
346 least 1 complete FT cycle before applying loads. Current construction practices in areas such as Alaska, often
347 involve re-levelling or adjusting foundations after the first winter before completing the structure (Perreault,
348 2016). Allowing sufficient time between thawing and finishing constructions could allow the weak slurry layers
349 along the ice lens planes to dissipate and the clay to regain some strength. The large reduction in shear strength
350 at low axial strains (due to the increase in stiffness) after 1 FT cycle should be considered for engineering
351 design, as the change in strength may be of greater influence than frost heaving. The undrained shear strength
352 after 1 FT cycle should be used as a conservative design value, as application of surface loads will accelerate
353 consolidation and result in a stronger soil in the long-term. If freezing clays as a soil stabilisation measure,
354 applying a freezing surface temperature below -10°C will result in smaller ice lenses and a higher shear strength
355 after thawing.

356

357 **5. Conclusions**

358 The shear strength of Illite clay reduced significantly after being exposed to freeze-thaw cycles. This behaviour
359 is strongly affected by the rate of freezing and the number of cycles. Moreover the stiffness of the samples was
360 seen to significantly change. After 1 FT cycle, the stiffness of the thawed sample with $T_{bf} = -20^{\circ}\text{C}$ was almost
361 double that of a never-frozen sample, and failed at a low axial strain. Strength recovery was seen between 1 and
362 3 freezing cycles, along with a decrease in stiffness. The strength recovery was attributed to changes in the soil

363 structure due to formation of ice lenses, where a horizontal lens formed across the entire width of the sample
364 after 1 FT cycle, which was not present at 3 cycles. With increasing FT cycles, the size of ice lenses in the soil
365 decrease and the distribution over the sample height becomes increasingly uniform until an equilibrium
366 condition is reached around 7 FT cycles. The shear strength equilibrium coincides with a stabilisation of the soil
367 structure and stiffness.

368 As the freezing rate decreases, the shear strength and soil stiffness decrease. The largest change in shear strength
369 occurred between $T_{bf} = -5^{\circ}\text{C}$ and -10°C , after which the shear strength continued to decrease at a diminishing
370 rate approaching an equilibrium strength. This was observed to be due to the formation of large horizontal ice
371 lenses, which are larger with greater temperatures. These lens formed a saturated slurry layer that acts as the
372 primary failure plane in the thawed soil and caused a reduction in shear strength. However, it is noted that with
373 different boundary conditions, different results would be yielded.

374 Additional research, varying the boundary conditions, confining pressures and drainage measuring the stiffness,
375 cohesion, angle of internal friction, and void ratio with increasing FT cycles would provide further insight in to
376 the relationship between these properties and shear strength development with freezing and thawing cycles.

377

378 **Acknowledgements**

379 The authors would like to acknowledge the help of Han de Visser, Kees van Beek and Marten van der Meer,
380 whose help in the construction, trouble-shooting and execution of the experiments was invaluable.

381

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422

423 **Figure captions**

- 424 Figure 1. Schematisation of soil behaviour: A) Soil profile; B) Temperature profile; C) Pore pressure profile; D)
425 Cryogenic suction profile (based on Andersland and Ladanyi, 1994, and Arenson et al., 2008)
426 Figure 2. Schematic of freeze-thaw apparatus
427 Figure 3. Schematic of insulated sample container and actual container
428 Figure 4. Mobilised shear strength vs. axial strain for samples subjected to multiple FT cycles
429 Figure 5. Mobilised shear strength vs. number of FT cycles at different axial strains
430 Figure 6. CT scans for different numbers of FT cycle and $T_{bf} = -20^{\circ}\text{C}$. TOP: Cracking on frozen sample before
431 loading into triaxial cell; MIDDLE: CT scan of frozen sample. Pale grey is ice, white is soil, and black is voids;
432 BOTTOM: Contrast CT showing ice distribution. White is solids, blue is ice, black is voids. (a) to (d) increasing
433 FT cycles: 1, 3, 7, 10. (e) schematic showing freezing direction
434 Figure 7. Mobilised shear strength vs. axial strain for samples subjected to 1 FT cycle at different freezing rates
435 Figure 8. CT scans for 1 FT cycle at different freezing rates. TOP: Cracking on frozen sample before loading
436 into triaxial cell; MIDDLE: CT scan of frozen sample. Pale grey is ice, white is soil, and black is voids;
437 BOTTOM: Contrast CT showing ice distribution. White is solids, blue is ice, black is voids. (a) to (d): $T_{bf} = -5, -$
438 $10, -15, -20^{\circ}\text{C}$. (e) schematic showing freezing direction
439 Figure 9. CT scan of frozen samples with location of largest ice lens and failure plane after triaxial tests
440 Figure 10. Stiffness vs. number of freeze/thaw cycles
441 Figure 11. Stiffness vs. applied freezing temperature T_{bf}
442 Figure 12. Stiffness vs. mobilised shear strength for different number of FT cycles
443
444

445 **Table captions**

- 446 Table 1. Sample details and the experimental procedure they were used for.

Table 1. Sample details and the experimental procedure they were used for.

T_{bf} [°C]	# cycles	w [%]	γ_{dry} [kN/m ³]	e [-]
-20	1	34	16.18	0.61
-20	1	33	16.31	0.62
-20	3	34	16.54	0.62
-20	3	33	17.67	0.67
-20	5	36	15.85	0.60
-20	5	34	16.54	0.62
-20	7	35	16.18	0.61
-20	7	34	16.54	0.62
-20	10	35	16.19	0.61
-20	20	35	15.86	0.60
-15	1	33	16.51	0.62
-10	1	35	16.18	0.61
-10	1	33	16.51	0.62
-5	1	34	16.18	0.61

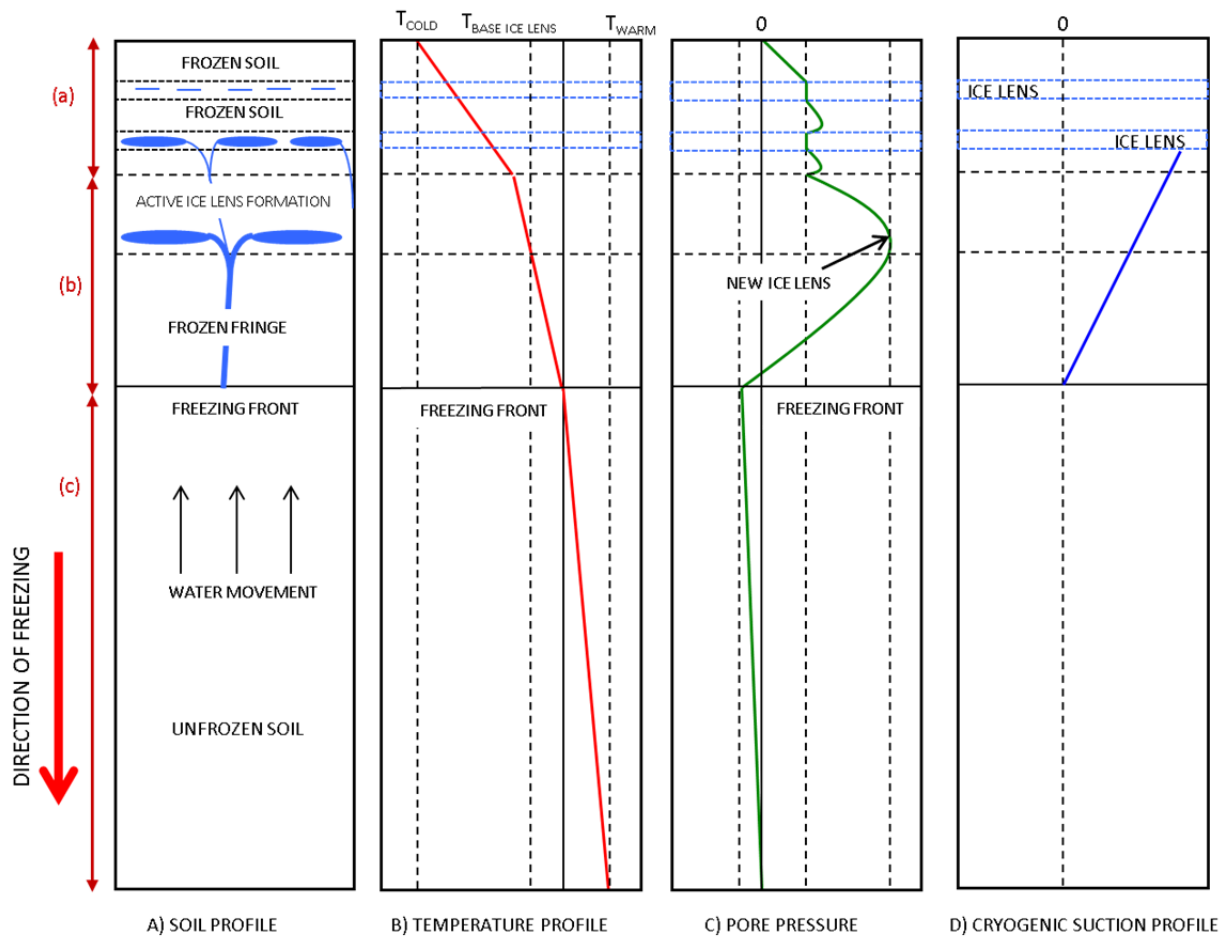


Figure 1. Schematisation of soil behaviour: A) Soil profile; B) Temperature profile; C) Pore pressure profile; D) Cryogenic suction profile (based on Andersland and Ladanyi, 1994, and Arenson et al., 2008)

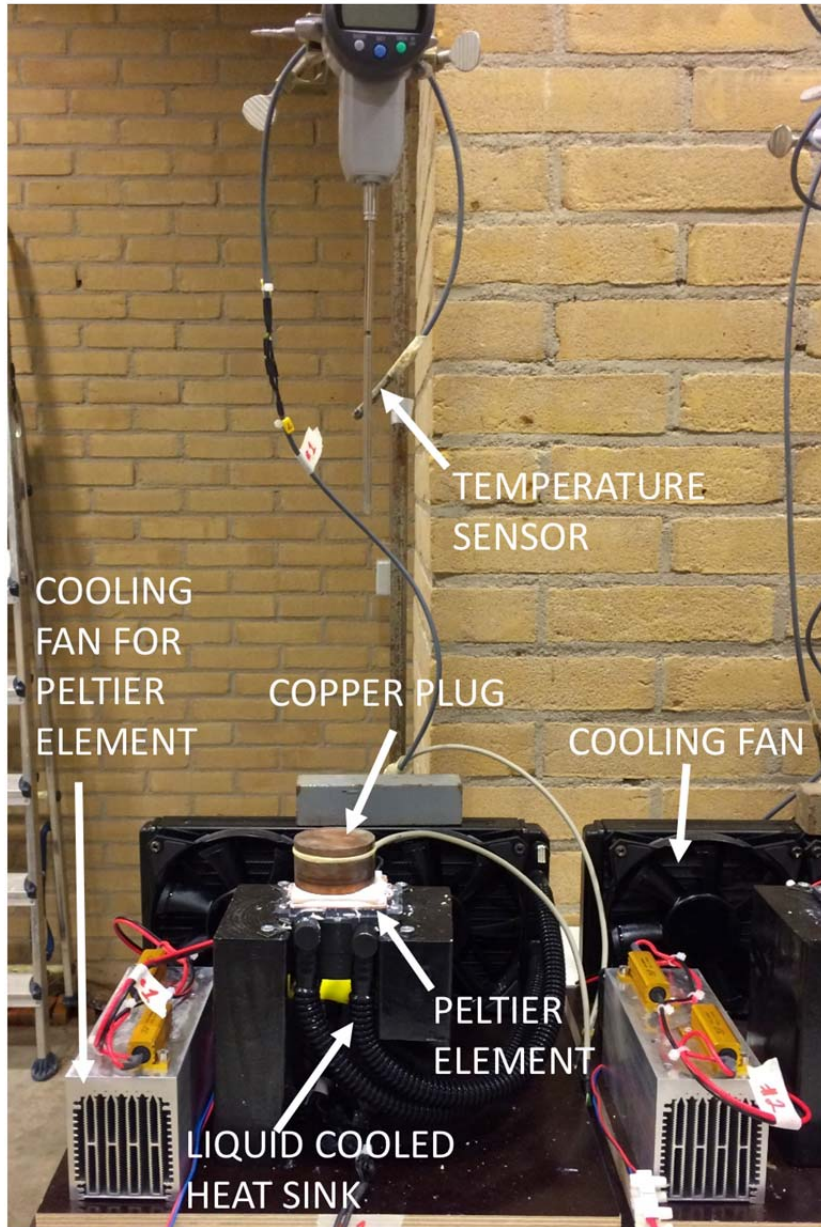
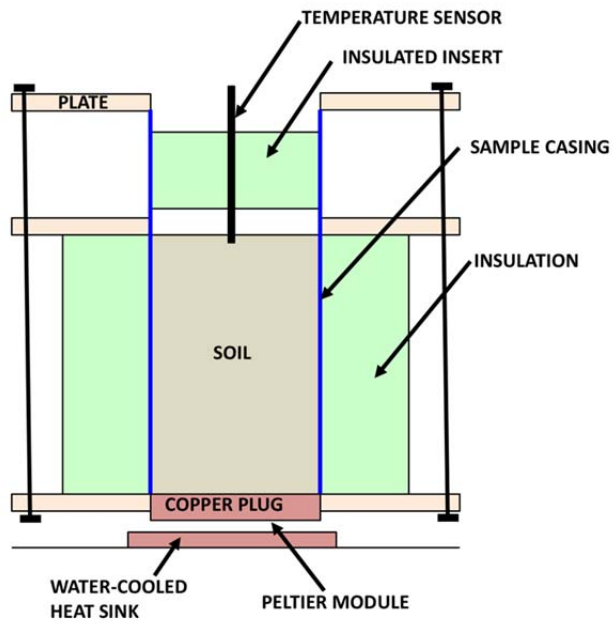


Figure 2. Schematic of freeze-thaw apparatus



a) Schematic sample box



b) Actual sample box

Figure 3. Schematic of insulated sample container and actual container

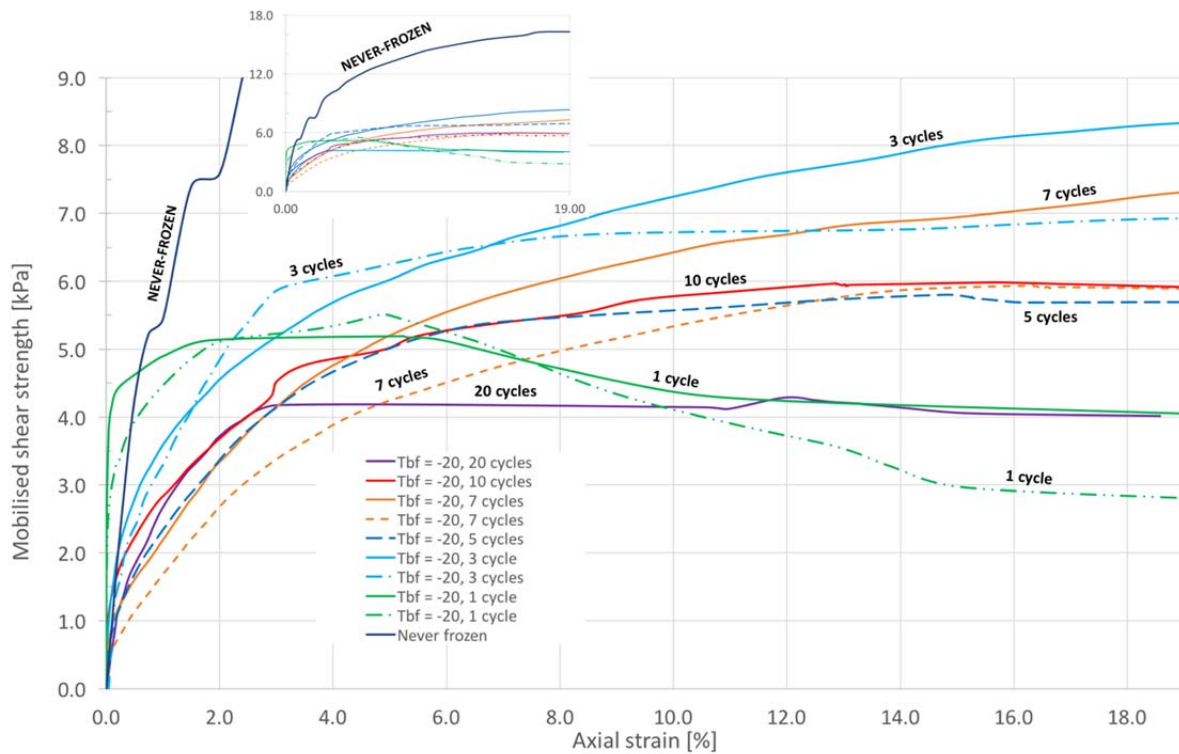


Figure 4. Mobilised shear strength vs. axial strain for samples subjected to multiple FT cycles

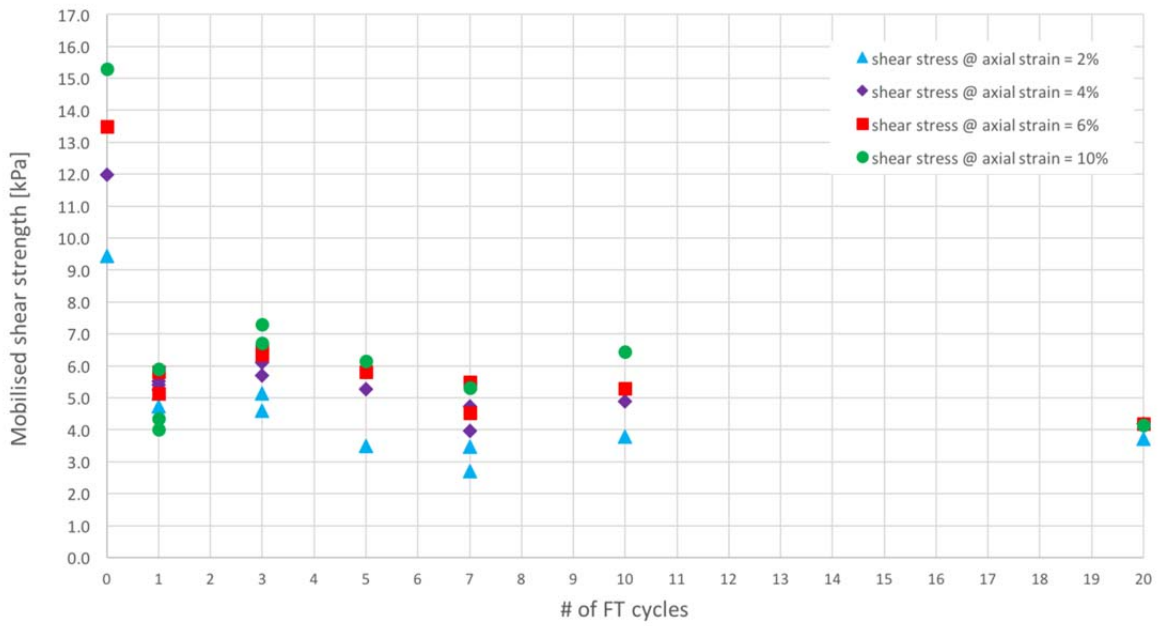


Figure 5. Mobilised shear strength vs. number of FT cycles at different axial strains

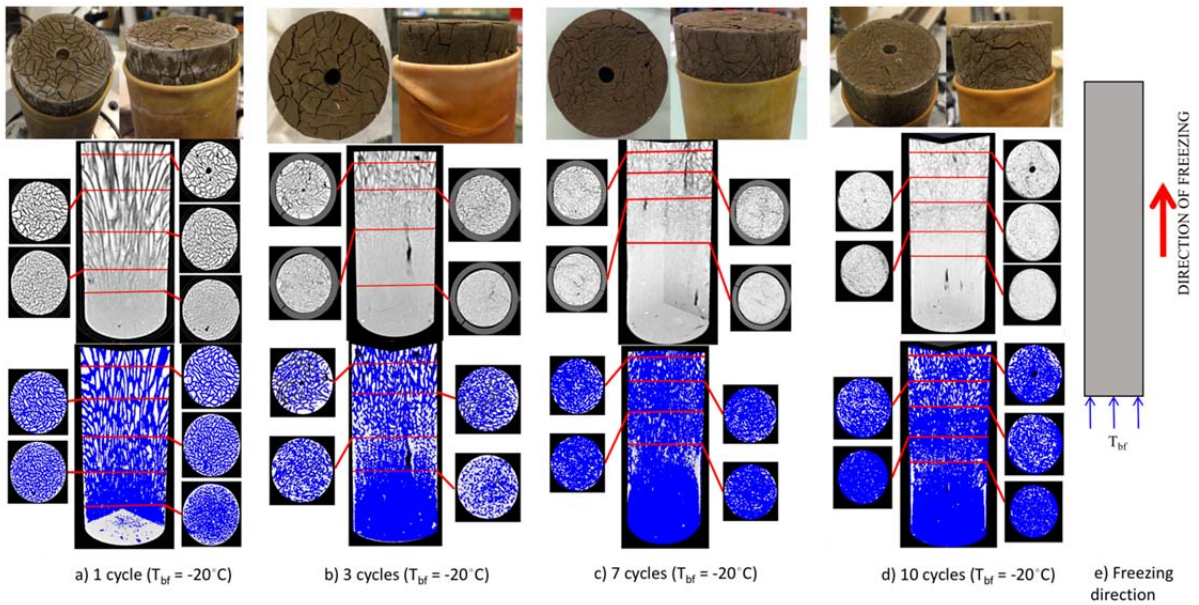


Figure 6. CT scans for different numbers of FT cycle and $T_{bf} = -20^{\circ}\text{C}$. TOP: Cracking on frozen sample before loading into triaxial cell; MIDDLE: CT scan of frozen sample. Pale grey is ice, white is soil, and black is voids; BOTTOM: Contrast CT showing ice distribution. White is solids, blue is ice, black is voids. (a) to (d) increasing FT cycles: 1, 3, 7, 10. (e) schematic showing freezing direction

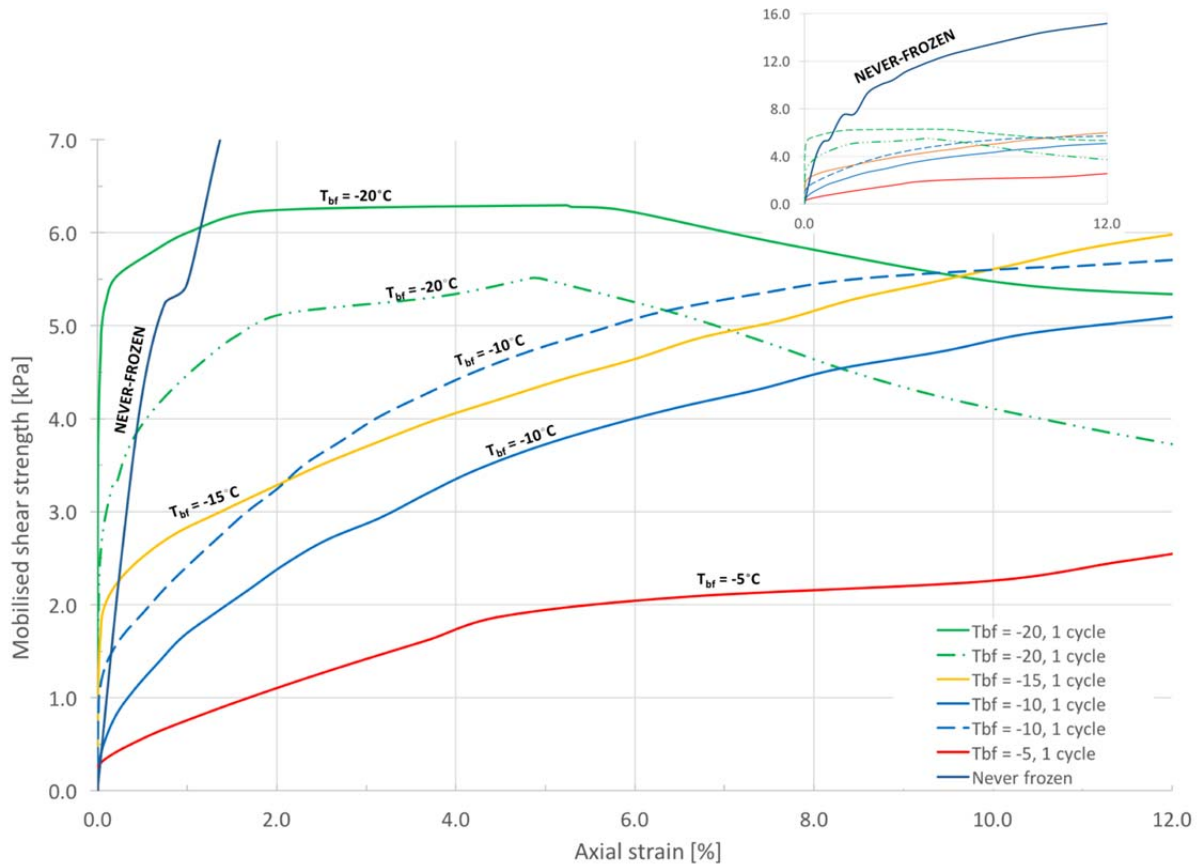


Figure 7. Mobilised shear strength vs. axial strain for samples subjected to one FT cycle at different freezing rates

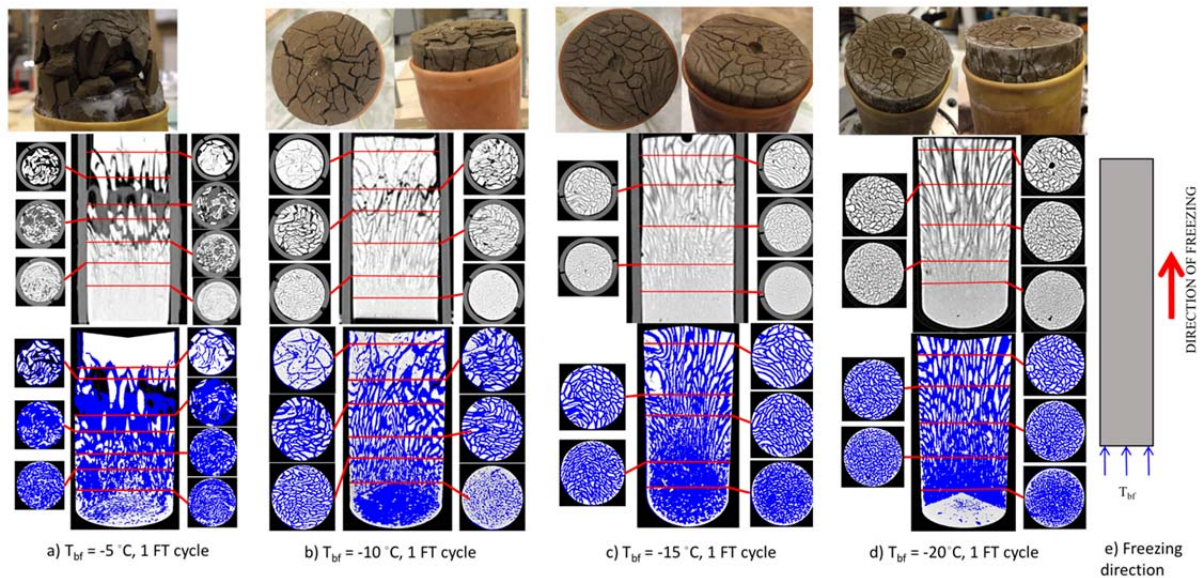


Figure 8. CT scans for one FT cycle at different freezing rates. TOP: Cracking on frozen sample before loading into triaxial cell; MIDDLE: CT scan of frozen sample. Pale grey is ice, white is soil, and black is voids; BOTTOM: Contrast CT showing ice distribution. White is solids, blue is ice, black is voids. (a) to (d): $T_{bf} = -5, -10, -15, -20^{\circ}\text{C}$. (e) schematic showing freezing direction

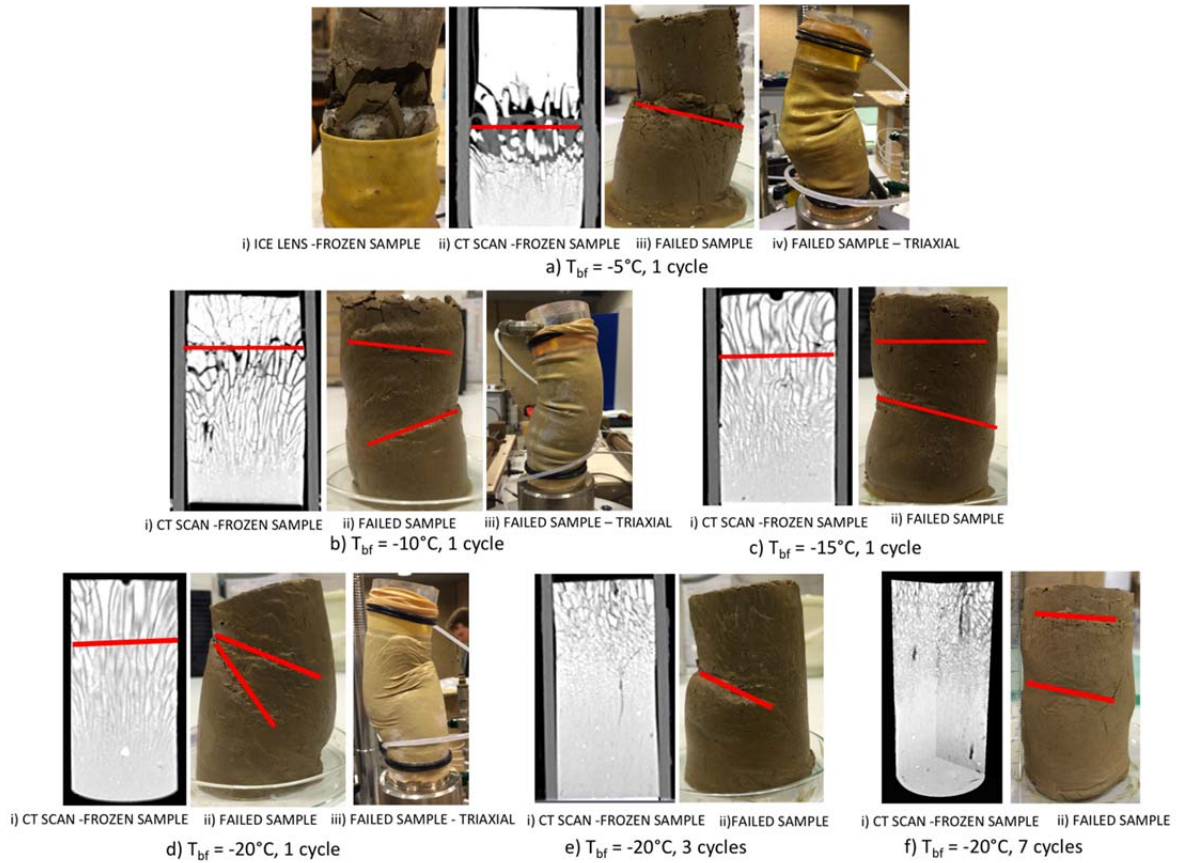


Figure 9. CT scan of frozen samples with location of largest ice lens and failure plane after triaxial tests

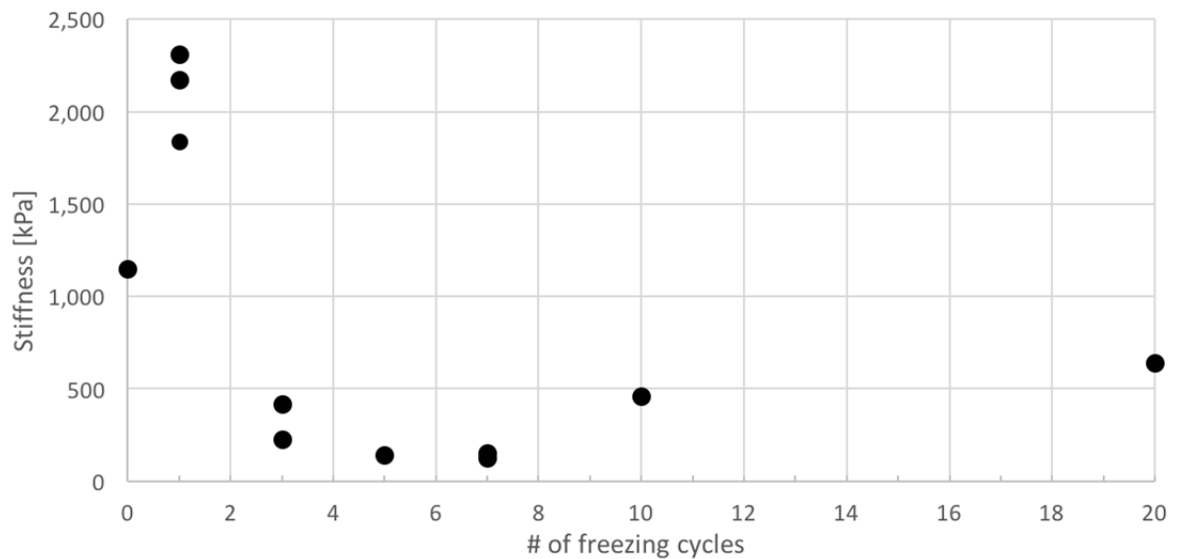


Figure 10. Stiffness vs. number of freeze/thaw cycles

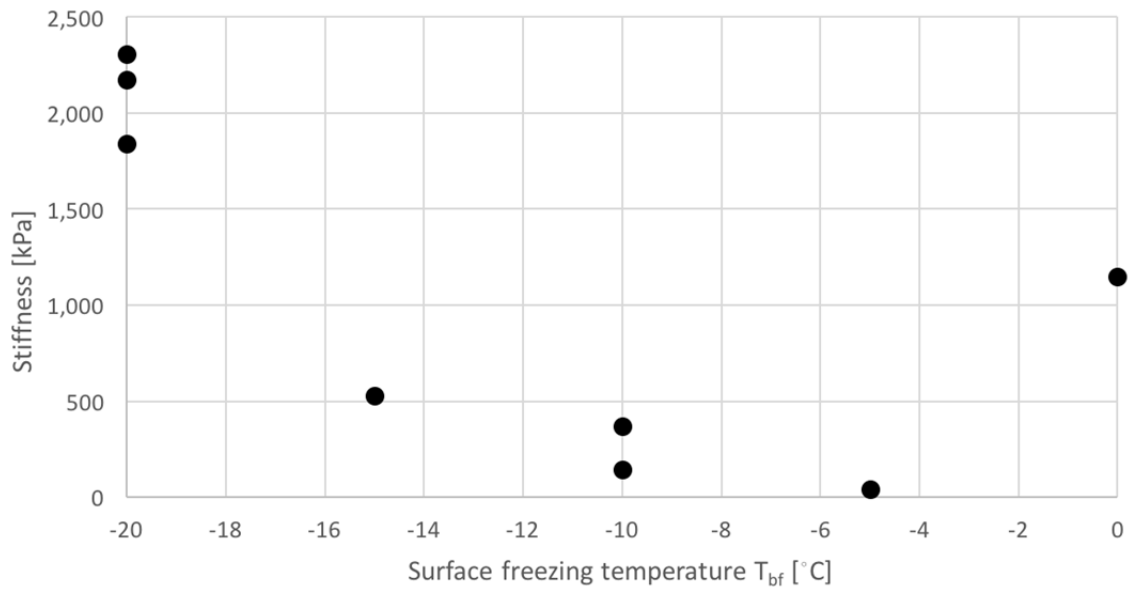


Figure 11. Stiffness vs. applied freezing temperature T_{bf}

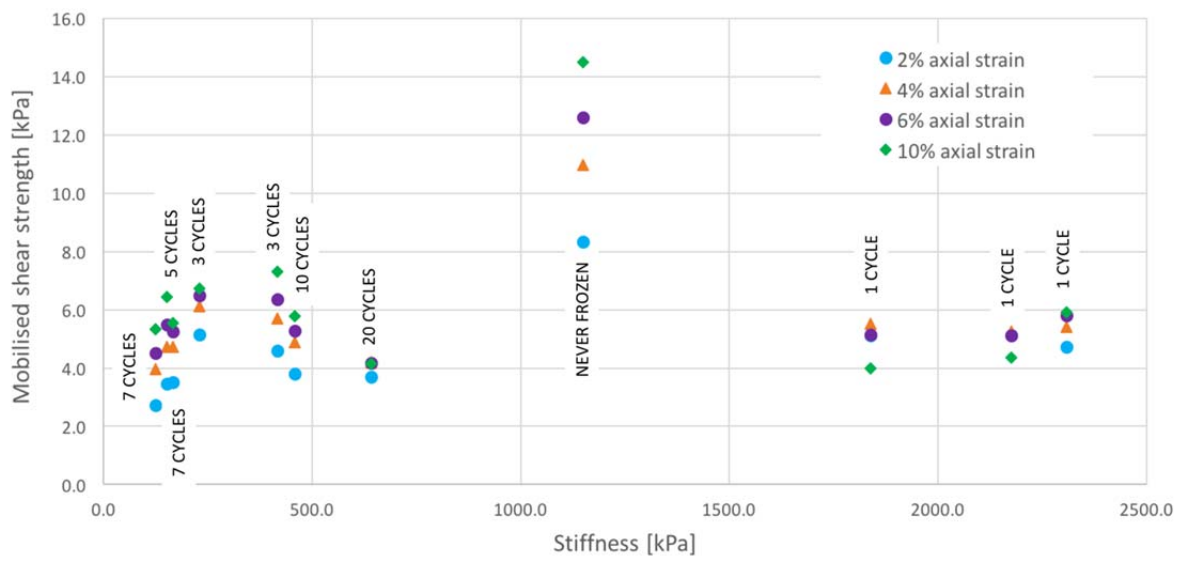


Figure 12. Stiffness vs. mobilised shear strength for different number of FT cycles