Mechanical behavior of frozen clay under constant- and varying-temperature and strain rate shear

Jinyuan Wangⁱ⁾ and Satoshi Nishimuraⁱⁱ⁾

i) Ph.D Student, Graduate School of Engineering, Hokkaido University, Kita-13 Nishi-8, Kita-ku, Sapporo, Hokkaido 060-8628, Japan.

ii) Associate Professor, Faculty of Engineering, Hokkaido University, Kita-13 Nishi-8, Kita-ku, Sapporo, Hokkaido 060-8628, Japan.

ABSTRACT

This study reports a series of triaxial compression tests on frozen clay. The tests were performed on reconstituted Kasaoka Clay frozen at -2, -5 and -10 °C from isotropic normal consolidation of 400kPa. The specimens were sheared at constant or varying strain rates and temperatures, and their observed strength and its dependence on these factors are discussed. The results show that, within the investigated range of conditions, the shear strength increases log-linearly with an increase in the strain rate. The shear strength normalized by that at a given temperature, or by that at a given strain rate formed unique relationships against the strain rate or the temperature, respectively. The stress in a temperature-varying condition can generally be predicted for a given strain if constant-temperature stress-strain curves are considered as backbone relationships. The same observation is probably true for the strain-rate, as described by the isotache rule. These effects are similar on the deviator stress for strains larger than 5% as on the strength. At these strain levels, the stress-strain curves suggest that the frozen specimens were at a sufficiently plastic stage. The above features of temperature and strain rate effects are relatively simple to formulate and will be useful in developing a general rate-dependent thermo-mechanical model for frozen clays.

Keywords: artificially frozen clay, shear strength, strain rate, temperature effect

1 INTRODUCTION

Artificial ground freezing techniques have been widely applied in construction for decades. Understanding of the artificial frozen soil's behavior is a prerequisite for application of ground freezing in construction such as tunneling (Andersland and Ladanyi 2004). The freeze-thaw processes in cold regions also directly affect the stability and safety of soil structures or upper structures based on them. With viscoplastic constituent (ice) in it, the frozen soil exhibits characteristic rheological behaviors. It is thus necessary to study the effects of temperature and strain rate on the mechanical and rheological behavior of frozen soils.

Early studies on the rheological (i.e. visco-plastic) characteristics of frozen soils mainly focused on the creep behavior under sustained stress or the stress responses against constant strain rates (Andersland and Akili 1967, Ladanyi 1972). Among them, Goughnour and Andersland (1968) studied the effect of confining pressure on the mechanical properties of frozen sand and found that creep rates decreased exponentially and creep strength increased with an increase in confining pressure. Zhu and Carbee (1984) carried out a uniaxial compression test program on remolded Fairbanks frozen silts under various deformation rates and found that the yield and peak compressive strengths were very

sensitive to temperature and strain rate. Arenson and Springman (2005) conducted triaxial tests on ice-rich cored alpine permafrost, and the results showed that the minimum strain rate of creep increased exponentially with an increase in temperature or applied deviator stress. The strain rates employed in these studies were often very large, ranging from 10^{-3} to 1 %/sec, although some researchers attempted studying at lower rates (5.69×10^{-5} to 1.78×10^{-1} %/sec by Bragg and Andersland, 1981, and 9×10^{-5} to 4.07×10^{-3} %/sec by Arenson and Springman, 2005). It has not been well established how frozen soils respond to general changes in the imposed strain rates ranging over different orders. Such rate changes are considered to be common in many geotechnical processes.

The strain rate and temperature have overriding effects; for example, Bragg and Andersland (1981) conducted uniaxial compression to investigate the effects of strain rate and temperature on the compression and tensile properties of frozen sand and found that the initial yield stress, the compressive peak strength and the initial tangent modulus increased with decreasing temperatures and increasing strain rate. The problem of shear strength must be considered with appropriate reference to the density and stress states. Chamberlain et al. (1972) investigated the effects of confining pressure on the shear strength of frozen soil

and summarized that confining pressure had a great influence on the shear strength of frozen soils. Hohmann-Porebska (2002) proposed that the temperature effects on the shear strength were mainly reflected in the cohesion. The frictional component of the strength did not vary significantly. There have been many other studies investigating the individual and combined effects of strain rate, temperature, density and stress levels (e.g. Aas, 1981, Wang et al., 2004, and Lai, et al., 2010).

Most of the aforementioned studies on artificially frozen soils, except Wang et al. (2004), were unclear about the specimens' consolidation history before freezing. As a volume-effective stress state is one of the most fundamental determinants of unfrozen soils' strength and stiffness, its strict control is strongly desired to bridge the understanding of frozen and unfrozen soil behavior (Ladanyi and Morel, 1990). In this study, a series of compression tests on the frozen and unfrozen clay were conducted with a common consolidation history before freezing, and a common swelling/expansion history before shearing. Different orders of strain rates were adopted during shearing. To seek a general rule to describe the effects of strain rate and temperature when they vary in general ways, the specimens were sheared at constant or varying strain rates and temperatures.

2 MATERIAL AND TEST METHOD

Commercially available Kasaoka Clay was selected for triaxial tests in frozen and unfrozen states. The specific gravity of the Kasaoka Clay is 2.65. Its liquid limit and plastic limit are 62% and 36%, respectively. The samples were K_0 reconstituted from slurry with water content of 100% (1.6 times the liquid limit) under a preconsolidation pressure of 200 kPa. The initial void ratio of the samples is 1.08. The specimen size was 30mm in diameter and 60mm in height having aspect ratio of 2. The tests were conducted in temperature- and strain rate-controlled triaxial compression apparatus, as shown in Fig. 1. The cell temperature was controlled by circulating low-temperature anti-freeze refrigerant through a spiral copper coil inside the cell. The low-temperature anti-freeze refrigerant came from and returned to a temperature-adjustable refrigerating bath which is not illustrated in Fig. 1. The cell was filled with the same refrigerant as confining fluid, of which temperature was measured by a thermocouple. The stages reported in this paper were all in temperature-equilibrium; i.e. the cell temperature was same as the specimen temperature. This was confirmed in a separate trial test, in which the temperature was measured by thermocouples embedded inside a specimen, at the specimen surface and in the cell. A rest period of some 80 minutes was necessary in achieving equilibrium in the adopted freezing method (described subsequently) and conditions.

The adopted machine was originally a temperature-controlled oedometer, but modified to permit triaxial loading. The specimen was enclosed by a rubber membrane. The specimen was subjected to back pressure from the bottom channel through a double burette which measured the drainage and thus the specimen's volumetric changes during consolidation. A high-resolution direct drive motor capable of applying constant strain rates was used to axially load the specimen through a loading ram. The axial load was measured by a load cell mounted outside the cell. The uplift due to the cell pressure and the friction was corrected for.

Fig. 1 Schematic diagram of the triaxial apparatus

The triaxial compression test on frozen clay was carried out in four steps: (1) Isotropic consolidation to the effective mean stress, $p' = 400\text{kPa}$. This process was meant to give an isotropic structure to the specimen pre-consolidated with the vertical stress of 200kPa under K_0 conditions. The creep after consolidation was allowed until the volumetric compression rate became less than 0.02 %/hour. (2) Replacing the cell water with the refrigerant pre-cooled at about -18°C while keeping the cell pressure. The specimen was thus quickly frozen to about -15°C to prevent ice segregation and kept for 12 hours. (3) Increasing the cell temperature to testing temperature (-2 , -5 or -10°C) by adjusting the temperature of the refrigerating bath, and then keeping it for 24 hours. (4) Performing undrained shearing at a constant temperature and at a constant axial strain rate (0.1, 0.01 or 0.001 %/min; the test at -5°C and 0.001%/min has not been completed yet) until the target axial strain (normally 20%).

In addition to these constant-condition tests, additional three tests were conducted, in which the strain rate and temperature were varied stepwise during shearing. These three tests were performed with an upgraded strain measuring system. To avoid the influence of imperfect coupling between the loading ram and the top cap and other compliances, on-specimen gap sensors measuring semi-local (i.e. the sensors themselves were attached to the apparatus, not the specimen) axial displacement were installed. The setup of the gap sensors is shown in Fig. 2. For the strain rate-varying test, Step (4) involved

switching abruptly between different strain rates (0.1, 0.01 or 0.001 %/min) and keeping it constant for the axial strain of 0-5%, 5-10%, 10-15% and 15-20%. For the temperature-varying tests, at the end of the above strain intervals, the shearing was suspended and a new temperature was set and kept for 24 hours. Then the shearing was resumed at the same strain rate as before for another strain interval of 5%. This was repeated until the axial strain reached 20%.

Fig. 2 Setup of the gap sensors and thermocouple

Another series of tests at unfrozen states was performed by following similar steps but without freezing: (1) Isotropic consolidation to $p' = 400 \text{ kPa}$. (2) Decreasing the confining pressure to unload the specimen. The specimen was allowed to swell by unloading by the same amount as the freezing expansion, calculated based on 9% expansion of pore water (resulting in the whole specimen expansion of $(1+1.09e_c)/(1+e_c)$, where e_c is the void ratio after stage (1)), as illustrated in Fig. 3. (3) Undrained shearing at $+24^\circ \text{C}$ and at a constant strain rate of 0.1 and 0.01%/min (the test at 0.001%/min has not been completed yet) until the axial strain of 20%. Both the frozen and unfrozen samples experienced the same volumetric strain history this way throughout the tests.

Fig. 3 Illustration of the presumed $e - \log p'$ relationship during freezing or unloading

The present study does not consider very high confining pressure situations ($>1 \text{ MPa}$), as they are not usually encountered in constructions such as tunneling and temporary excavation. Pressure melting and ice fracturing are thus not considered.

3 TEST RESULTS AND DISCUSSIONS

3.1 Constant-strain rate tests on frozen clay

The experimental results obtained from the constant-strain rate compression tests of the frozen clay include relationships of the shear strength with temperature and strain rate. The undrained shear strength, c_u , is defined here by half the maximum deviator stress, $(\sigma_1 - \sigma_3)_{\max}/2$. In case that the behavior was ductile and a maximum was not clearly defined, the deviator stress at an axial strain of 20% was adopted. As Fig. 4(a) shows, at a same strain rate, the strength of the frozen clay increased linearly with a decrease in temperature. With higher strain rates, the slope of the trend line is steeper. However, when the shear strength, c_u , is normalized by that at a give temperature (-2°C in Fig. 4(a)), the relationship is fairly unique, with a slope of -0.23 $^\circ \text{C}$ (the experiment at -5°C , 0.001%/min has not been performed yet). On the other hand, as Fig. 4(b)

Fig. 4 Relationships of shear strength with temperature and strain rate

shows, at a same temperature, the shear strength of frozen clay linearly increased with a logarithmic increase in the strain rate. The slope of the trend line is steeper at lower temperature. In a normalized form (by c_u at 0.1%/min), however, the results from the two complete sets (i.e. -2 °C and -10 °C) suggest broadly a unique relationship, with a slope of 0.13 (per log cycle of strain rate). The results of the unfrozen specimens are not complete yet; however, the two data points seem to indicate somewhat smaller degree of strain rate-dependency of the strength. The above observations suggest that the simultaneous influence of the temperature and the strain-rate on the frozen clay's strength is normalisable in a very simple way.

3.2 Temperature-varying and strain rate-varying tests

For the temperature-varying tests, the stress-strain relationships with the starting temperature of -5 °C (Case 1) and -10 °C (Case 2) at the axial strain rate of 0.01%/min are shown in Fig. 5(a) and (b). The interruption of loading upon a temperature change led to a stress relaxation in this transition period. A stress jump or drop was observed as the temperature decreased or increased. The stress-strain relationship at each temperature tended to approach that of the constant temperature test at the same strain rate and temperature, although slight overshooting was observed in some stages. The deviator stress shifts at the transitional strains (5%, 10% and 15%) between the two adjacent temperatures are summarized in Table 1. In this table, the stress shifts due to the temperature changes are represented by ratios $q(-5^\circ\text{C})/q(-2^\circ\text{C})$, $q(-10^\circ\text{C})/q(-5^\circ\text{C})$ and $q(-10^\circ\text{C})/q(-2^\circ\text{C})$, in which $q(-2^\circ\text{C})$, $q(-5^\circ\text{C})$ and $q(-10^\circ\text{C})$ denote the deviator stress at -2, -5 and -10 °C, respectively. The equivalent values read from the constant-temperature tests are also shown here. Consistent shifts of the deviator stress were observed between the two series of tests (i.e. constant- and varying-temperature). This agreement, as visualized in Fig. 5, suggests that the stress-strain relationships from the constant-temperature tests serve as backbone curves for the tests under generally changing temperature. The above ratios are fairly constant for the axial strain larger than 5%. For smaller strains, as we will discuss later in terms of the shear modulus, G , this ratio was less well-defined, but also of similar magnitudes as those in Table 1.

(a) Temperature varying order: -5 °C => -10 °C => -2 °C => -5 °C

(b) Temperature varying order: -10 °C => -5 °C => -2 °C => -10 °C

Fig. 5 Stress-strain relationship in constant- and varying-temperature tests

Table 1. The temperature effect on the deviator stress at the transitional strains under strain rate of 0.01%/min

Condition	Deviator stress ratio	Axial strain			
		5%	10%	15%	20%
T-Constant	$q(-5^\circ\text{C})/q(-2^\circ\text{C})$	1.76	1.68	1.70	1.79
	$q(-10^\circ\text{C})/q(-5^\circ\text{C})$	1.62	1.64	1.63	1.62
	$q(-10^\circ\text{C})/q(-2^\circ\text{C})$	2.84	2.75	2.78	2.89
T-Varying (Case 1)	$q(-5^\circ\text{C})/q(-2^\circ\text{C})$	1.60			
	$q(-10^\circ\text{C})/q(-5^\circ\text{C})$	1.59			
	$q(-10^\circ\text{C})/q(-2^\circ\text{C})$	3.03			
T-Varying (Case 2)	$q(-5^\circ\text{C})/q(-2^\circ\text{C})$	1.62			
	$q(-10^\circ\text{C})/q(-5^\circ\text{C})$	1.64			
	$q(-10^\circ\text{C})/q(-2^\circ\text{C})$	2.50			

In addition to the above, a strain rate-varying test at -2 °C was performed. The switching between axial strain rates after every strain interval of 5% was conducted in an order of 0.01, 0.001, 0.1 and back to 0.01%/min. The obtained stress-strain relationship is shown in Fig. 6. The stress-strain relationships of the constant-strain rate tests at -2 °C for the above three strain rates are also plotted in Fig. 6. The response in this strain rate-varying test turned out to be slightly stronger than those in the corresponding constant-strain rate tests at each stage. This can be attributed to the difficulty in ensuring the exactly same physical and

mechanical properties in preparing multiple specimens. Compared to the tests at the axial strain rate of 0.1 and 0.01%/min, shearing at the axial strain rate of 0.001%/min took much longer time (3.5 days for a strain of 5%), which made it difficult to avoid the fluctuations in the testing temperature and thus resulted in the non-smooth stress-strain curve at the 0.001%/min stage shown in Fig. 6. The deviator stress shifts at the transitional strains for the two adjacent axial strain rates are summarized in Table 2. The symbols $q_{0.1}$, $q_{0.01}$ and $q_{0.001}$ represent the deviator stress at the axial strain rate of 0.1, 0.01 and 0.001%/min, respectively. Although the above problem in preparing identical specimens did not permit direct comparison of the deviator stresses between the two test series, the strain-rate effect, as represented by the relative shift of the stress, is fairly consistent between them. This fact suggests a unique stress-strain backbone relationship for a given strain rate, at least when the strain is larger than 5% and the behavior is broadly plastic. This feature is potentially captured by the isotache theory (e.g. Leroueil, 2006), commonly accepted for unfrozen clays.

Table 2. The strain rate effect on the deviator stress at the transitional strains under temperature of -2°C

Condition	Deviator stress Ratio	Axial strain			
		5%	10%	15%	20%
Strain rate-Constant	$q_{0.1}/q_{0.01}$	1.07	1.06	1.09	1.13
	$q_{0.01}/q_{0.001}$	1.06	1.04	1.05	1.06
Strain rate-Varying	$q_{0.1}/q_{0.01}$	-	(1.09)*	1.11	-
	$q_{0.01}/q_{0.001}$	1.07	(1.09)*	-	-

* Square root value of $q_{0.1}/q_{0.001}$

Fig. 6 Stress-strain relationship in constant- and varying-strain rate tests

3.3 The shear stiffness at relatively small strains

The shear stiffness at relatively small strains was quantified with the aid of the semi-local axial displacement transducers deployed in the three temperature- or strain rate-varying tests. Based on the measurements from the motor movement (i.e. external displacement measurement) and the two symmetrically aligned gap sensors, the small-range stress-strain

relationships in the temperature-varying test with starting temperature of -2 °C are contrasted in Fig. 7. Because of the aforementioned imperfect coupling between the loading ram and the top cap, the specimen might have slightly bent when they got in contact as shearing began but got adjusted afterwards. As shown in Fig. 6, the gap sensor 2 output negative displacement in the initial stage. Taking an average of the two gap sensors output can correct for this imperfect coupling effect.

The stress-strain relationships representing the linear phase of shearing based on the average of the two gap sensor outputs are shown in Fig. 8, along with the initial shear modulus values, G , at the three testing temperatures at 0.01%/min based on the results of the gap sensors. It suggests that the stiffness increases as the temperature decreases. The G values normalized by that at -2 °C are shown in Fig. 9, along with the normalized shear strength trend line from Fig. 4(a). The general trend seems consistent with the strength-temperature trend, although the G -temperature trend appears to be slightly curved. More tests are necessary to establish the G -temperature relationships more generally against different strain rates.

Fig. 7 Small-range stress-strain relationship at temperature- or strain rate-varying tests

Fig. 8 Shear modulus values at axial strain rate of 0.01%/min

Fig. 9 Normalized shear moduli contrasted with normalized strength trend line

4 CONCLUSIONS

The shear strength and deformation characteristics of frozen clay at different temperatures and strain rates were investigated by constant-strain-rate triaxial compression tests and strain rate- and temperature-varying tests. In contrast to many existing studies, this work aimed to seek a general rule to describe the effects of strain rate and temperature when they vary in general ways. The conclusions are as follows:

1. The shear strength linearly increased with a decrease in temperature for the range from -10°C to -2°C , and log-linearly increased with an increase in the strain rate for the range from 0.001%/min to 0.1%/min. The shear strength normalized by that at a given temperature, or by that at a given strain rate formed unique relationships against the strain rate or the temperature, respectively.

2. The strain-rate effect on the shear strength appears to be more pronounced at the frozen states than at the unfrozen states, although the data for the latter are still incomplete.

3. The stress in a temperature-varying condition seems generally predicted for a given strain if constant-temperature stress-strain curves are considered as backbone relationships. The same observation is probably true for the strain-rate, as described by the isotache rule, although the current accuracy of the data allowed only rather indirect evaluation.

4. The temperature and strain rate effects on the deviator stress (i.e. percentage increase by certain temperature changes or logarithmic changes of strain rate) are similar and consistent for strains larger than 5%. At these strain levels, the stress-strain curves suggest that the frozen specimens were at a sufficiently plastic stage.

The above features of temperature and strain rate effects are relatively simple to formulate and will be useful in developing a general rate-dependent thermo-mechanical model for frozen clays.

ACKNOWLEDGMENTS

The work was partially funded by JSPS KAKENHI grant number 15K14025. The aid is sincerely acknowledged.

REFERENCES

- 1) Aas, G. (1981): "Laboratory determination of strength properties of frozen salt marine clay." *Engineering Geology*, 18(1), 67-78.
- 2) Alkire, B. D. and Andersland, O. B. (1973): "The effect of confining pressure on the mechanical properties of sand-ice materials." *Journal of Glaciology*, 12, 469-481.
- 3) Andersland, O. B. and Akili, W. (1967): "Stress effect on creep rates of a frozen clay soil." *Geotechnique*, 17(1), 27-39.
- 4) Andersland, O. B. and Ladanyi, B. (2004): "Frozen ground engineering." *John Wiley & Sons*.
- 5) Arenson, L. U. and Springman, S. M. (2005): "Triaxial constant stress and constant strain rate tests on ice-rich permafrost samples." *Canadian Geotechnical Journal*, 42(2), 412-430.
- 6) Bragg, R. A. and Andersland, O. B. (1981): "Strain rate, temperature, and sample size effects on compression and tensile properties of frozen sand." *Engineering Geology*, 18(1), 35-46.
- 7) Chamberlain, E., Groves, C. and Perham, R. (1972): "The mechanical behaviour of frozen earth materials under high pressure triaxial test conditions." *Geotechnique*, 22(3), 469-483.
- 8) Hohmann-Porebska, M. (2002): "Microfabric effects in frozen clays in relation to geotechnical parameters." *Applied clay science*, 21(1), 77-87.
- 9) Ladanyi, B. (1972): "An engineering theory of creep of frozen soils." *Canadian Geotechnical Journal*, 9(1), 63-80.
- 10) Ladanyi, B. and Morel, J.-F. (1990): "Effect of internal confinement on compression strength of frozen sand." *Canadian Geotechnical Journal*, 27(1), 8-18.
- 11) Lai, Y., Yang, Y., Chang, X. and Li, S. (2010): "Strength criterion and elastoplastic constitutive model of frozen silt in generalized plastic mechanics." *International Journal of Plasticity*, 26(10), 1461-1484.
- 12) Leroueil, S. (2006): "Suklje's Memorial Lecture – The isotache approach: Where are we fifty years after its development by Professor Suklje?" *Proc. of European-Danube Conference on Geotechnical Engineering*, Ljubljana, 1, 55-88.
- 13) Wang, D., Ma, W. and Chang, X. (2004): "Analyses of behavior of stress-strain of frozen Lanzhou loess subjected to K_0 consolidation." *Cold regions science and technology*, 40(1), 19-29.
- 14) Zhu, Y. and Carbee, D. L. (1984): "Uniaxial compressive strength of frozen silt under constant deformation rates." *Cold Regions Science and Technology*, 9(1), 3-15.