시베리아 동토지역 점성토의 압축강도 시험
Compressive Strength Tests on Frozen Siberian Clay

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SYNOPSIS : The objective of this study was to investigate the strength characteristics of frozen clay. Compressive strength tests were performed on frozen clay with different water contents at various temperatures. The dry density of specimens and strain rate was kept constant. Test results showed that compressive strength increased with increasing water content and decreasing temperature. The increase in peak strength became more significant the lower the temperature for a given water content. The failure mode changed from brittle to ductile deformation with increasing water content and decreasing temperature. Tests also showed an increase in deformation modulus with increasing peak strength, increasing water content and decreasing temperature.

Key words : frozen ground, clay, compressive strength, deformation

1. Introduction

In geotechnical engineering, the strength characteristics of frozen soils are one of the most important physical and mechanical properties. Soils are submit to significant changes in strength with freezing (Sellmann, 1989). The strength of frozen soils is governed by soil properties such as water content, degree of saturation, grain-size etc., and external conditions such as strain-rate and temperature (Zhang et al. 2007). There have been many investigations concerning the strength of frozen soils and the parameters influencing them. The dependence of strength on time and temperature has been reported from uniaxial compression tests on frozen sand and silt (Tsytovich, 1975; Akagawa et al. 1982; Bragg and Andersland, 1981; Jessberger, 1981; Zhu and Carbee, 1984; Zhu et al. 1988; and others). They found that compressive strength of frozen sand and silt increases with stress rate increasing and temperature decreasing. To date only few compression tests on frozen clay were conducted. Li et al. (2004) studied the strength behavior of frozen clay with different dry densities at various temperatures and strain rates. They reported an increase in compressive strength with decreasing temperature, increasing strain rate and increasing dry density.

This study intends to provide a better understanding of the water content and temperature dependent strength characteristics of frozen clay. Compressive strength tests were performed on clay with various water contents and temperatures at constant strain rate.

2. Experiment

2.1 Soil properties

The tested soil in this study was remolded clay from Primorsky Krai, Russia. The grain-size distribution curve is shown in Fig. 1. The clay had an optimum water content of 19.8% and maximum dry unit weight of 1.53g/cm^3. The specific gravity was 2.50 and the liquid and plastic limit was 59.8% and 32.1%, respectively. The soil was classified as CH under Unified Soil Classification System (USCS).

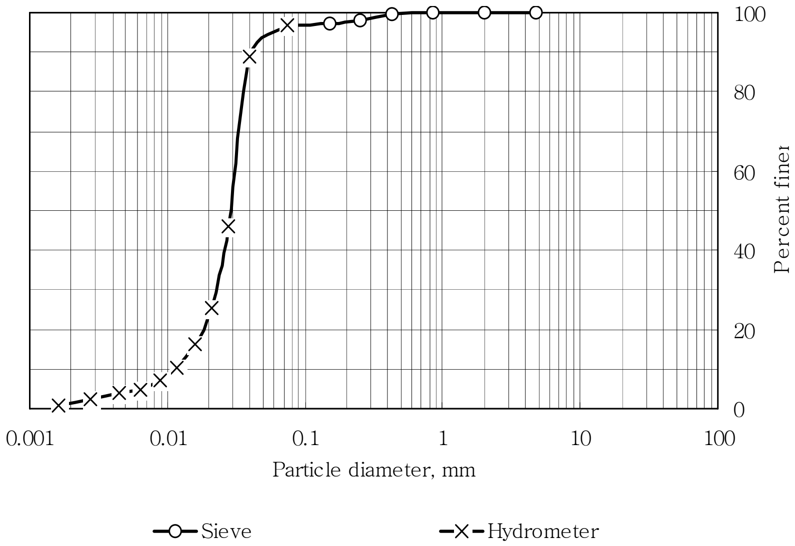


Figure 1. Grain-size distribution curve of Siberian clay

2.2 Specimen preparation

Pre-weighed quantities of oven dried clay were mixed thoroughly with distilled water to the anticipated water content by weight. The specimens were then prepared by compacting to the maximum dry density given for water contents tested in specially designed steel molds (Kim, 2003). Water contents, unit weights and specimen weights are summarized in Table 1. After specimen preparation the split molds were closed at the top and bottom and placed in the freezing chamber. After freezing the specimens were taken out from the molds.

w (%)	g_d (g/cm^3)	g_t (g/cm^3)	Volume (cm^3)	Weight (g)
15	1.51	1.74	196.25	341
19.8*	1.53	1.84	196.25	360
25	1.49	1.86	196.25	370
30	1.36	1.77	196.25	347

*optimum water content of tested clay

Table 1. Specimen parameters for mold preparation

2.3 Experimental methods

Compressive strength tests were performed in a walk-in freezing chamber. All specimens were set aside to temperate at least 24 hours before testing. In this experiment, the test temperatures were 0, -2, -5, -10, -15 and -20°C (±0.2°C temperature range within the specimens). The strain rate was set constant to 1mm/min. Compressive strength was tested on specimens with a dimension of 50mm in diameter and 100mm in height (D/H ratio of 0.5).

3. Test Results

Compressive stress-strain curves for typical specimens at various water contents and temperatures are shown in Fig. 2. Test results and conditions for all tests are listed in Table 2. Based on the stress-strain curves, the peak strength and time to failure of the specimens were determined. The deformation modulus E_{50} was calculated as the inclination of a straight line connecting the origin and the half value point of q on the stress-strain curve.

w (%)	T (°C)	q_{max} (kgf/cm^2)*	$T_{failure}$ (min)*	E_{50} (kgf/cm^2)*
15	0	0.947	3.667	0.344
15	-2	1.783	3.650	0.533
15	-5	4.584	2.242	3.291
15	-10	8.925	2.917	4.894
15	-15	11.536	2.258	6.635
15	-20	20.652	2.900	9.334
19.8**	0	0.886	3.667	0.367
19.8**	-2	3.692	7.083	0.904
19.8**	-5	11.777	3.808	5.152
19.8**	-10	15.534	6.617	4.045
19.8**	-15	20.117	6.577	5.803
19.8**	-20	23.428	7.100	5.840
25	0	1.008	10.000	0.252
25	-2	12.974	10.000	5.157
25	-5	20.588	10.000	5.913
25	-10	29.947	10.000	10.925
25	-15	39.661	10.000	13.342
25	-20	47.937	10.000	16.328
30	0	0.535	10.000	0.127
30	-2	7.478	10.000	2.374
30	-5	18.790	10.000	6.358
30	-10	29.414	10.000	15.367
30	-15	45.694	10.000	17.296
30	-20	52.039	10.000	24.737

* average value of three tests

** optimum water content

Table 2. Test results and conditions

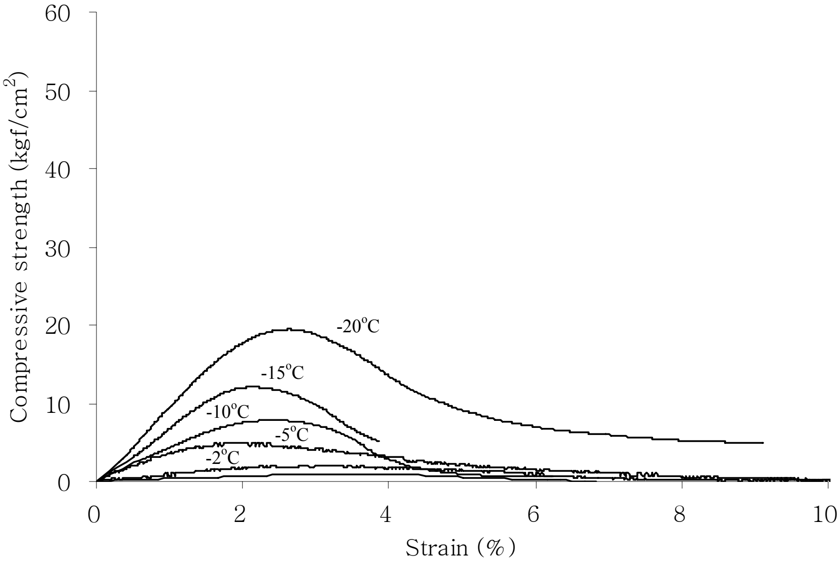


Figure 2a. Stress-strain curves for 15% water content at 0, -2, -5, -10, -15 and -20°C

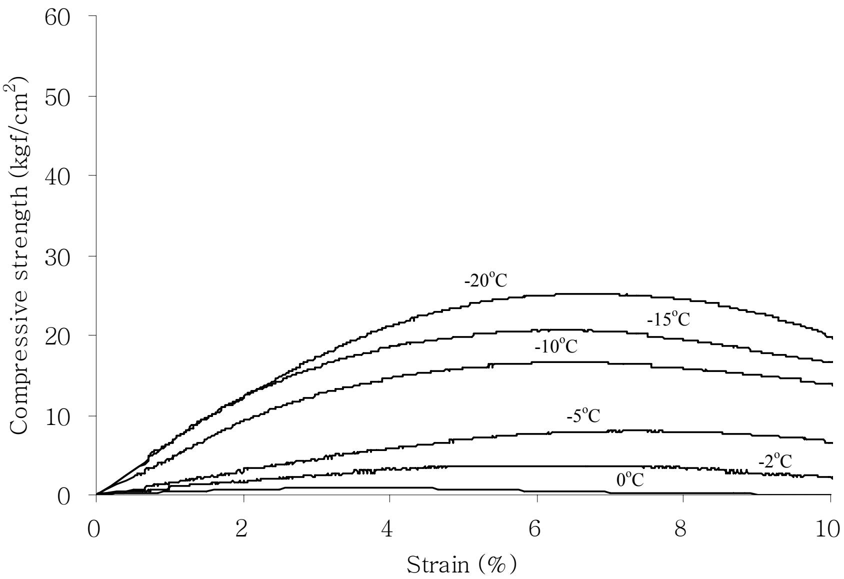


Figure 2b. Stress-strain curves for 19.8% water content at 0, -2, -5, -10, -15 and -20°C

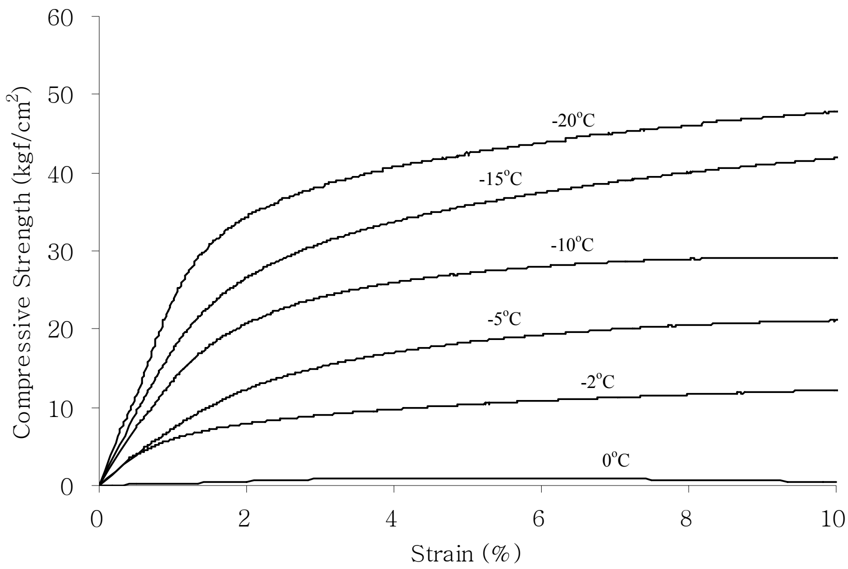


Figure 2c. Stress-strain curves for 25% water content at 0, -2, -5, -10, -15 and -20°C

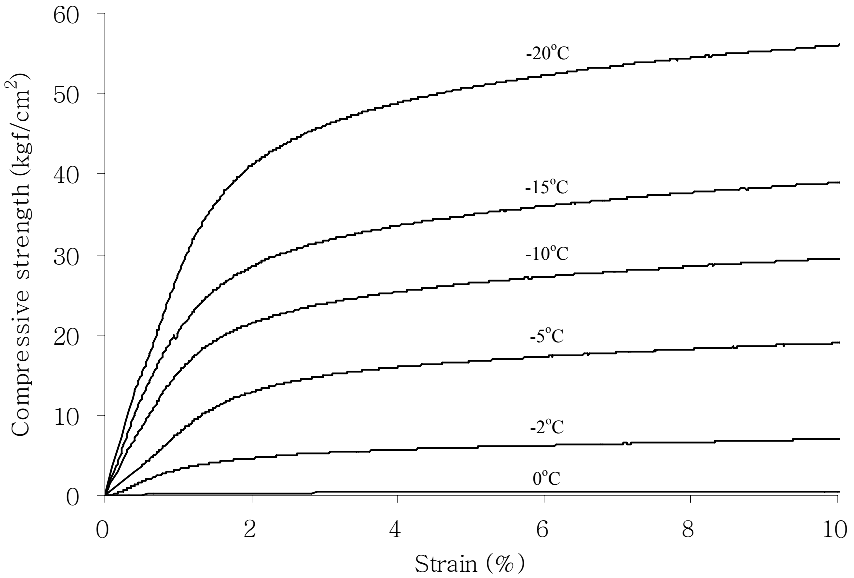


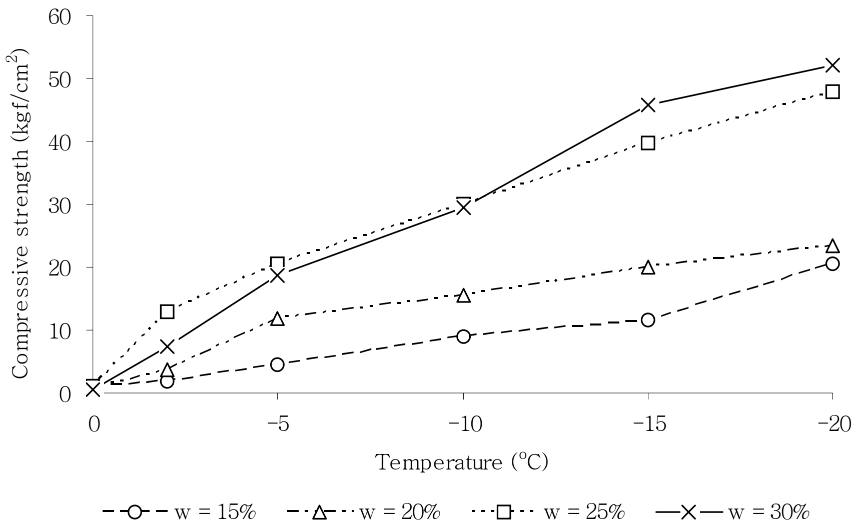
Figure 2d. Stress-strain curves for 30% water content at 0, -2, -5, -10, -15 and -20°C

4. Discussion

Test results showed that the stress-strain behavior of frozen clay was strongly dependent on the water content and temperature. Strength was significantly increased with decreasing temperature and increasing water content.

4.1 Temperature and water content vs. peak strength

The peak compressive strength as function of water content and temperatures is plotted in Fig. 3a and 3b. Tests results showed that the peak strength increases with increasing water content and decreasing temperature. The increase in peak strength becomes more predominant the lower the temperature for a given water content. Further, a higher peak strength was achieved for water contents on the wet side of the optimum.



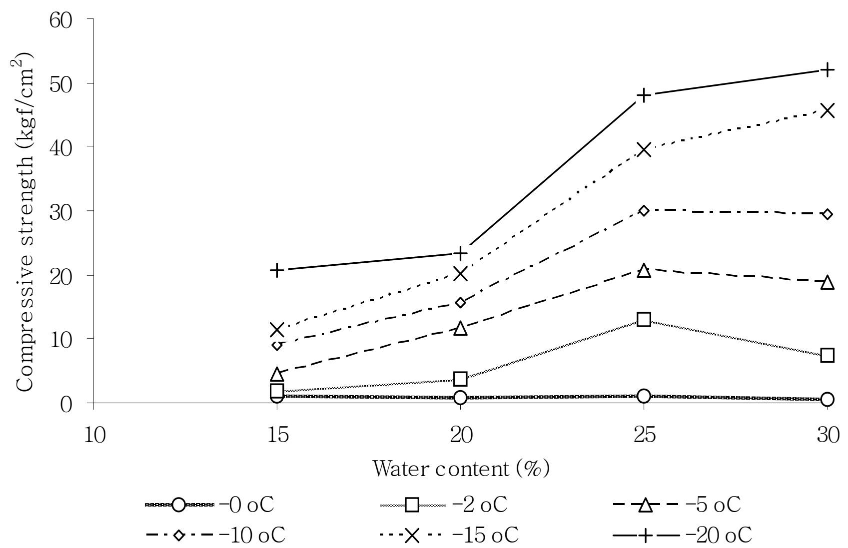
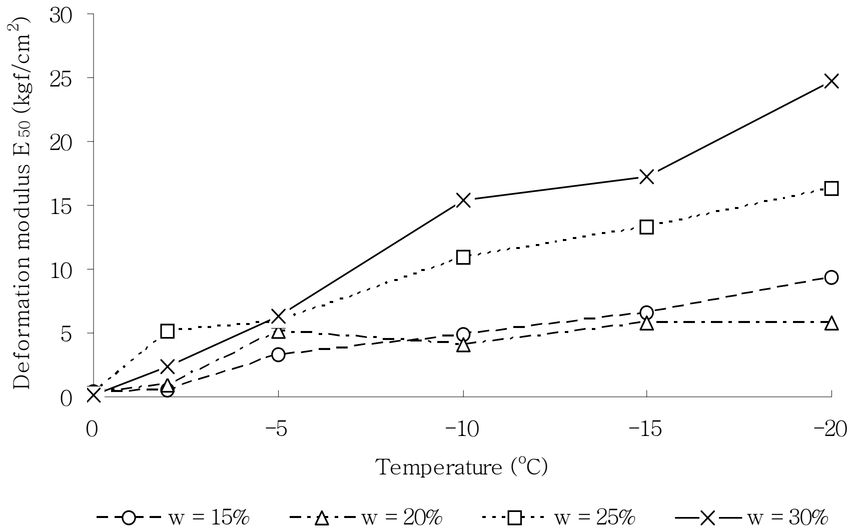


Figure 3. a) Temperature vs. peak strength and b) water content vs. peak strength for Siberian clay

4.2 Temperature and water content vs. deformation modulus

As with strength properties the deformation properties of the frozen clay might be influenced by the temperature and water content. The effect of temperature and water content on the deformation modulus are shown in Fig. 4a and 4b. E_{50} is increasing with decreasing temperature and increasing water content. A change from brittle to ductile deformation was observed by increasing the water content to the wet side of the optimum.



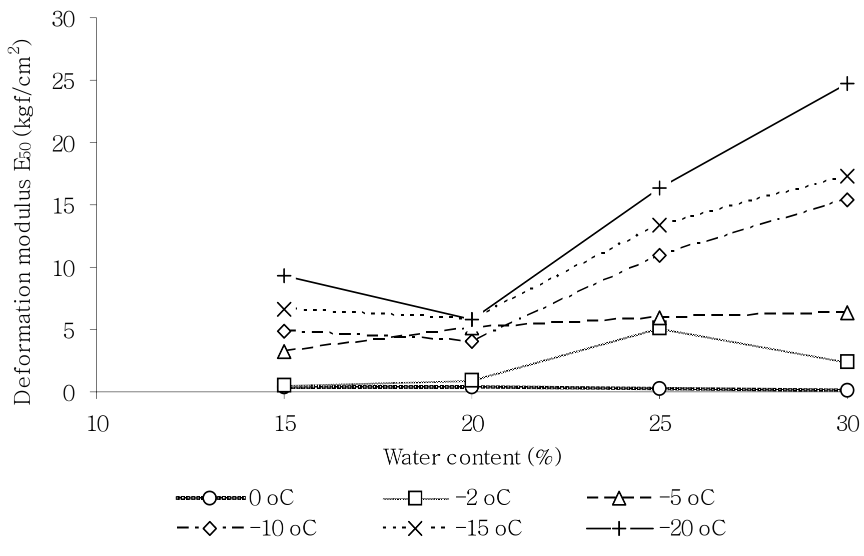


Figure 4. a) Temperature vs. deformation modulus and b) water content vs. deformation modulus for Siberian clay

5. Conclusion

Compressive strength tests were performed on frozen clay with different water contents at various temperatures. Test results showed that compressive strength increased with increasing water content and decreasing temperature. The increase peak compressive strength was more significant the lower the temperature for a given water content. A change in failure mode from brittle to ductile deformation was observed for water contents to the wet side of the optimum. Tests also showed an increase in deformation modulus with increasing peak strength, increasing water content and decreasing temperature.

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