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Strength properties of ice-rich frozen silty sands under uniaxial compression for a wide range of strain rates and moisture contents

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A R T I C L E I N F O

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A B S T R A C T

With the increase in engineering construction in ice-rich permafrost regions, the strength characteristics of ice-rich frozen soils have attracted the attention of researchers and engineers. However, few laboratory data address the uniaxial compressive strength of frozen soils for a wide range of strain rates and moisture contents. In the present study, a series of uniaxial compressive tests were conducted on ice-rich frozen silty sands using temperature conditions of −0.5, −1.0, −2.0, and −5.0 °C, moisture contents of 16.7–480.0%, and strain rates of 1.07×10^{-5} to 1.13×10^{-2} s^{-1}. The results show that brittle failure occurs easily in the ice-rich frozen silty sands, except for those with a moisture content of approximately 31.0%. When the moisture content is low, the strength increases nonlinearly with increasing strain rate. However, when the moisture content is high, a peak strength appears on the strength–strain rate curve. For strain rates less than 5.33×10^{-4} s^{-1}, as the moisture content increases, the strength first decreases from a maximum value at optimum dry density to a minimum value that is less than the ice strength. The strength then increases to the ice strength. For strain rates greater than 2.00×10^{-3} s^{-1}, as the moisture content increases, the strength first decreases to a minimum value, then increases to a maximum value, and finally decreases toward that the ice strength; the minimum strengths are not always less than the ice strength, and the maximum strengths are not also always greater than the strengths at the optimum dry densities.

1. Introduction

With the economic development in cold regions and the requirements of national infrastructure (for example, the Qinghai–Tibet Railway), more and more engineering activities are developing or will develop in permafrost and seasonally frozen regions. Monitoring data have shown that the moisture content in regions traversed by engineering projects varies widely (Wu et al., 2006), and the mechanical parameters differ between high and low moisture content conditions. Therefore, according to the distribution of moisture content *in site*, ice-rich frozen soil is defined as a soil with a volumetric ice content greater than 20% (Arenson et al., 2007; Ma et al., 2011). The general relationship between the uniaxial compression strength and moisture content was described by Shusherina and Bobkov (1978). The authors found that under fully saturated conditions and with increasing moisture content, the uniaxial compressive strength of frozen soils initially decreases to a minimum value less than the ice strength, remains constant (i.e., independent of moisture content), then increases gradually to the ice strength. The relationship varies with soil type, saturation degree, temperature, and other factors. Goughnour and Andersland (1968) showed that the uniaxial compressive strength of saturated sands decreases with an increase of moisture content, which is similar to the test results from Baker (1976, 1979), but Sayles and Carbee (1981) found that the uniaxial strength of frozen silts always increases with increasing volumetric ice content (from 30.0% to 60.0%). Through testing, Li et al. (2004) found that temperature and moisture content have significant influences on several fitting parameters in the relationship between strength and strain rate. Ma et al. (2008) also suggested that the uniaxial strength of ice-rich frozen clays changes with different moisture contents and temperatures. Yang et al. (2015) obtained certain strength properties of undisturbed samples with moisture contents ranging from 80.0% to 240.0%.

Many researchers have suggested that strain rate also has a large impact on the strength of frozen soils that have low moisture contents. Sayles (1966, 1968) and Sayles and Epanchin (1966) conducted uniaxial compressive tests on saturated frozen sands and found that compressive strength increases linearly with an increase in strain rate on a log–log scale, which is consistent with the results of Baker (1979) and Parameswaran (1980). Based on triaxial compression tests, similar conclusions were obtained by Sayles (1974), Parameswaran and Jones (1981), Baker et al. (1982), and Arenson et al. (2004). However, Perkins and Ruedrich (1973) observed that

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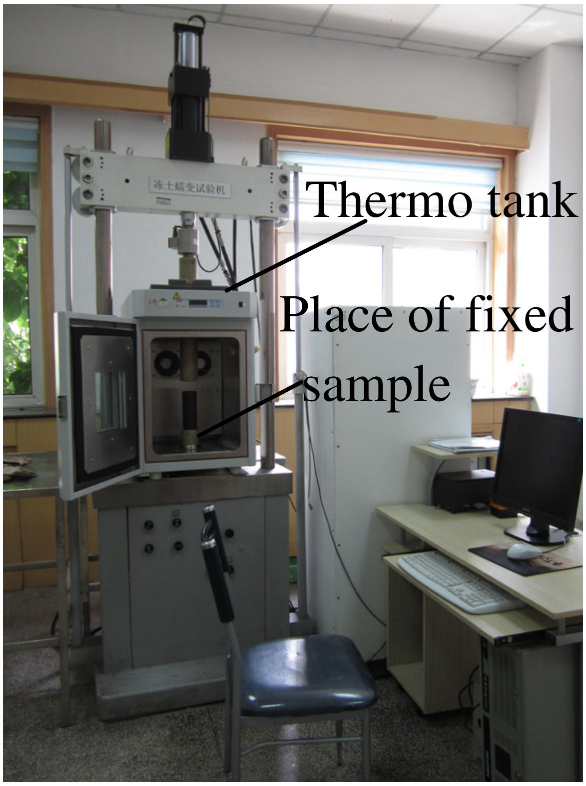

Fig. 1. Photograph of the uniaxial compression apparatus.

with increasing strain rates, the strength first increases before becoming independent of the strain rate above a strain rate threshold value of $3.0 \times 10^{-5}\ s^{-1}$ on a log–log scale. Eckardt (1978) and Parameswaran (1980) also found a similar tendency in the strain rate dependence. Other authors (e.g., Sayles and Epanchin, 1966; Sayles, 1974) did not propose the transition, which may be because the strain rates were greater than $10^{-4}\ s^{-1}$. Parameswaran (1980) wrote that the threshold value is sensitive to temperature, but did not carry the discussion further. Several linear relationships between strength and strain rate on a log–log scale were experimentally derived in the aforementioned investigations (Sayles, 1966, 1968; Sayles and Epanchin, 1966; Baker, 1979; Parameswaran, 1980; Sayles, 1974; Parameswaran and Jones, 1981; Baker et al., 1982), but in those studies, the effects of temperature and moisture content were not analyzed.

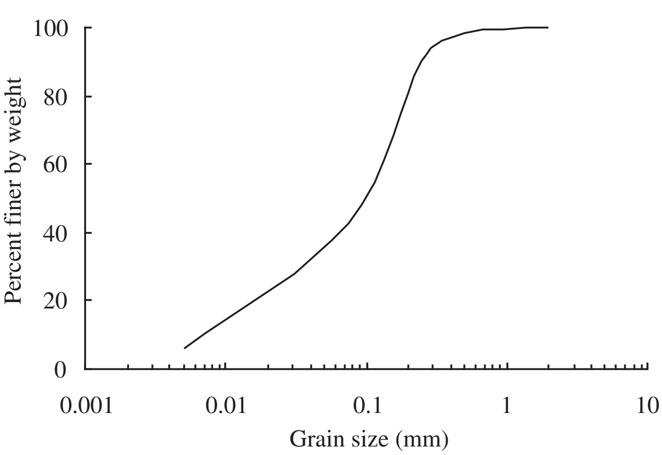

Fig. 2. Grain size distribution.

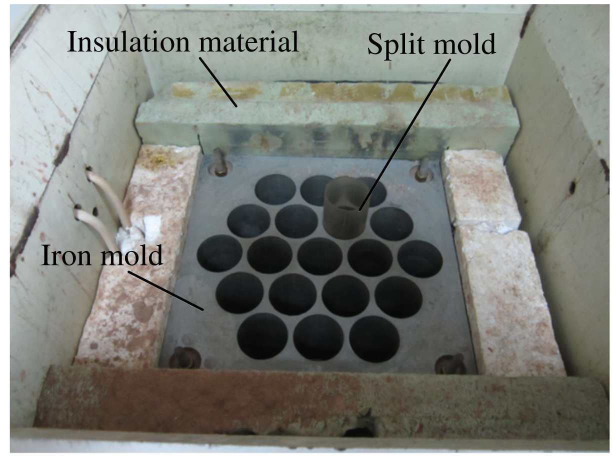

Fig. 3. Sample preparation equipment.

Table 1
Moisture contents and corresponding dry densities of the samples.

Moisture content (%)	16.7	24.0	41.5	82.0	108.0	140.0	220.0	480.0
Dry density ($g \cdot cm^{-3}$)	1.82	1.53	1.02	0.78	0.64	0.52	0.36	0.18

Although many investigations have been conducted regarding the influences of moisture/volumetric ice content and strain rate on the strength of frozen soils, differing test conditions have yielded differences in findings that are problematic if those results are used as references in engineering design. Thus, the objective of the work reported here is to systematically investigate the uniaxial compressive strength of remolded ice-rich frozen silty sands over a wide range of strain rates and moisture contents.

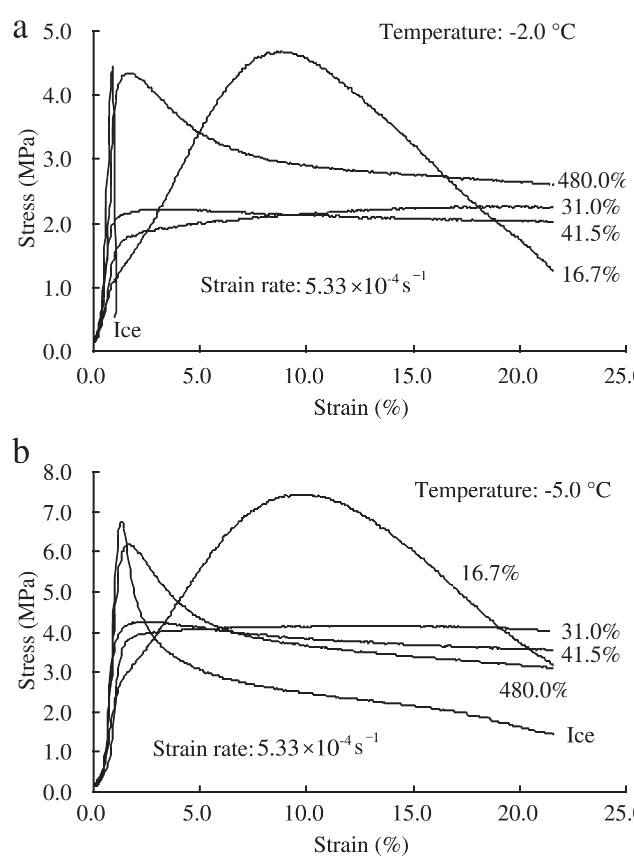

Fig. 4. Typical stress–strain curves.