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The effects of water content, temperature and loading rate on strength and failure process of frozen rocks

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ABSTRACT

The effects of water content, temperature and loading rate on the strength and failure process of rock at sub-zero temperatures were investigated and are presented in this paper. Over the range of temperatures studied there was little change observed in the properties of dry rock. The presence of water in the rock, however, resulted in a marked increase in rock strength and the fracture initiation stress. Rock strength increased with amount of water present and the rate of load application, with the effect being exacerbated at the colder temperatures. Interestingly, the changes in strength were not uniform as there was a greater rate of increase in the tensile strength of rock with temperature than compressive strength. It is postulated that these changes in mechanical properties may be explained in part by a reduction in the stress concentration within the interstitial spaces and cracks of the rock samples tested.

1. Introduction

In colder regions of the world where air temperatures regularly fall below zero degrees Celsius, the ground is often frozen. Diurnal as well as seasonal changes in temperature can lead to cyclic actions of freezing and thawing causing expansion and contraction which accelerates the weathering process of rocks close to surface. The magnitude of these changes varies with the depth below surface being dependent on the thermal inertia and thermal conductivity of the soil and rock mass. Moreover, in addition to gravity and hydrostatic stresses, these frozen rock slopes can be subjected to ground water pressure because the frozen zone acts as an impermeable layer [1].

In order to account for the instability that is sometimes observed in rock slopes with changes in the seasons, it is important to understand the impact of changes in temperature on the behavior and failure process of frozen rock. It is known that the mechanical behavior of ice varies with both temperature and loading rate [2,3]. When water is combined with rock at sub-zero temperature it is likely that the behaviors of rock might be similarly affected depending on the degree of water saturation.

Previous studies have confirmed that the level of deterioration in rock can be assessed based on changes in physical properties including weight loss, water content, dynamic Young's modulus and P-wave velocity [4–6]. In order to account for the often variability in behavior, Nakamura in his analysis used a stochastic based on probability theory [7]. Kodama et al. reported on observations made on the deterioration process using X-ray CT scans [8]. Based on these studies, an assessment of the durability or rock according to its physical properties has been proposed [4,8]. The reduction in rock strength has been estimated in terms of the number of cycles of freezing and thawing [9–11].

There have been many studies undertaken of frozen soil and sand [12–14], but only a limited number of studies involving uniaxial compression and indirect tensile tests involving frozen rocks. Inada et al. [15] and Matsunaga et al. [16] investigated changes in strength, Young's modulus and Poisson's ratio of frozen rocks within the temperature range of −180 °C to +20 °C as part of the stability assessment of an underground LNG storage facility. Kodama et al. [17] examined the relationship between changes in temperature with rock strength as well as some other physical properties including effective porosity, specific surface area and content rate of unfrozen water in the range of −30 °C to 0 °C. It was found that the strength of frozen rock varied inversely with temperature. Further there were more pronounced changes in tensile strength of rock than the compressive strength with temperature. However the extent of the deformation and the mechanism driving the failure process in frozen rocks were not well understood.

The stability of a rock slope is often based on monitoring changes in displacement and/or deformation [18,19]. An understanding of any

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changes in the deformation behavior and failure process that might occur when rock is frozen is therefore essential to assessment of rock slope stability in cold regions.

Many studies have reported on changes in strength and deformation with varying loading rate in non-frozen rock above 0 °C [20–23]. It has been argued that these changes are related to sub-critical crack growth such as stress corrosion cracking [21,23]. More recent studies on the effect of loading rate on the strength of sands containing methane hydrate have been reported [24,25]. There is little published data though concerning the loading rate dependency of frozen rocks.

The purpose of this study was to gain an understanding of the effects of temperature, loading rate and water content on the strength and failure process of frozen rocks. Both uniaxial compression tests and indirect tensile tests were carried out on two different rock types at different levels of water content, over a range of temperatures and loading rates. The effects of these changes are discussed in terms of changes in mechanical properties induced by the ice contained in the interstitial spaces of rock under ambient conditions for more than a minimum of two weeks prior to testing.

2. Experimental method

2.1. Rock specimens

Samples of Noboribetsu welded tuff and Soubetsu andesite were prepared for testing. Differences in the values of average porosity based on true and apparent specific gravities together with the water saturation level between the two rock types are shown in Table 1. The porosity of Noboribetsu welded tuff was found to be about four times that of Soubetsu andesite. The voids in the two rock types were observed to be different both in magnitude and shape. The Soubetsu andesite was found to have sharp cracks as illustrated in Fig. 1 which shows a micrograph thin section of both rocks. By contrast, most of the voids in Noboribetsu welded tuff were spherical and distributed around mineral particles and within the pumice.

P-wave velocity measurements in three orthogonal axes of the rock blocks were used to decide on the direction of core drilling in the block specimens. The test samples for the uniaxial compression tests were drilled in a direction parallel to the axis in which *P*-wave velocity was at a minimum. The 30 mm diameter cores were cut to lengths of 60 mm. The samples for the indirect tension tests were drilled in a direction in which the *P*-wave velocity was intermediate. In this case cores of 30 mm were used.

Slight differences in *P*-wave velocities were observed between the three blocks of Noboribetsu welded tuff used in the test program. They are referred to as Blocks A, B and C.

Three sets of test samples having different water content were prepared, these being defined as Specimens (a), (b) and (c) in Table 1. Specimen (a) were dry samples that had been air-dried

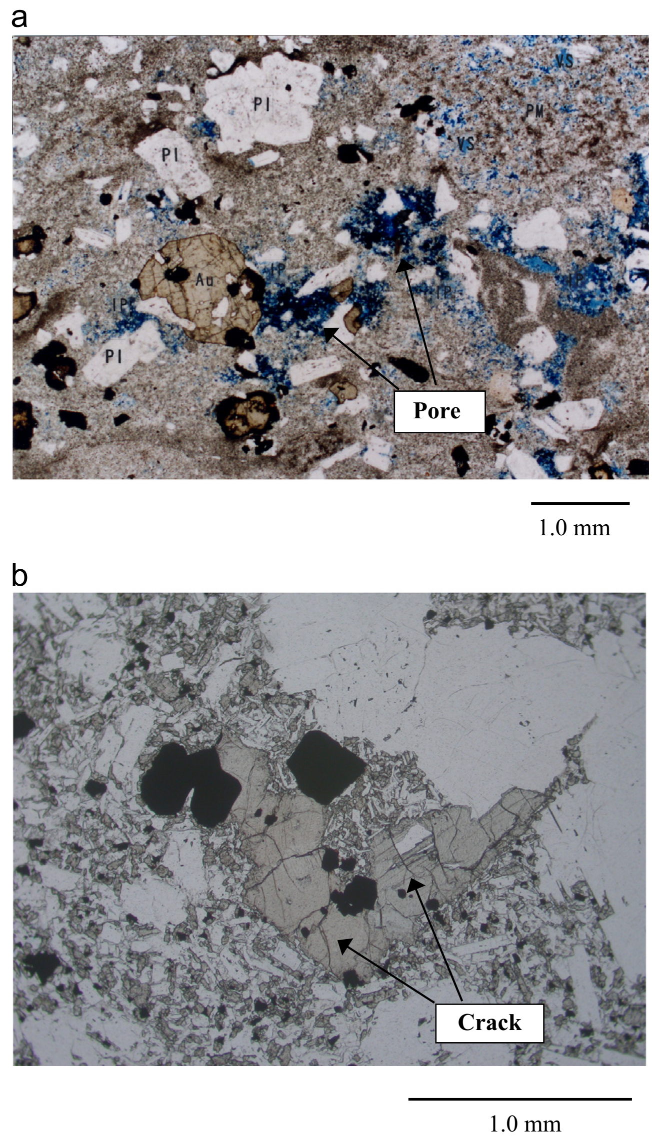

Fig. 1. Micrograph of used rocks sliced into thin section.(a) Noboribetsu welded tuff (b) Sobetsu andesite.

Table 1
Porosity, water content and water saturation ratio.

Rocks	Porosity (%)	Case	Water content (mass %)	Water content (vol %)	Water saturation ratio (%)
Noboribetsu welded tuff	24.1	(a)	0.30	0.54	2
		(b)	6.00	10.8	45
		(c)	12.0	21.6	90
Sobetsu Andesite	5.38	(a)	0.02	0.05	1
		(b)	0.80	2.06	38
		(c)	1.50	3.87	72

under ambient conditions for more than a minimum of two weeks prior to testing. Specimens (c) were saturated samples that had been submerged in pure water for a minimum of two weeks. The third set of test samples, Specimen (b), was partially saturated having been submerged in pure water for a much shorter duration. The three Specimens (a), (b) and (c) were referred to as dry, partially saturated (or partially wet) and saturated (or wet) samples respectively.

Two kinds of water content were determined for each of the three specimens using:

$$w_m = \frac{m_w - m_d}{m_d} \times 100 \quad (1)$$

$$w_v = \frac{m_w - m_d}{\rho_w V_d} \times 100 \quad (2)$$

where w_m and w_v are the water contents expressed on a mass and volume basis respectively; m_w and m_d are the weights of the specimen before and after drying; ρ_w is the density of water; V_d is the volume of the specimen; and the water saturation ratio is defined as the ratio of w_v to porosity.