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Degradation characteristics of shear strength of joints in three rock types due to cyclic freezing and thawing

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ABSTRACT

With massive engineering projects carried out in cold regions where freeze-thaw processes can affect the mechanical properties of rock material, the temporal variation of geotechnical stability is highly concerned. Three typical types of jointed rocks were selected to undergo a number of freeze-thaw cycles after which direct shear tests were conducted on samples of joints in the rock material. The degradation characteristics of the rock joints were examined by the changes of the shear parameters after increasing numbers of freeze-thaw cycles. The results show that the cohesion is more sensitive to cyclic freezing and thawing than the joint friction angle and that the influence on cohesion and joint friction angle is different between hard rocks and soft rocks. Based on the damage mechanics theory and the fact that the deterioration degree rises with increasing numbers of freeze-thaw cycles, the damage state variable was redefined to develop an exponential decay model of freeze-thaw cycles. The comparison of the fitting curves obtained by the proposed model with the experimental results shows that the model reasonably well reflects the degradation characteristics of the shear strength under cyclic freezing and thawing. The model can thus be used to predict the tendency of geotechnical strength degradation of rock masses in cold regions.

1. Introduction

For engineering projects in cold regions, it is of great importance to understand the influence of freeze-thaw cycles on the degradation of rock mass mechanical performance. Numerous authors have already published about the freeze-thaw damage issue of rock masses and its consequences for the safe construction and operation of projects (Weeks, 1969; Hutchinson, 1974; Li et al., 2014). The freeze- thaw damage is usually ascribed to the thermal expansion-contraction and frost-volume expansion forces caused by the volume increase of the pore water in the rock material and the rock joints when freezing to ice (Franssen and Spiers, 1990; Hori and Morihiro, 1998). It involves thermo-hydro-mechanical (THM) field coupling and ice-to-water phase changes (Neaupane et al., 1999; Kang et al., 2013).

The earlier freeze-thaw studies of intact rock samples mainly focus on the physical-mechanical properties and failure characteristics of rock material under cyclic freeze-thaw action. These studies show that temperature, presence of water, rock type, and number of freeze-thaw cycles play a role (Yamabe and Neaupane, 2001; Nicholson et al., 2000; Chen et al., 2004; Takarli et al., 2008; Matsuoka, 1990), and that the rock deterioration is caused by the formation of micro-cracks and the extension of existing cracks (Remy et al., 1994).

To describe the mechanical behavior affected by discontinuities, damage mechanics is a proper method (Kawamoto et al., 1988), and many constitutive models and damage equations have been established (Mazars, 1982; Loland, 1980; Frantziskonis and Desai, 1987). Afterwards, the method was applied in freeze-thaw damage field to search for the evolution of mechanical damage and strain softening (Lai et al., 2009; Tan et al., 2011; Liu et al., 2015). As for the mechanical property and damage model of jointed rock, some studies on the samples with pre-existing cracks have been made (Li et al., 2003; Lu et al., 2014; Li et al., 2013). However, limited work has been done on the degradation of primary joint in rock, which is usually very important to the stability of rock engineering.

The main objective of this work was to investigate the degradation characteristics of shear strength of rock joints due to cyclic freezing and thawing. A series of direct shear tests were carried out on rock joints in three typical rock types to determine the changes of cohesion and joint friction angle. Moreover, a damage evolution model was proposed

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to describe the relations between the shear parameters and the number of cycles, and then extrapolated the damage evolution. In addition, two degradation modes were proposed to distinguish between the degradation behavior of soft and hard rocks.

2. Direct shear tests

2.1. Apparatus

The equipment used for the direct shear tests is a portable shear box developed by our laboratory (Su, 2008), which can test samples with irregular form such as rock joints by corresponding pretreatment. It is composed of an upper and a lower shear box, normal and shear load systems and gauges. Before direct shear tests, the irregular samples need to be casted in the two parts of shear boxes by concrete to get a standard form, and a gap of approximately 1 cm is left between the upper and lower concrete casts, in such way that the rock joint to be tested is aligned in the middle of the gap (Fig. 1).

2.2. Test samples and sample preparation

Three typical rock types: granite (hard rock), sandstone (medium-hard rock), and phyllite (soft rock) were selected for the cyclic freeze-thaw tests. The joint samples of these rock types were collected by cutting them from their outcrops of which the weathering degree is weak, and were then wrapped in tape to avoid them falling to pieces during transport. 60 Cubical samples (20 samples for each rock type) of approximately 9 cm × 9 cm × 9 cm in size were collected.

Before the cyclic freeze-thaw tests, these samples were water-saturated. To achieve water-saturation, the samples were dried in an oven (at a temperature of 105 °C) for 48 h, until they reached a constant weight, and were then water-saturated. In order to avoid the influence of pore gas pressure, each sample was immersed first for a quarter of its volume, then half, and then for three quarters in water for two hours. Finally, all samples were immersed in water completely for 48 h. The amount of water increase due to suction was calculated. Physical properties of the three rock types are listed in Table 1.

2.3. Cyclic freeze-thaw test

The 20 samples of each rock type were divided into four groups, with approximately 5 samples in each group. Freeze-thaw tests were then conducted on these groups for 0, 15, 30 and 50 freeze-thaw cycles.

Table 1
Physical properties of the three rock types.

Sample	Dry density(g/cm^3)	Porosity(%)	Water absorption(%)
Granite	2.59	0.82	0.32
Sandstone	2.55	2.71	1.06
Phyllite	2.76	1.21	0.44

These freeze-thaw cycles were carried out as follows: (1) The water-saturated samples were put into a thermostatic freezer at −30 °C for 4 h; (2) The samples were then taken out and immersed in water at room temperature to thaw for 4 h; (3) Step 1 and 2 were repeated. Each freeze-thaw cycle had a duration of 8 h in total, which possibly represents the freeze-thaw weathering process for one year in a cold region.

2.4. Shear test program

All samples, after having undergone different numbers of freeze-thaw cycles, were casted in concrete in a standard block form of 15 cm × 15 cm × 15 cm (Fig. 2). The rock joint was aligned in the middle of the gap reserved between the two parts of the concrete casts. The direct shear tests were then conducted along the joint to determine its shear strength.

During the shear test of the five sample groups, the stress normal to the shear plane was maintained at a fixed value of 0.4 MPa, 0.8 MPa, 1.2 MPa, 1.6 MPa and 2.0 MPa respectively. The shear stress was increased progressively. When the value of the shear stress (monitored on the pressure gauge) no longer increased or even decreased, we assumed that the sample had failed in shear (Fig. 3(a)). Each test took about 5–10 min. Finally, we recorded the values of normal and shear stress and measured the area of the sheared plane. In addition, several typical joint samples were selected after they had failed to measure their profiles by a stylus sensing system (Tan et al., 2014), and the calculated joint roughness coefficients (JRC) values are shown in Fig. 3(b), (c) and (d).

3. Direct shear test results of rock joints

3.1. Normal stress-shear stress relation

After test data processing, the peak shear stresses and normal stresses act on the joints of each rock type after different numbers of freeze-thaw cycles were shown in Table 2, and the scatter diagrams

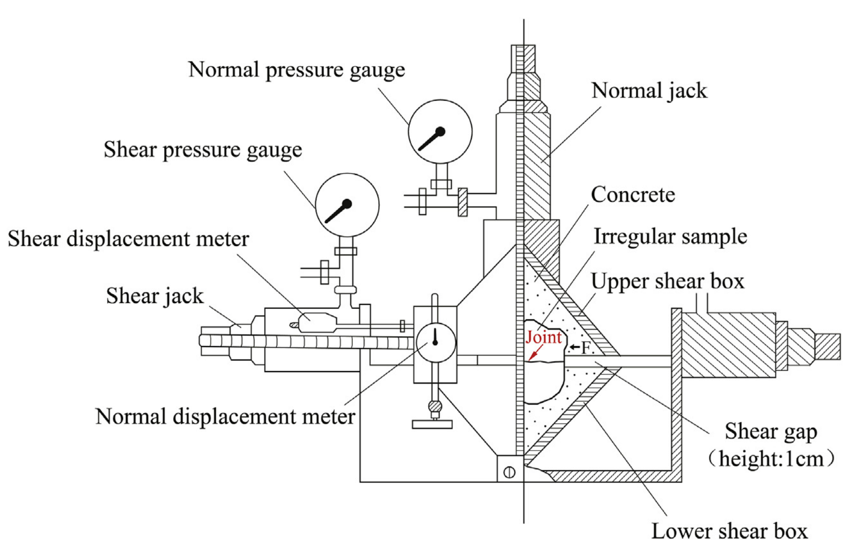

Fig. 1. Shear box used to test the structural planes.