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A prediction model for the dynamic mechanical degradation of sedimentary rock after a long-term freeze-thaw weathering: Considering the strain-rate effect

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A B S T R A C T

Rock engineering and stone construction in cold region are always suffering the recurrent freeze-thaw (F-T), and rock mechanical behaviors in projects usually involve responses to stress pulses or impact loads due to the widely existed blasting operation, mechanized construction and seismic oscillation. In this work, physical tests as well as static and impact mechanical experiments were carried out on red-sandstone free from and after F-T weathering. Totally five specimen groups were prepared for static and dynamic compressive tests respectively, of which one group was water-saturated and free from F-T, and four groups were water-saturated and then respectively suffered by 5, 10, 15, 25 cycles of artificial F-T. Changes of physico-mechanical properties of red-sandstone after F-T cycles, including density, porosity, P-wave velocity, uniaxial compressive strength (UCS) and deformation modulus (E_d), illustrated the F-T induced damages of sedimentary rock. For a better predicting of the dynamic mechanical degradation of sedimentary rock after a long-term F-T weathering, decay models of mechanical properties reflecting the strain rate effects were built. The UCS and E_d were adopted as the integrity indexes of rock in the decay model, and the model parameters, decay constant (λ) and half-life ($N_{1/2}$) were expressed as functions of strain rate.

1. Introduction

Exposed to the earth's water and atmosphere, rocks are always suffering various kinds of weathering. Cycling freeze-thaw (F-T) is a common and serious rock weathering factor in cold region (Yatsu, 1988), where the environment temperature floats up and down the freezing point of water. F-T induced deterioration of rock is crucial concern during the preliminary design, project construction and maintenance stages of cold region geotechnical works (Shen, 2004; Zhang, et al., 2004; Lai, et al., 2012).

F-T weathering has long been discussed as a major physical deterioration process. F-T induced changes of physical and mechanical properties of various rocks have been investigated (Nicholson, et al., 2000; Ruedrich, et al., 2011; Tan, et al., 2011), including density, porosity, P-wave velocity, point load strength, uniaxial compressive strength (UCS), etc. The frequent freezing and thawing of pore water inside rock expands the cracks and pores and promotes the development of new micro-fractures (Park, et al., 2015) and thus does great damage to rock engineering (Sousa, et al., 2005). Despite the extensive use of accelerated weathering tests in durability assessments (Altindag, et al., 2004; Benavente, et al., 2004; Akin and Ozsan, 2011; Tan, et al., 2011), it's insufficient to evaluate the long-term durability of rocks. As a result, many decay models (Mutlutürk, et al., 2004; Fatih, 2012; Liu, et al., 2015) were built by scholars to analyze the durability of rocks suffered a long-term weathering. Mutlutürk, et al. (2004) proposed a decay model that uses the decay constant (λ) and half-life ($N_{1/2}$) parameters to express the disintegration rate of rock. This decay model fitted the test results well and was much more concise, and was adopted widely (Jamshidi, et al., 2013; Khanlari, et al., 2015). However, almost no decay models take the strain rate effect into consideration and predict the dynamic mechanical degradation of rocks after a long-term freeze-thaw weathering.

In fact, because of the extensively existed blasting operation, mechanized construction as well as seismic oscillation, rock engineering disasters often involve rock responses to stress pulses or impact loads, and the corresponding prevention and cure researches come down to the analyses on dynamic mechanical properties of rock-like materials (Li and Gu, 1994; Zhang and Zhao, 2014). Stain rate is a key factor to the mechanical properties of rock-like materials, which could change the strength and deformation characteristics substantially. Rock behaviors under different strain rate varied a lot and these differences are enough to change the rock responses to loads or weathering environments. Due to the rate sensitivity, dynamic mechanical behaviors of rocks after F-T weathering differ from those presented under static

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loading conditions. Literature reviews show that investigations about the F-T weathering are concentrated on physical and static mechanical properties (Yavuz, et al., 2006; Ghobadi and Babazadeh, 2015), only a few works have been published about the dynamic mechanical behaviors of F-T weathered rock. Wen et al. (2015) obtained the relationship between the dynamic strength and the freeze-thaw cycles according to the results of numerical simulations and experiments. Zhou, et al. (2015) obtained the microscopic damage characteristics and dynamic mechanical parameters of sandstone after freeze-thaw from the nuclear magnetic resonance (NMR) tests and impact loading tests. Investigations about the effects of F-T cycles on the rock dynamic mechanical properties during the weathering process are far from enough.

Sedimentary rock distributes extensively in the superficial lithosphere, of which the distribution area is the main provider of minerals and the main place of human beings for engineering geological and hydrogeological works. Due partly to the mineral composition and porous structure, sedimentary rock is generally more affected by F-T weathering. For a deeper understanding of F-T effects on the static and dynamic mechanical properties, predicting the dynamic mechanical degradation of sedimentary rock after a long-term freeze-thaw weathering, static and dynamic compressive experiments on red-sandstone, a common sedimentary rock, free from and after cycling F-T were carried out in this work. Totally five groups of specimens were prepared for static compression and dynamic impact tests respectively, of which one group was water-saturated and free from F-T weathering, while the other four groups were water-saturated and then respectively suffered 5, 10, 15, 25 artificial F-T cycles. Impact loading tests were carried out using the split Hopkinson pressure bar (SHPB) system (Xia and Yao, 2015), with the impact condition set at five strain rate grades. Decay models of dynamic mechanical properties reflecting the strain rate effects were built, and the model parameters were identified based on experimental results. Influences of strain rate on the model parameters were analyzed.

2. Material and methods

2.1. Red-sandstone specimen preparation

Red-sandstone in this work was quarried from the underground construction field in the Hengduan Mountains, located at the southeastern corner of the Qinghai-Tibet plateau in China. It is a typical kind of sedimentary rock, with a uniform red surface. With the determination environment set at 25 °C and 40% humidity, X-ray diffraction analysis was carried out to determine the mineral composition of red-sandstone samples, as listed in Table 1.

Red-sandstone was made into standard cylinder specimens, Φ96 × 48 mm, for dynamic impact compression tests. Attention was paid to prepare red-sandstone samples which were free from visible defects and flaws, and ultrasonic detection was performed during the selection to minimize differences between specimens used in tests.

2.2. Accelerated F-T weathering

Followed the boiling water saturation method, as introduced in the DL/T 5368-2007 (National Development and Reform Commission of the People's Republic of China, 2007), red-sandstone specimens were water-saturated before the F-T weathering tests. Artificial F-T weathering tests were carried out using an automatic cycling F-T machine (Fig. 1), with the temperature control program set as Fig. 1: a 4-h freezing period after the test chamber temperature reaching the preset value (−20 °C), followed by a 4-h thawing period during which the specimens were immersed in water at 20 °C. These were considered as one F-T cycle. In this work, four experimental groups were carried out with the F-T cyclic number set as 5, 10, 15, 25 respectively, and one control group was designed with the specimens saturated and free from F-T weathering. Since Newton's Law of Heating and Cooling applied to those F-T cycles, the temperature changes followed almost the same path during each cycle (see Fig. 1) for cycling F-T tests (Mutlutürk, et al., 2004).

Table 1
Mineral composition of red-sandstone in this paper.

Composition	Quartz	Plagioclase feldspar	Potash feldspar	Calcite	Chlorite	Illite	Hematite
Content/%	81	10	3	3	1	1	1

Except for a short time for the nondestructive physical determination, red-sandstone specimens were kept in water at 20 °C after F-T weathering tests, till surface-wiped for the loading tests. The whole mechanical experiments were carried out also at room temperature (20 °C).

2.3. Index property determination

F-T weathering involves disintegration in index properties of rocks. Therefore, comparison between index properties measured before and after F-T tests can be used to quantify the weathering degree. In this study, F-T weathering effects on index properties were investigated by measuring the block density, porosity, P-wave velocity and static UCS of fresh and deteriorated rocks.

2.3.1. Bulk density and porosity

Determination of bulk density, as the ratio of the saturated mass to bulk volume, was applied on red-sandstone samples before and after F-T weathering.

The total porosity and effective porosity of red-sandstone samples were determined using buoyancy techniques, as recommended by ISRM (1981). The total porosity and effective porosity calculation are as follows:

$$\phi = \frac{M_{sat} - M_{dry}}{M_{sat} - M_w} \times 100\%; \quad \phi_e = \frac{M_{wet} - M_{dry}}{M_{sat} - M_w} \times 100\% \tag{1}$$

where ϕ signifies total porosity, i.e., the ratio of total pore volume to bulk sample volume; ϕ_e, named effective porosity, indicates the volume ratio of opened voids to the entire rock sample; M_{sat} is the saturated-surface-wiped mass of specimen saturated through boiling water saturation method; M_{dry} is the mass of specimens completely dried; M_{wet} is the wet-surface-wiped mass of specimen after 48-h of unforced water absorption; M_w is the saturated-submerged weight measured with the saturated red-sandstone specimen immersed in water. Meanwhile, it should be pointed out that, the "degree of saturation (Sr)" (Brown, 1981) of saturated specimen prepared as the method in this paper was supposed to be 100%, which was theoretically hard to reach completely.

Porosity characteristics of red-sandstone samples were determined before artificial F-T. For experimental groups after F-T, reserved specimens which suffered F-T weathering but free from destructive loading tests were set aside to determinate the porosity properties again with the same methods as above-mentioned.

2.3.2. Ultrasonic inspection

Ultrasonic longitudinal wave testing was applied on the samples prior to and after F-T weathering. The direct method proposed by Kahraman (2002) was adopted and a nonmetal supersonic test meter with two transducers of 50 kHz was used to detect the P-wave velocity of red-sandstones. To improve the sample-header contact, vaseline was distributed on the interface as the ultrasonic coupling fluid.

2.3.3. Static compressive tests

Static uniaxial compressive tests were done by hydraulic servo material testing system, with the loading rate set at 0.16–0.18 MPa/s