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# A statistical model for predicting the triaxial compressive strength of transversely isotropic rocks subjected to freeze–thaw cycling

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## ABSTRACT

Freeze–thaw damage to rock masses is one of the most significant durability problems in many regions worldwide. This study conducts triaxial compression tests to experimentally investigate the strength properties of freeze–thawed core samples of Carboniferous slates with bedding angles of 30°, 45°, 60°, and 75° under different confining pressures. The triaxial compressive strength decreases as the number of freeze–thaw cycles increases, continuously increases with increasing confining pressure, and initially decreases and then increases as the bedding angle increases from 30° to 75°. Additionally, to satisfy the requirements of engineering projects in cold regions, a statistical model is proposed to predict the triaxial compressive strength of freeze–thawed transversely isotropic rocks based on the single discontinuity theory. In this model, the cohesive strength and angle of internal friction of the discontinuity are assumed to be functions of the number of freeze–thaw cycles. The validity and accuracy of this model are verified by comparing the results of the proposed model with those of the experiments. It is found that the model can correctly describe the influences of the number of freeze–thaw cycles, confining pressure, and bedding plane orientation on the triaxial compressive strength of freeze–thawed transversely isotropic rocks.

## 1. Introduction

Freeze–thaw cycling, a phenomenon in which a material undergoes alternating freezing and thawing because of variations in the external environmental temperature around the freezing point, most commonly occurs in cold regions at high altitudes (Chen et al., 2004; Yu et al., 2015; Yang et al., 2016). The strength properties of rock deteriorate significantly due to the recurrent freezing and thawing processes, which may lead to serious disasters in construction projects (e.g., Zhang et al., 2004; Grossi et al., 2007). In addition, the strength properties of transversely isotropic rock depend on the confining pressure and orientation of the bedding planes (Singh et al., 2015). It is essential that the influences of the number of freeze–thaw cycles, confining pressure, and bedding plane orientation on the triaxial compressive strength of transversely isotropic rocks are investigated. Therefore, statistical prediction models, which are used to describe the strength properties of transversely isotropic rocks subjected to freeze–thaw cycling, must be constructed to improve rock engineering design techniques and the safety of rock engineering projects.

Considerable efforts has been made by various researchers to investigate the influence of freeze–thaw cycling on the mechanical properties of rocks (Altindag et al., 2004; Yang et al., 2010; Yavuz, 2011; Bayram, 2012; Cárdenes et al., 2012; Jamshidi et al., 2013; Khanlari et al., 2015; Liu et al., 2015; Ismail and Mustafa, 2016; Jamshidi et al., 2016; Wang et al., 2016). Altindag et al. (2004) conducted uniaxial compression tests, Brazilian splitting tests, and point load tests on freeze–thaw influenced ignimbrite, and reported the influence of freeze–thaw cycling on the mechanical properties of ignimbrite. Tan et al. (2011) investigated the effect of freeze–thaw cycling on the mechanical properties of biotite granite using uniaxial and triaxial compression tests. They found that the elastic modulus, compressive strength and cohesive strength decayed exponentially with the number of freeze–thaw cycles. Bayram (2012) developed a statistical model to estimate the reduction in the uniaxial compressive strength of limestones after freeze–thaw cycling. Ismail and Mustafa (2016) experimentally investigated various rock index properties, including the dry

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**Table 1**
Basic physical properties of the Carboniferous slates.

| Rock | Dry density (g/cm$^3$) | Natural water content (%) | Saturation water absorption (%) | Porosity (%) |
|---|---|---|---|---|
| Carboniferous slate | 2.59 | 0.47 | 1.76 | 3.46 |

density, ultrasonic velocity, point load strength, and slake–durability test indexes, after freeze–thaw cycles and proposed a statistical model. Wang et al. (2016) investigated the physical properties of sandstone specimens, including the density, porosity, P–wave velocity, uniaxial compressive strength, and deformation modulus, subjected to freeze–thaw cycling. In addition, a corresponding prediction model of mechanical degradation was developed. Most studies have focused on experiments and prediction models for isotropic rocks, and anisotropic rocks have seldom been studied.

Anisotropic rocks, especially transversely isotropic rocks, are frequently encountered in underground engineering, and their mechanical properties exhibit inherently anisotropic and directional dependency. The mechanical behaviors of transversely isotropic rocks have been extensively studied by various researchers, and some corresponding models have been developed in detail (e.g., Jaeger, 1960; Tien and Kuo, 2001; Tien et al., 2006; Lee and Pietruszczak, 2008; Saeidi et al., 2014; Asadi and Bagheripour, 2015; Singh et al., 2015; Tan et al., 2015). The single discontinuity theory proposed by Jaeger (1960), which considers sliding failure along the discontinuity through the intact material, has been widely applied to predict the strength behavior of transversely isotropic rocks. Jaeger's theory was further developed, modified and validated by researchers through many laboratory and in situ observations. However, little attention has been paid to the development of prediction models of transversely isotropic rocks to study strength deterioration induced by freeze–thaw cycling. This research gap was the motivation for the research outlined below. Due to the naturally weak planes that exist in transversely isotropic rocks, the strength deterioration induced by freeze–thaw cycling could be much more serious and complicated, thereby requiring special attention and investigation.

A series of experiments was conducted in this study to examine the influences of the number of freeze–thaw cycles, confining pressure, and bedding plane orientation on the triaxial compressive strength of Carboniferous slate specimens. Based on the experimental results, a statistical model was developed to predict the triaxial compressive strength of transversely isotropic rocks subjected to freeze–thaw cycling.

## 2. Experimental procedures and results

### 2.1. Experimental material and procedure

The Carboniferous slate material used in this study was cored at the Guanjiao tunnel of the Xining–Geermu Railway in China. Several large rock chunks were first obtained at the project location, and the intact rock was cut using special machines to avoid any damages to the rock. Then, the rock chunks were firmly clamped onto the tilting pedestal of a drilling machine at different orientations of apparent bedding to facilitate coring at specific orientations. Cylindrical specimens with diameters of 50 mm and heights of 100 mm were obtained by boring, cutting, and polishing the slate chunks according to the suggested methods and standard requirements of ISRM (ISRM, 2007). The ends of each specimen were ground to within 0.05 mm of flat and parallel to each other. The deviations in the diameters and heights of the specimens were < 0.3 mm, and the vertical deviation was < 0.25°. Thirty-two samples were prepared for each bedding orientation (30°, 45°, 60°, and 75°); in total, 128 samples were prepared. The physical properties of the Carboniferous slates were determined and are listed in Table 1.

The samples were tested under different conditions, including various numbers of freeze–thaw cycles, confining pressures, and bedding plane orientations, and the detailed procedures of testing and conditioning are illustrated in Fig. 1. The number of applied freeze–thaw cycles was 0, 10, 20, or 30 cycles. For each number of applied

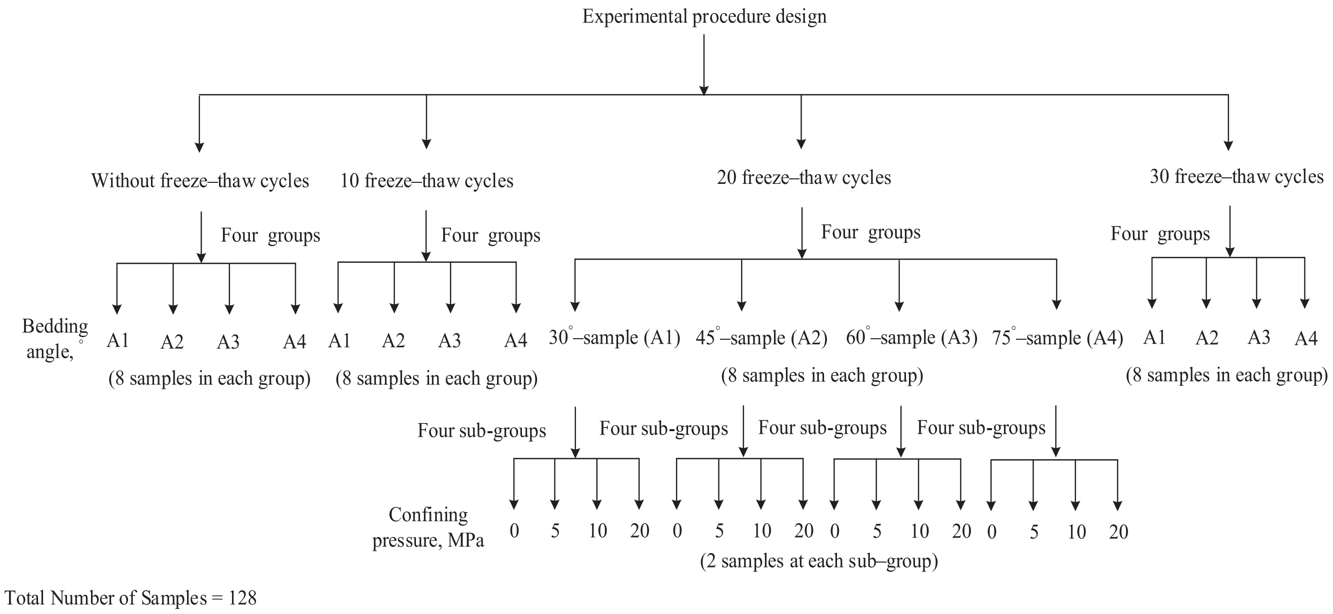

**Fig. 1.** Scheme of the testing procedure.