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The impact of environmental temperature change on the interior temperature of quasi-sandstone in cold region: Experiment and numerical simulation

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ABSTRACT

The purpose of this study was to simulate the internal temperature (*T*) change behavior of rocks as environmental *T* passes through the freezing point, 0 °C, in cold region. These data are important to determine the overall heat transfer rules of rock bodies during freeze-thaw cycles. First, a series of indoor experiments were carried out to measure the interior *T* changes of quasi-sandstone specimens when environmental *T*s were cycled from 20 °C to − 20 °C. The results of these tests show that interior T curves exhibit a typical 'three-period' change during the freezing or thawing process, in particular incorporating a clear slowdown period around environmental *T* that range between 0 °C and − 4 °C. Second, using these data, we established an apparent heat capacity model (AHCM) based on heat transfer theory. This model was then embedded into the COMSOL program to simulate change rules of the interior *T* field. Moreover, latent heat linked to phase change was also considered based on three common correlation formulas that relate unfrozen water content and phase *T*. These comparisons indicate that simulated results based on a previously proposed empirical expression seemed to fit best with experimental results. Finally, five groups of symmetric and asymmetric environmental *T*s were selected respectively in order to discuss the influence of these environmental variables on the interior *T* changes of rock samples. We therefore generalize that these three parameters are the key factors influencing the duration of the freezing period.

1. Introduction

Heat transport within the earth's near-surface bedrock is a common phenomenon in permafrost and seasonal periglacial region zone (Kurylyk et al., 2014). Atmospheric temperature, which is always subject to cycling above and below the 0 °C isotherm in cold regions, will cause the temperature (*T*) fluctuations in subsurface rocks due to the heat transport phenomenon. Moreover, expansion during cooling and contraction during the warming of bedrock usually happens as a result of *T* changes because of the special frost heave and thaw settlement of water-filled pores (Murton et al., 2006). In certain cases, frost heaving or contraction-related pressure in saturated pores leads to frost cracking and weathering of the bedrock, and can induce serious geodisasters such as debris flows, rock collapses, solifluction, and landslides affecting engineering projects in cold regions (Thomachot et al., 2005; Wu et al., 2008; Kawamura and Miura, 2014; Luo et al., 2015). Heave and settlement damage to bedrock are likely to become more common with the increasing numbers of infrastructure construction projects being undertaken or planned in cold regions. It should be notable that the inherent *T* fluctuation cycling from above and below 0 °C is a primary factor to cause the volumetric expand or contract of bedrock (Wang et al., 2016, 2017). At the same time, the inherent *T* distribution of bedrock is very important to seek the proper physical and mechanical properties, and apply to the engineering design scheme. However, it is difficult to investigate the accurate *T* distributions of bedrock during temperature change directly because the bedrock is usually too hard to insert the thermal probes into the interior body. Theoretical models and numerical calculations have therefore become the two common methods to evaluate *T* distributions of the shallow and deep subsurface bedrock in cold regions.

Over recent decades, researchers have developed amount of heat transport theories to determine the *T* distribution characteristics of the

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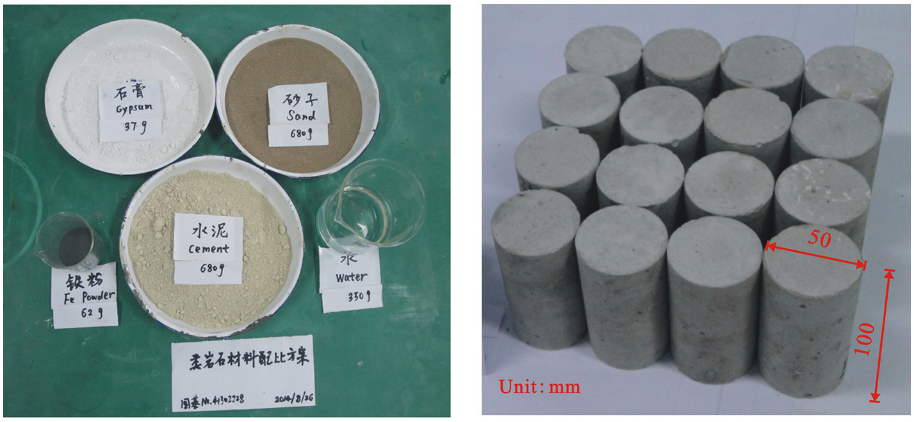

(a)

(b)

Fig. 1. Basic materials of quasi-sandstone and rock-like specimen products.

porous medium in the ground such as soil and bedrocks. Some simplified mathematical models of heat transport laws in freezing soils were initiated by Williams (1967), and Lunardini (1981) based on the Fourier's heat conduction theories. Walder and Hallet (1985) presented a systematic mathematical model for the porous rock by the growth of ice within cracks, which was founded upon well-established heat transport principles and recent advances in freezing soil physics. But all these above-mentioned models assumed that the significant latent heat does not occur during the water-ice phase transition. In fact, the release or absorption of latent heat during the pore-water phase changes can dominate the heat transport of the subsurface soil or bedrock (Kay et al., 1981; Huang et al., 2018), so some modified models of freezing soils and rocks that taking the latent heat of water during phase changes into account were proposed by Williams and Smith (1989), Lunardini (1991), Exadaktylos (2006), and Hasler et al. (2011).

However, most analytical solutions that are subject to the heat conduction and phase change theories represent just one- or two-dimensional forms because of the limitations of complicated calculation processes and numerous unknown variables. The numerical simulation method is therefore a better tool to study the *T* fields of soils and bedrocks in cold regions given significant improvements in computer technology since the 1980s (Flerchinger and Saxton, 1989; White and Oostrom, 2000). Newman and Wilson (1997) presented the heat transfer model SoilCover to analysis the effects of phase changes and ice formation, which were successfully reappeared the *T* and moisture content results as the freezing tests by Jame and Norum (1980). Similarly, Tan et al. (2011) established a numerical model considering heat transfer with ice-water phase change to calculate the *T* field in porous media based on the “three-zone” analytic solutions presented by Lunardini (1985), while Scherler et al. (2014) introduced a numerical model named the Coup Model to simulate permafrost *T*s observed from a borehole at the Murtel rock glacier in the Swiss Alps in the period ranging from 1997 to 2008. The numerical simulation method provides a good choice to observe directly the interior *T*s change rules of bedrocks suffered from the environmental *T* fluctuations for cold region geo-engineering applications.

Besides, some attempts to measure the in-situ *T* fields of surrounding rocks or bedrocks associated with the external *T* changes in permafrost and seasonal frozen zone have been done in some thermal-transfer governed engineering projects. Cha et al. (2007) monitored the inherent *T* changes by the thermometers installed around the distance from the surface of the LNG pilot storage during freeze-thaw processes, while Hou et al. (2015) analyzed the thermal variations of the embankment during the cooling process based on in-situ observational implementations from the Qinghai-Tibet Railway in Beiluhe. These indoor laboratory experiments have focused on the interior *T* changes of rocks with respect to the environment condition cycling with above and below 0 °C and have not been well-studied to date. Research in this area is important in order to directly acquire interior *T* changes characteristics of rocks during the freeze and thaw cycle and provide proper input parameters to the frost-susceptible bedrocks for the long-term safety in cold and high altitude regions.

The main objective of this work is to evaluate the visible *T* change behavior of saturated quasi-sandstone specimens as environmental *T* passes the freezing point. Additionally, a coupled thermal numerical model that apparent heat capacity model (AHCM) is used to compare measured tests considering the latent heat of the water-ice phase change. Some possible reasons for these slight deviations are also discussed to gain an enhanced understanding of the heat conduction process. Furthermore, these key factors influencing the duration of the freezing period for rock samples are discussed by means of the comparisons of symmetric environmental *T*s and asymmetric environmental *T*s. The results and conclusions of this research will be of benefit to understanding rock interior *T*s rules and their background reasons under freeze-thaw environmental condition in cold regions.

2. Laboratory tests

2.1. Quasi-sandstone specimen preparation

Because it is almost impossible to layout numerous *T* sensors at predetermined orientations and situations into the interior body of brittle rock specimens, our model experiments are based on the dimensional similarity method. Thus, in this experiment, basic materials such as sand, cement, iron powder, gypsum, and water were selected as a mix combination for targeted mid-grain sandstones from the surrounding rock of one coal mineshaft in Shaanxi Province. Aggregates were used in fine sands sieved via a pulp classifier to a size < 1.25 mm. At the same time, a sulfoaluminate high-strength cement mixed with some gypsums was chosen as a bonding material, and iron powders were added to improve the thermal conductivity effect of specimens (Fig. 1a); the number of matching tests were compared to determine the closest similar physical and mechanical parameters for rock-like modeling specimens to the original sandstone. Finally, the appropriate ratio of sand, cement, gypsum, iron powder, and water was determined to be 0.45:1.0:0.1:0.1:0.55; using a specialized molding fixture, the products of this rock-like mixture were then manufactured (Fig. 1b). The height and diameter of specimens were 100 mm and 50 mm, respectively, while detailed comparisons, test processes, and mixture matching procedure are as described in our previous paper (Shen et al., 2016).

We carried out a series of comparative tests to verify similar effects between model specimens and sandstone samples, comprising measurements of water-saturated density, acoustic velocity, characteristics of thermal conductivity, and uniaxial compressive strength (Table 1). It