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Experimental investigations on the thermal conductivity characteristics of Beishan granitic rocks for China's HLW disposal

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ABSTRACT

Crystalline rocks are potential host rock types for the construction of high-level radioactive waste (HLW) repositories. A better understanding of thermal conductivity of rocks is essential to safe evaluation and engineering optimization of a HLW disposal system in the rock at depth. In the present study, experimental investigations on the thermal conductivity characteristics of 47 pairs of granitic rock specimens were conducted using the Transient Plane Source (TPS) method. The specimens were collected from borehole cores in the Beishan area, which is being considered as the most potential candidate area for China's HLW repository. To evaluate geological nature of the rocks, mineralogical compositions of the rocks were identified, and porosity of the specimens was measured. The thermal conductivities of the specimens under dry and water-saturated conditions were determined, and the effect of water saturation on the thermal conductivity was investigated. In addition, the influence of temperature and axial compression stress on the thermal conductivity of dry specimens was studied. The results revealed that the thermal conductivity of tested rocks was dependent on water saturation, temperature and compression stress. Based on the obtained data, some models considering porosity were established for describing the thermal conductivity characteristics of the tested rocks. Furthermore, when the rocks have a similar porosity, the quartz content dominates the thermal conductivity, and there exists an obvious increase of the thermal conductivity with increasing quartz content. The test results constitute the first systematic measurements on the Beishan granitic rocks and can further be used for the development of thermal models for predicting thermal response near the underground excavations for HLW disposal.

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1. Introduction

Deep geological disposal has been the internationally accepted approach for the permanent disposal of high level radioactive waste (HLW) generated from nuclear power plants and other nuclear facilities. An HLW repository can be constructed in a host rock at a depth of several hundred meters below the ground surface. The design of HLW repositories often relies on a multi-barrier system, which typically consists of the natural geological barrier and an engineered barrier system. As the last defense to the biosphere, the natural geological barrier (i.e., the host rock) plays a critical role in ensuring the long-term safety of the HLW repositories. Because crystalline rocks such as granite and diorite have low permeability, high solidity, and good excavation stability, they have been considered as potential HLW repository formations in some countries (Hudson et al., 2011; Wang, 2014). Site selection for China's HLW repository started in 1985 (Wang, 2010). The efforts have been focused on potential HLW repository sites located within granite intrusions in mainland China. Since 1999, the Beijing Research Institute of Uranium Geology (BRIUG) has performed site characterization studies in the Beishan area, China. So far, the Beishan area has been considered as the most potential candidate area for China's HLW repository.

Among all the engineering properties of crystalline rocks at a potential HLW repository site, the thermal conductivity is one of the most important parameters in design consideration because it has a direct impact on the evaluation of the necessary repository volume and the optimization of the repository layout (Sundberg and Hellström, 2009). For instance, in the Swedish KBS-3 concept for geological disposal of spent fuel, copper canisters with cast iron inserts containing the spent fuel are surrounded by bentonite for isolation and mechanical protection (Brantberger et al., 2006). The heat generated by the spent fuel will increase the temperature of all components of the repository. For the bentonite buffer outside the canisters, the peak temperature must not exceed 100 °C. This requirement implies that the canisters cannot be deposited arbitrarily close to each other. On the other hand, unnecessarily large distances between the canisters will mean inefficient and costly use of the repository rock volume (Hökmark et al., 2009). To fulfill the temperature requirement, the rocks with low thermal conductivities will

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lead to a larger distance between canisters than for a case with high thermal conductivities. This is because the rocks with low thermal conductivities will give rise to higher temperatures in the bentonite (Sundberg et al., 2008). Hence, to design and construct repositories successfully, it is essential to perform an accurate assessment of the thermal conductivity characteristics of the host rock.

Over the past few decades, various experimental approaches have been employed to measure the thermal conductivity of rocks. The results indicate that the thermal conductivity of rocks is closely associated with mineral composition, porosity, texture, and density, etc. (Birch and Clark, 1940; Clauser and Huenges, 1995; Hartmann et al., 2005; Özkahraman et al., 2004; Pasquale et al., 2015; Ray et al., 2007; Sundberg et al., 2009). For crystalline rocks with relatively homogeneous texture and low porosity, the mineral composition dominates the thermal conductivity. In volcanic and sedimentary rocks, the high variability of porosity in these rocks is a major factor controlling the thermal conductivity (Clauser and Huenges, 1995; Özkahraman et al., 2004). For example, increasing porosity, which acts as barrier to the flow of heat, often results in both lower P-wave velocity and lower thermal conductivity values (Özkahraman et al., 2004). For a given rock, water content and temperature have an influence on its thermal conductivity. Generally, the thermal conductivity of the rock increases and decreases with increasing water content (Cho and Kwon, 2010; Cho et al., 2009) and temperature (Abdulagatova et al., 2009; Birch and Clark, 1940; Heuze, 1983; Miao et al., 2014; Mottaghy et al., 2008; Vosteen and Schellschmidt, 2003), respectively. Moreover, the effect of water saturation on the thermal conductivity of rocks shows a generally increasing trend with increasing porosity (Nagaraju and Roy, 2014). Given that the thermal conductivity of surrounding rocks around the excavations will be changed by the excavation-induced stress, some researchers studied the influence of pressure on the thermal conductivity of rocks (Abdulagatova et al., 2010; Abdulagatova et al., 2009; Demırcı et al., 2004; Görgülü et al., 2008; Sibbitt, 1976; Walsh and Decker, 1966; Zimmerman, 1989). One of the main findings achieved from these investigations shows that the thermal conductivity varies with the pressure exerted on the rock. With increasing applied pressure, the thermal conductivity starts to increase and subsequently the increase rate tends to be a constant value due to gradual closure of cracks and pores within the rock (Görgülü et al., 2008; Walsh and Decker, 1966).

While the above-mentioned studies provide meaningful insight into the thermal conductivity of various rocks, the thermal conductivity characteristics of low-porosity crystalline rocks subjected to different external factors such as water saturation, temperature and compression stress have not been fully understood. On the other hand, the information on the thermal conductivity of rocks in a potential HLW repository site must be known with sufficient confidence to provide necessary input conditions for its long-term safety assessment, which is one of the motivations for this study. In this work, experimental investigations on the thermal conductivity of the Beishan granitic rocks are conducted using the Transient Plane Source (TPS) method. In the following discussion, rock sampling and basic physical properties of the rock specimens are introduced first. Testing facilities and procedures are then described. Subsequently, the water saturation, temperature and compression stress dependent thermal conductivity characteristics of the tested rocks are evaluated comprehensively, and finally some insights are obtained.

2. Rock sampling and preparation

The Beishan area is situated in Gansu Province of northwestern China (see Fig. 1). After a long geological evolution and weathering process, the topography of this area is characterized by a flat Gobi and small gentle rolling hills with elevations ranging between 1400 and 2000 m above the sea level. The crust in this area possesses a blocky structure with many granite intrusions (see Fig. 2). Other surrounding rocks include mainly metamorphic and sedimentary rocks, as well as Quaternary cover. Rock sampling was carried out in the Jijicao and Xinchang rock blocks, which are currently considered as two of the key investigation sub-areas during site selection and characterization.

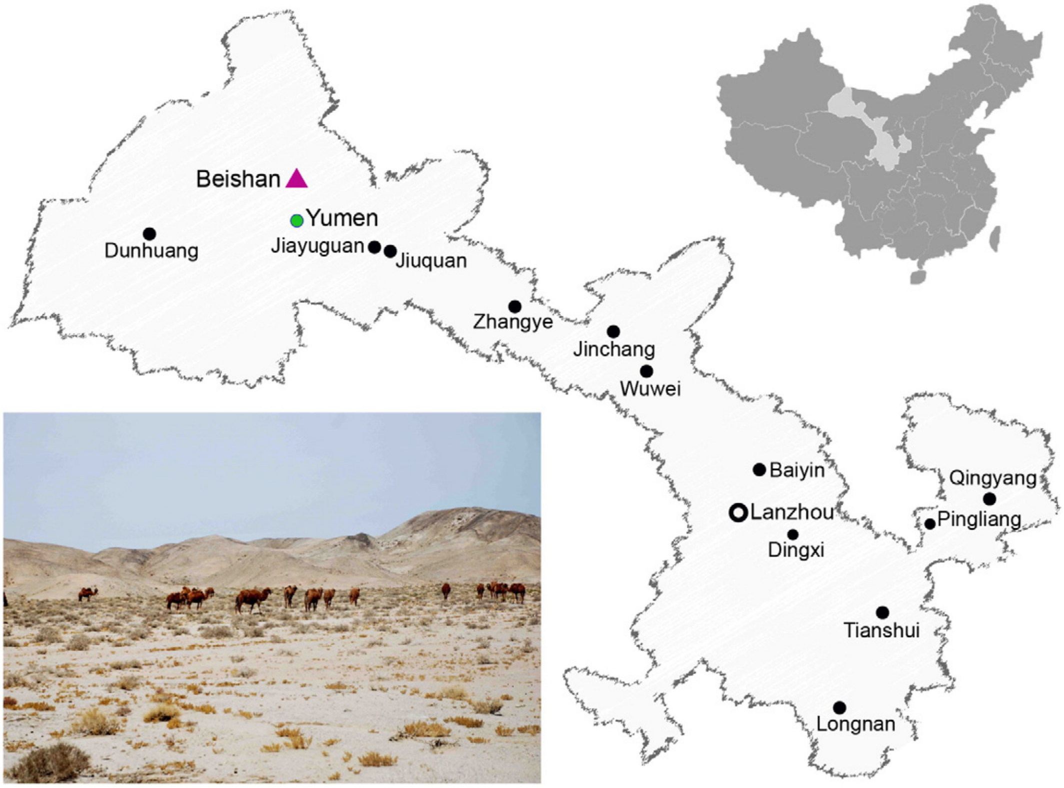

Fig. 1. Geographical location of the Beishan area and a photo showing its typical topography.

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