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Research Paper

Pore characteristics and mechanical properties of sandstone under the influence of temperature

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HIGHLIGHTS

- 400 °C is a threshold temperature of the sandstone in our research.
- 0.01 μm and 3 μm are two threshold diameters.
- Explain the macroscopic properties based on the mineral transformation.

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ABSTRACT

This paper experimentally studies the variation of pore characteristics and mechanical properties of sandstone at different temperatures (from 25 °C to 600 °C). The results show that the sandstone samples mainly have holes with diameters between 0.7 μm and 3 μm and at threshold diameters of 0.01 μm and 3 μm, the cumulative pore volume changes drastically. The threshold temperature of sandstone is 400 °C. If the temperature is lower than 400 °C, the elastic modulus reduces quickly, while the pore characteristics and other mechanical properties change slightly. Between 400 °C and 600 °C, the cumulative pore volume and porosity increase rapidly, while the fractal dimension of pore volume decreases drastically. In this case, the porosity increases by about 234%; the peak strength decreases by 31.1% and the peak strain rises rapidly by 83.3%. The Poisson's ratio decreases drastically at 500 °C. The difference in crack expanding speed at the temperature below or above 400 °C, and the inflation and the decomposition of minerals such as kaolinite and quartz are the main reasons for the variation of relevant parameters. This research is of great significance for studying the changes of physical and mechanical properties of rock after heating treatment.

1. Introduction

In recent years, the exploitation of underground resources, development and utilization of geothermal energy and underground space, deep burying of high radioactive waste of underground engineering, geotechnical post-disaster reconstruction of cities and the absorption of greenhouse gas [1] have become the international hot spots. Under certain conditions, such as fire, explosion and intrusion of magma and geothermal water, rock will be affected by high temperature and its properties will change. This makes the physical and mechanical properties of rock become an issue to be solved [2,3].

In the past, many researchers studied the influence of temperature caused by events such as fire and heating which mainly focused on chemical and mineral changes of materials [4–7]. However, physical properties should also be studied for engineering purposes. The transfer of heat from the surface to the interior of material is a complex process, and the interactions between structural, mechanical, and thermal properties have been actively studied theoretically and numerically [8–11]. In recent years, some researchers have studied the variations of relevant parameters of rock exposed to high temperature, including the porosity [12–15], compressive strength [16], elastic modulus, wave velocity [17–19], cracks [20,21], acoustic emission [22,23] and resistivity [24–27]. The geometrical characteristics of thermal cracks and

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pores in rock are the main parameter which has a significant impact on many rock properties [28]. The changes of density, longitudinal wave velocity and peak strength of sandstone in the range of 25–800 °C have been studied [29]. Wu et al. analyzed the apparent morphology, peak stress, peak strain, elastic modulus, Poisson's ratio, changes of the complete stress-strain curve, etc., and made a preliminary discussion on the degradation mechanism of sandstone at high temperature [30]. Sandstone exposed to high temperature in the range of 100–900 °C was studied regarding the pattern of variation of the average wave velocity, compressive strength, modulus, deformation modulus and ultimate strain with temperature [31]. Other researchers studied the compressive strength of sandstone, and found that the mutational points at which the compressive strength changes drastically were at 400 °C [32], 250 °C, 300 °C [33], 200 °C, 500 °C, 600 °C [34], and 500 °C [35]. Ranjith et al. studied the strength and acoustic emission of sandstone after temperature treatment in the range of 25–900 °C [35]. Thermal analysis was also used to determine the rock's thermal properties and the transformation of minerals [36–38].

The mercury intrusion method [39–41], which has its unique advantages in the determination of pore characteristics, was mainly used in this paper to determine the pore characteristics, changes of porosity and fractal law. A uniaxial compression test was also carried out and the compressive strength, Poisson's ratio and Protodyakonov were analyzed. The results will provide theoretical basis and support for underground exploitation and the rock surrounding underground engineering involving fire and intrusion of magma.

2. Materials and method

2.1. Description of sandstone samples

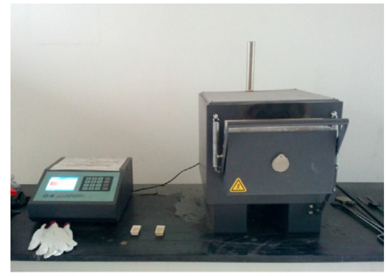
Sandstone, dark red in nature, was taken from Linyi, Shandong Province of China. Altogether 52 sandstone samples were taken and divided into 13 groups. They had uniform texture and were cut into normative $\Phi 50 \times 100$ mm cylinders. The permissible deviation of height is not greater than 5 mm and that of the diameter is less than 0.3 mm. The end faces with the maximum non-parallelism within 0.05 mm should be perpendicular to the specimen axis and the maximum deviation is within 0.25°.

2.2. Experimental instruments

Heating treatment was carried out in a CTM300A high-temperature furnace made by the Xuzhou Weike Technology Company, as shown in Fig. 1(a). Its main parameters are as follows: the temperature range is 1000 °C, the resolution is 1 °C, the precision of temperature control is 5 °C, and the furnace size is 200 mm × 130 mm × 300 mm (width × depth × height). The pore characteristics of the samples were tested using an AutoPore Ⅳ 9510 automatic mercury injection apparatus made by the Micromeritics Instrument Company of America, as shown in Fig. 1(b). The mechanical characteristics were observed using a WES-D1000 electro-hydraulic servo universal testing machine, as shown in Fig. 1(c).

2.3. Experimental procedure

Thirteen groups of sandstone samples were heated to thirteen levels of temperature, i.e. 25 °C, 100 °C, 150 °C, 200 °C, 250 °C, 300 °C, 350 °C, 400 °C, 450 °C, 500 °C, 530 °C, 570 °C and 600 °C, respectively. The heating process was divided into three stages:



(a) CTM300A high temperature furnace

(b) AutoPore Ⅳ 9510 automatic mercury injection apparatus

(c) WES-D1000 electro-hydraulic servo universal testing machine

Fig. 1. The main experimental instruments.

(1) For each group of sandstone samples, heat the rock samples at a rate of 5 °C/min until the target temperature was reached.
(2) When the target temperature is reached, stop heating and keep the temperature to be constant for two hours so as to also enable the sample's interior to reach the target temperature.
(3) The samples were cooled down to room temperature in the heating furnace at a rate of 0.5 °C/min to ensure that the internal and external parts had the same cooling rate, thus to reduce the influence of cooling on the sample's physical and mechanical properties.

Upon finishing the above, seal samples in plastic bags to conduct the mercury injection test and uniaxial compression test.

3. Experimental results and discussion

3.1. Variation in pores

3.1.1. Variation in cumulative pore volume

Mercury injection test was carried out to measure the porous characteristics, including porosity and other relevant parameters.