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Physical and mechanical properties of sandstone containing a single fissure after exposure to high temperatures

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ABSTRACT

In order to investigate the physical and mechanical properties of sandstone containing fissures after exposure to high temperatures, fissures with different angles α were prefabricated in the plate sandstone samples, and the processed samples were then heated at 5 different temperatures. Indoor uniaxial compression was conducted to analyze the change rules of physical properties of sandstone after exposure to high temperature, and the deformation, strength and failure characteristics of sandstone containing fissures. The results show that, with increasing temperature, the volume of sandstone increases gradually while the quality and density decrease gradually, and the color of sandstone remains basically unchanged while the brightness increases markedly when the temperature is higher than 585 °C; the peak strength of sandstone containing fissures first decreases then increases when the temperature is between 25 °C and 400 °C. The peak strain of sandstone containing fissures increases gradually while the average modulus decreases gradually with increasing temperature, and the mechanical properties of sandstone show obvious deterioration after 400 °C. The peak strain of sandstone containing fissures increases gradually while the average modulus decreases gradually with increasing temperature; with increasing angle α of the fissure, the evolution characteristics of the macro-mechanical parameters of sandstone are closely related to the their own mechanical properties. When the temperature is 800 °C, the correlation between the peak strength and average modulus of sandstone and the angle α of the fissure is obviously weakened. The failure modes of sandstone containing fissures after high temperature exposure are of three different kinds including: tensile crack failure, tensile and shear cracks mixed failure, and shear crack failure. Tensile and shear crack mixed failure occur mainly at low temperatures and small angles; tensile crack failure occurs at high temperatures and large angles.

1. Introduction

In projects like deep mineral mining, underground nuclear waste disposal, underground coal gasification, and exploitation of geothermal resources, the physical and mechanical properties of rock have a great influence on engineering safety when it is in a high-temperature environment. Thus, research on the physical and mechanical properties of rock at high temperature has become an active research field in rock mechanics [1–3]. Many scholars, at home and abroad, have conducted studies on rock properties at high temperature and produced many results. Su [4] processed gritstone with high porosity at high temperature to study the variation in wave velocity, compressive strength, average modulus, deformation modulus and limiting strain of sandstone at different temperatures through laboratory uniaxial compression tests; Bai [5] used XRD and SEM-EDX powder diffractometer to analyze the change in mineral matter elements in Yanzhou mining area from 1100 to 1500 °C using the FTIR method of analysis; Liu [6,7] utilized the SHPB experimental system to conduct dynamic experiments on sandstone samples at different temperatures to examine the evolution characteristics of the mechanical properties of rock under dynamic load at high temperature. Xu [8] analyzed the phase variation of granite from room temperature to 1300 °C, to examine the complete stress-strain curves of sandstone after exposure to different temperatures. Wu [9] processed sandstone samples from Jiaozuo at different temperatures (100–1200 °C) to analyze the change laws of the macro-mechanical parameters of sandstone after exposure to high temperatures and discussed the degradation mechanism of sandstone at high temperature through laboratory uniaxial compression tests. Su [10] conducted uniaxial compression tests on sandstone after exposure to six different high temperatures between 25 °C and 800 °C under different loading rates, to investigate the influence of temperature on the loading

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rate effect on rock. Chen [11,12] used a heat swelling power experimental system and a porosity test apparatus to study the changes in heat swelling power and the porosity of sandstone and limestone and their microstructure variation characteristics at different temperatures.

As a typical type of heterogeneous material, rock contains many original microscopic and macroscopic flaws such as fissures, voids, faults and weak surfaces, and the mechanical behavior of rock containing flaws is also one research topic in the field of rock mechanics. Yang [13–15] explored the mechanical properties of sandstone containing a single fissure, double fissures, and intermittent three fissures by prefabricating flaws in plate-shaped sandstone samples. Zhao [16,17] prefabricated regular fissures in samples made of rock-like materials and conducted uniaxial compression tests and double torsion tests to analyze the influence of the features of fissures on the strength of rock and the breakage law of a rock bridge. Zhao [18] conducted uniaxial compression tests on plate-shaped granite samples containing pre-existing holes in the center by adopting AE technology, revealing the spatial distribution of crack propagation and failure mechanism of the rock containing holes. Wang [19] utilized the real rock failure analysis system RFPA^{3D} to analyze the influence of holes with different physical dimensions and different spatial distribution on the failure modes and mechanical parameters of a Brazilian disc.

In a high temperature environment, flaws in the rock will increase due to thermal stress, which leads to degradation of the mechanical parameters to different extents. However, little research on the mechanical behavior of rock containing flaws after exposure to high temperature has been reported. Based on this lack of data, this paper describes uniaxial compression tests which were conducted on plate-shaped sandstone samples containing a pre-existing fissure. The samples were exposed to five temperatures ranging from 25 °C to 800 °C, in order to examine the variation in physical properties and the evolution law of the strength, deformation and the failure mechanism for the cracked sandstone after exposure to different high temperatures.

2. Test method

2.1. Sample processing

In the research described in this paper, sandstone, which is widely distributed in coal measures, was chosen as the experimental material. The sandstone has an average density of about 2.39 g/cm^3 in its natural state, and mainly consists of quartz, illite, feldspar and a small quantity of magnetite and hematite. The shape of all tested sandstone specimens was rectangular −160 mm in height, 80 mm in width and 30 mm in thickness through multiple processes such as cutting and polishing. By using a high pressure water-jet cutting machine, a single fissure 24 mm and an aperture thickness of about 1.5 mm was prefabricated in the central part of the intact sandstone sample. The test sample and the geometry of the pre-existing fissure are shown in Fig. 1a, in which α is the fissure angle (the angle between the fissure and the horizontal direction) and b is the fissure length. The samples were then exposed to high temperatures (25 °C, 200 °C, 400 °C, 600 °C and 800 °C) by using the GWD-02A high temperature oven. The heating rate was 5 °C/min until the set temperature level was achieved and this temperature was then maintained for 50 min to ensure that the samples were heated evenly. The samples were then naturally cooled to room temperature (25 °C) and used for the uniaxial compression tests. At each temperature, 2 or 3 intact sandstone samples and 5 kinds of flawed samples containing a pre-existing single fissure with a fissure angle of 15°, 30°, 45°, 60° and 75° respectively were processed.

2.2. Loading method

Uniaxial compression tests on intact and flawed sandstone samples containing a fissure were conducted by using a rock mechanics servo-controlled testing system (YNS2000) in the China University of Mining and Technology, as shown in Fig. 1b. The pressure exerted by the testing machine ranges from 0 to 2000 kN. All tests were conducted under displacement control conditions with a loading rate of 0.08 mm/min. Prior to that, a layer of petroleum jelly was evenly coated on both the top and bottom boundaries of the samples to reduce end effects on the final test results. The axial loads and deformations were recorded simultaneously during the loading process.

3. Evolution characteristics of physical properties of sandstone

The appearance of the intact sandstone samples after exposure to different temperatures are presented in Fig. 2. Under different operational conditions, the change in the appearance of the samples is basically the same as after identical temperature exposure, and one group is chosen to illustrate this in this paper. It can be seen from Fig. 2 that when the temperatures are 200 °C and 400 °C, the surface color of the sandstone sample is similar to that in the natural state. When the temperature is higher than 600 °C, the surface color of the sandstone sample changes markedly which is mainly due to the sandstone containing a small quantity of hematite and magnetite whose main components are Fe_2O_3 and Fe_3O_4. Both of these components are relatively stable in the natural state, presenting a dark red color to the sandstone surface. Ferromagnetic and ferrous magnetic materials will experience a second-order phase transition to the paramagnetic material when the temperature is higher than the Curie temperature. The Fe_3O_4 will react with the oxygen in the air to generate α Fe_2O_3 (Transparent Iron Red Oxide) when the temperature is higher than the Curie temperature of 585 °C. Therefore, when the temperature is at 600 °C or 800 °C, the surface color of the sandstone remains basically unchanged while its value improves obviously.

The change laws of the volume ratio and the density ratio of the intact sandstone samples before and after high temperature exposure are shown in Fig. 3 and the specific values are listed in Table 1 in which M refers to the sample mass, ρ is the sample density, V represents the sample volume, V_1 and ρ_1 are the volume and density of the sandstone sample in its natural state respectively, V_2 and ρ_2 are the volume and density of the sandstone samples after different temperature exposure levels. It can be seen from Fig. 3a and Table 1 that, with increasing temperature, the volume of the sandstone increases gradually, which can mainly be divided into two stages:

(1) 25–400 °C: The volume of the sandstone samples increases slowly, which results mainly from the fact that the inside and outside of the sandstone samples are heated unevenly. Thermal stress caused during the heating process leads to micro cracks in the sandstone, which cannot close when the temperature is cooled to room temperature, resulting in an increase in the sandstone volume. As the heating rate in the test is relatively small (only 5 °C/min), the thermal stress has little impact on the samples. When the temperature increases from 25 °C to 400 °C, the volume ratio of the samples increases by only 0.064%. At this stage, thermal expansion of the mineral components in the sandstone occurs, while the thermal expansion is reversible. When the sample is cooled to room temperature, the volume change caused by the thermal expansion is recovered.