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Electromagnetic radiation characteristics and mechanical properties of deformed and fractured sandstone after high temperature treatment

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ABSTRACT

In this paper, the electromagnetic radiation (EMR) characteristics and mechanical properties observed during sandstone deformation and fracture after high-temperature treatment were studied. The sandstone mechanical strength was found to decrease after high-temperature treatment. EMR signals and acoustic emission (AE) signals were produced during the process of sandstone deformation and fracture. The EMR signals increased with the increase in stress. The EMR signals' change trend was varied after different temperature treatments. Overall, the change trend of EMR and AE signals was consistent, but not strictly synchronized. In addition, the mechanisms of generation of the EMR and AE signals were different. The EMR signals were consistent with the Hurst statistical law, with the Hurst index being greater than 0.5. The main frequency of the EMR signals increased with the increase in stress. At the initial loading stage, the main frequency of EMR signals was low and its intensity was small. With the increase in temperature, the intensity of the EMR signals increased at the same stress level. As the loading increases, the main frequency and the EMR intensity fluctuated significantly. Under conditions of instability and failure, the EMR frequency changed notably, and the EMR intensity reached the maximum. Application of EMR count as a damage variable reflected the sandstone deformation and fracture process. This study provides guidance for application of EMR to detect and evaluate the thermal stability of rocks after high-temperature treatment.

1. Introduction

Development of the economy and the growth of population promote the extension of rock engineering to special geographical regions or severe environments (Wang et al., 2015). Several of the challenges in this field that require immediate attention are the selection of a suitable underground area for nuclear waste storage (Kwon and Cho, 2008), the limited selection of methods available for radioactive waste disposal (Chen et al., 2015), increased exploitation of geothermal resources (Korkmaz et al., 2014; Vázquez et al., 2015), stability of the dams (Zhang et al., 2015) and protection and restoration of nearby buildings following a fire accident (Mccabe et al., 2010). A majority of these problems are related to the impact of high temperature on the rock.

In recent years, there is growing interest in studying the problems of rock mechanics in high-temperature environments; such studies have paved the way for development in the field of rock engineering. The depth of coal mining in China is increasing at an annual rate of 8–12 m (He et al., 2005). Coal mining at greater depths causes an environment of high gas, high stress, and high temperature. The increase in mining depth corresponds to an increase in the occurrence of rock burst and coalmine fires (Zhou et al., 2013; Liu et al., 2014). It is well-known that rock materials subjected to a high-temperature environment or fire baking, will experience changes in their microstructure and mechanical properties (Ide et al., 2010; Ranjith et al., 2012; Ozguven and Ozcelik, 2013). Thus, it is necessary to study the deformation and fracture features of rock after high-temperature treatment.

AE technique has been widely applied to detect coal and rock dynamic disasters (He et al., 2010a; He et al., 2010b; Xie et al., 2011; Mastrogiannis et al., 2015). The intensity of AE waves was found to grow with the increase of the sample temperature for the entire range of temperature studied (i.e., from 20 °C to 600 °C) by Chmel and Shcherbakov (2014). Pronounced AE events occurred during stress drops, which corresponded to the initiation or coalescence of cracks in red sandstone samples (Yang et al., 2014). After treating sandstone at 20–800 °C, the higher the temperature was, the more intense was the AE activity during the deformation and failure of rock (Li et al., 2014a, 2014b).

EMR technique is a geophysical method that is quite effective in monitoring rock bursts and coal and gas outburst (Frid, 1997; Lichtenberger, 2006; He et al., 2011). EMR is closely related to the process of coal rock deformation and fracture (Wang and He, 2000; Frid and Vozoff, 2005). A large number of experimental tests (He et al., 2010a, 2010b; Wang et al., 2011a, 2011b; Song et al., 2015) were conducted to study the EMR characteristics of coal rock under loading conditions. Two forms of EMR emerge during the deformation and fracture

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of coal rock (Wang et al., 2011a, 2011b; He et al., 2012; Wang and Zhao, 2013): one is coulomb field (or electrostatic field), which is induced by electric charges, especially the accumulated charges on the sample surface; and the other is the pulse wave, which is generated by charged particles undergoing variable velocity motion. As research continues, EMR has been used to forecast and predict rock burst, and evaluate the stability of rock and concrete buildings and tunnels (He et al., 2010a, 2010b; Wang et al., 2007; Lichtenberger, 2005).

After high-temperature treatment, various physical and mineralogical changes occur in the rock matrix (Tian et al., 2012). As noted earlier, rock deformation and rupture can produce EMR signals. However, the EMR characteristics during the deformation and fracture of rock after high-temperature treatment have not been studied to date. EMR signals exhibit obvious frequency spectrum characteristics at room temperature. Based on the frequency spectrum characteristics, the optimal frequency band of the EMR antenna was chosen for the field test (Wang et al., 2014). By analyzing the time domain, frequency domain, and time series characteristics of the EMR signals, the progress of sandstone deformation and failure after high-temperature treatment can be obtained. The findings of this study will provide guidance in the application of EMR to detect the thermal stability of rocks after high-temperature treatment and to evaluate surrounding structures and rock stability after a coal fire accident.

In this paper, uniaxial compression tests of sandstone were conducted after 30 °C, 200 °C, 400 °C, 600 °C, 800 °C, 1000 °C treatment. The EMR and AE signals of sandstone samples were tested simultaneously, the time domain, frequency domain, R/S statistics, and fractal characteristics of EMR signals were analyzed. Next, we studied the effect of high-temperature treatment on the EMR signals, and we evaluated the EMR signal characteristics during deformation and damage of sandstone following high-temperature treatment.

2. Previous research

When marble, sandstone, limestone, and granite specimens were subjected to a high-temperature treatment under uniaxial compression loading, the peak strength and the elastic modulus decreased (Liu and Xu, 2015; Ozguven and Ozcelik, 2014; Yang et al., 2014; Guo et al., 2015), as shown in Fig. 1. The uniaxial compressive strength and elastic parameters of calcarenite (Brotóns et al., 2013) decreased as the temperature increased for the tested range of temperature (from 105 °C to 600 °C).

Changes in the rock physical and mechanical properties were not only related to temperature, but also affected by other parameters such as temperature increase, temperature history and stress mode (Tian et al., 2012). Following heat treatment, rock samples experienced chemical changes (Brotóns et al., 2013). For example, the color of sandstone changes following high-temperature exposure (Hajpál and Török, 2004). Before heat treatment at 400 °C, the mass of sandstone reduced gradually with the increase in temperature; however, the change rate of the mass is less than 1.5%, and the volume change rate is less than 0.5%. For treatment above 500 °C, the sandstone peak deformation increased by 27.8%, the deformation modulus decreased slightly, and the change rate was 7.5% (Su et al., 2008; Tian et al., 2012). After heat treatment at 600 °C, the changes to the mass of sandstone were very obvious, and the mass reduction rate was 2.59%; after 600 °C, 800 °C, and 1000 °C treatment, the volume average growth rate was 1.14%, 2.41%, and 3.57%, respectively (Wu et al., 2007).

High-temperature treatment had the following effects on the mechanical properties of sandstone (Wu et al., 2007; Su et al., 2008; Brotóns et al., 2013; Sun et al., 2013). (1) The sandstone volume and the degree of density increased, whereas the primary fracture healing and fracture quantity decreased; in addition, the bearing capacity and the ability to resist deformation were enhanced. (2) Different thermal expansion coefficients can induce the incoordinate thermal stress, thus producing micro-cracks in the specimen. As a result, the bearing capacity and the ability to resist deformation decreased.

Temperature has a significant (destructive) effect on the structures of marble, granite, and sandstone. A comparison study showed that 600 °C and 800 °C are the brittle–ductile transition critical temperatures of granite and sandstone stress–strain curves (Liu and Xu, 2015).

3. Experimental

3.1. Sample preparation and experiment system

Large rocks were obtained from the Shanxi Linfen mining area. The sandstone samples were chosen according to the size standards (Φ 50 mm $\times$ 100 mm cylinders) specified by the International Society for Rock Mechanics (ISRM). The samples were selected with a surface parallelism value within 0.05 mm and a surface flatness within 0.02 mm.

As shown in Fig. 2 below, the experimental system includes the following: uniaxial compression test system and the EMR and AE testing systems.

The uniaxial compression test system used was a SANS computer-controlled electrohydraulic servo pressure testing machine. The system comprised of the following: press, DCS controller, and PowerTestV3.3 control program. The system can display the test data and the stress-strain curve, load-deformation curve, and load-time curve in real time.

The EMR and AE data were acquired using the CTA-1-type sono-electro data-acquisition system (Physical Acoustics Corporation, USA). The system is comprised of the following: preamplifier, filter circuit, A/D converter module, waveform processing module, and computer. The system has the capability to simultaneously acquire, at high speeds, eight channels of AE and EMR signals. The signals received by the electromagnetic antennas and AE sensors are amplified by the preamplifier, and converted into the 16-bit A/D conversion module. The digital signal is converted into a parameter-forming circuit, stored in the buffer, and subsequently transmitted to the computer for further processing and display.

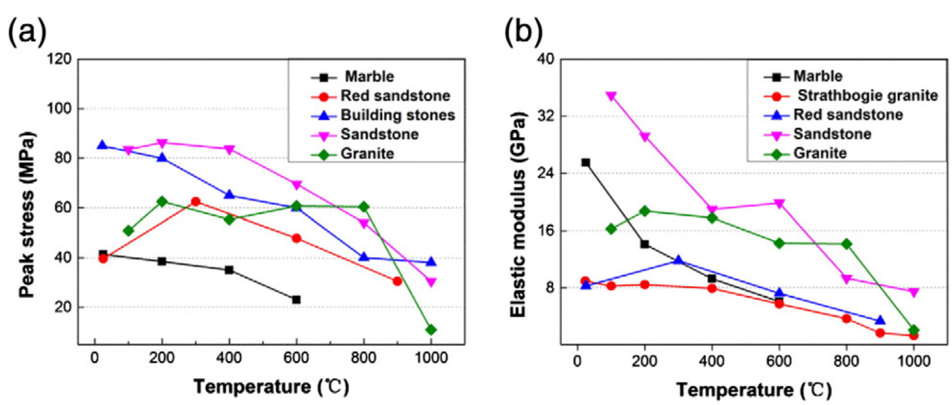

Fig. 1. Changes of the rock mechanical properties after high-temperature treatment: (a) peak stress; (b) elastic modulus.