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A coupled thermo-mechanical damage model for granite

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ABSTRACT

With the increasing demand for mineral and energy resources, deep underground operations in mining, oil and gas industries become more frequent. This also resulted in problems associated with high temperature and pressure (HTP) that rock is exposed to in deep underground conditions. It is therefore imperative to understand and correctly model the coupled thermo-mechanical (TM) behavior of rocks for better and safer designs. For this purpose, based on the Weibull distribution and Lemaitre's strain-equivalent principle, a framework for the coupled thermo-mechanical (TM) damage model for granite is developed to simulate the deformation and failure process of rock under the high temperature and pressure (HTP) conditions. The thermal damage caused by the temperature change and the mechanical damage caused by high pressure were analyzed, and a nonlinear coupled total damage parameter is proposed in this study. The Weibull distribution parameters involved in the damage model are derived by combining the geometric conditions obtained from the conventional triaxial compression tests. In order to compare the performance of the proposed damage model, Drucker-Prager failure criterion is used as an example in the nonlinear TM damage model. For the validation of the proposed model, test results for granite samples at various temperature and confining pressures were compared in which the theoretical results are found to be in a good agreement with the experimental results. The proposed coupled TM damage model can be used in conjunction with any other failure criteria to account the damage evolution under HTP conditions.

1. Introduction

The near-surface mineral resources have been gradually depleted due to increasing demand for minerals and energy resources. Therefore, the mining operations and many other resource extractions started to take place in deep undergrounds.[1–4] For example, the depth of current coal mining has reached over 1500 m; the exploitation depth of the geothermal exploitation is greater than 5000 m; the deepest gold mine is located nearly 4000 m below the surface and oil and gas development is reaching over 7500 m.[5] On the other hand, the temperature of underground coal gasification and underground fire reach up to 1000 °C.[6] With these deep engineering operations, the rock will be subjected to complex natural environments such as HTP. Therefore, understanding the coupled thermo-mechanical behavior of rocks is of significant importance to the design of deep underground structures.[7–9]

Over the last few years, a large number of investigation on thermo-mechanical (TM) coupling has been carried out to obtain the complex behavior of various rocks such as claystone,[10,11] sandstone,[3,12,13] marble[14] and limestone.[15] However, granite, as the most common rock type in deep underground, in conjunction with the coupled effect of TM was less studied.[16,17] For example, Dwivedi et al.[1] studied various TM properties of Indian granite (IG) at high temperatures ranging from 30 °C to 160 °C in which the scanning electron microscope (SEM) research of micro-cracks for IG revealed that opening of pre-existing micro-cracks took place at 65 °C. These gaps in the micro cracks were marginally reduced at a temperature range of 100–125 °C. On further heating to 160 °C, the pre-existing micro-cracks closed considerably. Development of new micro-cracks was not observed at any temperature up to 160 °C. Chen et al.[18] indicated that the crystal structure of the phlogopite in granite transforms to a more stable structure between 400 °C and 600 °C with an associated increase in volume. A dehydroxylation reaction also occurred in the phlogopite at 400 °C, after which the uniaxial compressive strength (UCS) decreases and the ductility increases. Intercrystalline cracking was the main failure mode for samples exposed to temperatures below 800 °C, whereas transcrystalline cracking can be observed in samples exposed to 1000 °C. Sun et al.[19] investigated the variation of physical and mechanical properties of granite into five temperature phases: from room temperature to 100, 100–300, 300–400, 400–600, and 600–800 °C, and they reported that 400 °C may be a critical threshold for thermal damage. Guo et al.[20]

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studied the effect of hydrostatic pressure and preheating temperature on the strength properties and failure type of Beishan granite with the use of a large-diameter Split-Hopkinson Pressure Bar (SHPB). The results indicated that the value of peak stress can be linearly correlated with the temperature level and the elastic modulus can be associated with temperature by a functional form, defined as the temperature shift factor.[20] Finally, an elasto-plastic damage constitutive model was established to predict the dynamic mechanical behavior of the Beishan granite after high-temperature treatment under different confining pressures.[20] Becattini et al.[21] investigated six types of rocks of Alpine origin for their suitability for high-temperature packed-bed thermal-energy storage. To avoid fracturing of rocks, foliated rocks and rocks rich in calcite and/or quartz, such as limestones and sandstones, are found to be unsuitable when exposed to temperatures higher than about 600 °C or 573 °C, respectively. Mafic rocks, felsic rocks, serpentinite, and quartz-rich conglomerates are suitable for high-temperature thermal-energy storage.[21]

The establishment of damage model is an effective method to investigate the failure process of quasi-brittle materials,[22–27] but the temperature effect considered in the damage models is limited. Some of these models developed by many researchers are summarized in Table 1. Initiation and propagation of micro-cracks in the rock exposed to HTP will reduce the rock strength due to induced thermal and mechanical damage. In recent years, the concept of thermal damage (D_T) have been introduced using the relationship between elastic modulus and temperature for marble,[30] and a linear relationship was proposed among the damage variables such as temperature, peak stress and peak strain.[31] However, the experimental results[30,31] were obtained only by uniaxial compression tests after high temperature, not by triaxial compression tests which is not consistent with the actual engineering situation (Table 2).

This paper presents three main studies. Firstly, in order to provide the basic data for damage evolution, the triaxial compression tests on granite samples after exposing the specimens to the high temperatures ranging from 25 °C to 1000 °C are introduced. Secondly, based on the Weibull distribution and Drucker-Prager criterion, a coupled TM damage model for granite is proposed. The parameters in the proposed model were derived by combining the geometric condition of test results, and the effects of temperature and confining pressure on rock damage. Thirdly, the proposed TM model is validated by the experimental data and the further improvement on the proposed model is suggested.

Table 1
Various damage model for rock.

Damage model	Calibration tests	References
$D = 1 - \exp\left[-\left(\frac{F}{F_0}\right)^n\right]$, D is damage variable, n and F_0 are Weibull parameters.	Triaxial tests on argillaceous quartzite	Wang et al. (2007)[24]
$D = 1 - \left[1 - (r+1)\left(\frac{\sigma^*}{B}\right)^r t\right]^{\frac{1}{r+1}}$, σ^* is damage equivalent stress, B and r are material constants.	Uniaxial and triaxial compression tests on a bedded salt rock	Ma et al. (2013)[26]
$D_i = \beta_i(\bar{e} - \bar{e}_{0ei})$, $\bar{e} = \sqrt{\varepsilon_{ij} S_{ijkl}^{-1} \varepsilon_{kl}}$ β_i is damage parameter, $\bar{e}$ is energy factor, S is elastic flexibility matrix, and $\bar{e}_{0ei}$ is the energy factors corresponding to the elastic damage starting point.	Triaxial tests on boom clay	Yu et al. (2014)[28]
$D = 1 - \frac{v^2}{v_0^2} = 1 - \frac{E}{E_0}$, V and V_0 are the P-wave velocity of the damaged and undamaged rocks, respectively; E and E_0 are the damaged and initial undamaged elastic modulus.	Triaxial compression tests on Wudongde Limestone	Zhang et al. (2016)[29]

2. Experimental methodology

The rock samples were retrieved from granite block at a depth of about 1000–1200 m in the Yanzhou hard coal mine, Shandong Province, China. In order to ensure the homogeneity of rock samples, a massive intact granite block with 60 × 50 × 20 cm dimension was collected. The rock block is coarse-grained and relatively isotropic in texture and composition. It is mainly comprised of feldspar, quartz and mica based on X-ray diffraction analysis. Core samples with the diameter of 50 mm and the length of 100 mm were then drilled out from the large block. The ends of all samples were finely ground and polished to meet the specifications recommended by ISRM.[32] The longitudinal wave velocity of the samples was measured through an ultrasonic pulse transmission technique and the average longitudinal wave velocity is 4420 m/s. Through laboratory test, the average density of rock sample is $2.612 g/cm^3$ and the average uniaxial compressive strength (UCS) is 120.37 MPa at room temperature.

2.1. Testing procedure

Firstly, the rock samples were heated to the temperatures of 200, 400, 600, 800, 1000 and 1200 °C at a rate of 10 °C/min in a high-temperature furnace. The heating device used in this study is an SX3-10-12 box-type resistance furnace. The maximum operating temperature is 1200 °C and the rated power is 10 kW. Melting temperature of the granite is 1200 °C (see Fig. 1). In order to ensure the uniform heating of the rock, each rock specimen was kept for 2 h at the predetermined temperature level, and then naturally cooled down to room temperature. Five rock samples were used at each temperature point, totaling 30 rock samples. Secondly, the triaxial compression tests under different confining pressures of 0, 10, 20, 30 and 40 MPa were carried out on the preheated samples, using MTS815.02 electro-hydraulic servo material test system in the State Key Laboratory for Geomechanics and Deep Underground Engineering of China University of Mining and Technology. Triaxial tests were conducted under displacement control mode with a loading rate of 0.003 mm/s to capture the post-peak behavior.

2.2. The results of the experiments

In this section, the evolution of the stress-strain curve, the peak stress, and the elastic modulus of granite with the different temperature and confining pressure was discussed to provide a basic data for the establishment of coupled TM damage model.

The stress-strain curves of the granite after high temperature undergo several stages, namely compaction, elastic stage, yield, failure, softening and residual. Granite shows typical brittle failure at low confining and temperatures as can be seen in Fig. 2. With the increase of temperature, the compaction stage becomes more obvious and the peak strain increases (See Fig. 2a). With increasing confining pressure, the brittle failure becomes ductile gradually after reaching the peak stress (see Fig. 2b).

With the increase of temperature, internal defects would grow and change the physical and mechanical properties of granite. In Fig. 3, peak stress and elastic modulus of rock with temperature can be divided into three stages: (I) 25–400 °C: in this phase, the absorbed water would escape around 100 °C; the bounded water escape between 100 °C and 300 °C and the crystal water would escape below 400 °C, and structural water of mineral would escape above 300 °C.[19] The loss of crystal water and structural water leads to the damage of mineral crystal lattice skeleton, increasing the defects of granite. (II) 400–600 °C: in this stage, especially between 500 and 600 °C, the minerals in granite are exposed to chemical changes.[33] At roughly 573 °C, quartz has a phase transformation from α phase to β phase,[34] which can be used to explain the