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Damage modeling of basaltic rock subjected to cyclic temperature and uniaxial stress

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ABSTRACT

The deformation characteristics of basalt rocks subjected to cyclic uniaxial stress and cyclic temperature were investigated, and a corresponding damage model was established. Cyclic uniaxial stress–temperature tests were conducted in which stress upper limit was 80% or 65% of the uniaxial compressive strength and peak temperature was 60 °C or 90 °C. A damage model for rocks subjected to cyclic stress–temperature was proposed, which applied statistical damage mechanics and continuum damage mechanics. Cyclic stress–temperature tests exhibited superposition of cyclic stress and temperature effects. Basalt specimens were damaged gradually as the cycle number increased, and failed in cycles where maximum stress was 80% of the uniaxial compressive strength. However, the specimens hardened and did not fail when maximum stress was 65% of the uniaxial compressive strength and the highest temperature was 60 °C. The peak strain of damaged specimens underwent initial, steady, and acceleration stages; the Young's modulus decreased rapidly in the initial cycles, but the reduced rate decreased further in subsequent cycles. The peak and residual strains of hardened specimens decreased as the cycle number increased. However, the Young's modulus had an opposite trend; moreover, the higher the temperature, the less the Young's modulus increased. The proposed damage model can be degenerated into existing models or be regarded as an extension of them.

1. Introduction

Rocks are subjected to simultaneous cyclic stress and cyclic temperature in basically two cases: underground rock caverns for compressed air energy storage, and rock engineering in cold regions. Compressed air energy storage (CAES) is an energy storage and power generation technology with broad application prospects [1]. However, the frequent and rapid inflation and discharge of compressed air induces significant temperature variation in CAES caverns. Moreover, varying air pressure is simultaneously acted on the cavern surface. Consequently, the rock around the cavern is subjected to cyclic stress and cyclic temperature [1,2]. Rock engineering in cold regions, particularly tunnels or slopes, are subjected to cyclic diurnal temperature variation and cyclic seasonal temperature. Cyclic stress variations occur in rocks because of constraint conditions, and adversely affect rock structure safety. Therefore, the effects of cyclic stress and temperature must be considered. The deformation characteristics of rocks subjected to cyclic stress and cyclic temperature must be investigated from the perspective of engineering safety.

The past years have seen considerable effort in investigating the mechanical properties of rocks subjected to either cyclic stress or cyclic temperature. Several studies focused more on the response of rock to cyclic stress than to cyclic temperature. Ray et al. [3] studied the mechanical properties of Chunar sandstone subjected to cyclic stress and related the strain rate to fatigue stress. They found that the elastic modulus decreased as the strain rate increased. Lee et al. [4] investigated the influence of asperity degradation on the mechanical behaviors of rough rock joints under cyclic shear loading. Li et al. [5] focused on the mechanical properties of jointed rock masses subjected to dynamic cyclical loading, and proposed a fatigue-damage model. Gatelier et al. [6] reported an extensive laboratory investigation of the mechanical properties of transversely anisotropic porous sandstone in cyclic uniaxial and triaxial tests. Li et al. [7] investigated the fatigue properties of cracked, saturated, and frozen sandstone samples under cyclic loading. Ge et al. [8] conducted extensive laboratory tests to determine the mechanical properties of marbles, sandstones, and granites. They identified three stages of irreversible deformation and the threshold value for fatigue failure. Badge et al. [9] studied the fatigue property of intact sandstone samples

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subjected to dynamic loading. Wang et al. [10] applied a triaxial cyclic loading test system to study the fatigue performance of granites. Liu et al. [11,12] conducted tests to study the influence of frequency and confining pressure on the dynamic performance of sandstones. However, all of these studies were aimed at normal atmospheric temperature. Temperature was rarely considered in studying the mechanical properties of rocks subjected to cyclic stress.

Few studies explore the influence of cyclic temperature on the mechanical properties of rocks [13–15]. Fang [13] conducted uniaxial compression tests on marbles that underwent periodic temperature variations, and studied the influence of cyclic temperature on the strain, elastic modulus, and uniaxial compressive strength. Mahmutoglu [14] exerted several temperature cycles on sandstones and marbles and observed a reduction in the mechanical properties of the rocks after temperature cycling. Qin et al. [15] investigated the Young's modulus variations of silty mudstones and argillaceous siltstones under temperature cycle increase. The mechanical property of rocks subjected to cyclic stress–temperature is more complex than that of rocks subjected to either cyclic stress or cyclic temperature alone; further systematic and basic experiments must be conducted. However, investigations of simultaneous cyclic stress and cyclic temperature on the deformation characteristics of rocks, which is practically significant to CAES engineering and rock engineering in cold regions, have not been reported.

One of the main purposes of studying the deformation characteristics of rocks subjected to cyclic stress–temperature is to master the law of rock damage accumulation with cycle number and derive an applicable rock damage model. The damage model subjected to cyclic stress–temperature can evaluate rock fatigue life or establish a thermomechanical damage model for CAES cavern stability. However, we found only damage models for rocks subjected to cyclic stress [5,16–19]. Li et al. [5] established a damage model for rock mass subjected to cyclic loading. Xiao et al. [16] provided conclusions for the law of rock damage and several damage models. Li et al. [17] derived a damage model for low-cycle fatigue. Xiao et al. [18,19] proposed an invested-S damage model and a damage model representing the damage evolution of rocks as a logarithmic cycle function. Qiu et al. [20] proposed a model for the pre-peak unloading damage evolution of marble. David et al. [21] proposed a sliding crack model for nonlinearity and hysteresis in the uniaxial stress–strain curve of rock during one entire loading and unloading cycle. Their model was able to provide good fits to experimental data, even those on thermally cracked specimens. The influence of cyclic temperature is not yet considered in these damage models. Therefore, the influence of both cyclic stress and cyclic temperature must be considered in establishing a damage model for rocks subjected to cyclic stress–temperature according to cyclic stress–temperature tests.

This study conducted cyclic uniaxial stress–temperature tests and analyzed the deformation characteristics of basalt specimens. The influence of cyclic stress–temperature on the peak strain, residual strain, and Young's modulus were explored in particular. A damage model for rocks subjected to cyclic temperature alone was established based on existing cyclic temperature tests. A damage model for rocks subjected to cyclic stress–temperature was then derived, which applied statistical damage mechanics and continuum damage mechanics. The proposed model was compared with existing models and the cyclic stress–temperature test results to analyze its applicability.

2. Cyclic stress–temperature tests

2.1. Specimen preparation

The rock samples for the cyclic stress–temperature tests were collected from Hanwula Wind Farm in Inner Mongolia, China. The wind farm is a potential site for underground CAES cavern excavation. Rock specimens were drilled from a large basalt block, and a close sampling position was conducted to reduce the adverse effects of relatively discrete rock properties. The basalt specimens were all gray and slightly weathered. Each rock specimen was prepared according to the Chinese Rock Mechanics Testing Standards and was made into cylinders with a diameter of 50 mm and height of 100 mm. The end-face flatness of each rock specimen was controlled within ±0.05 mm. The moisture content and dry density of each specimen were tested and determined before the designed tests were initiated. The results showed that the moisture content and dry density varied in small ranges, which directly reflected a relatively small dispersion.

2.2. Testing procedure

Regular uniaxial compression tests were first conducted to obtain the average and minimum uniaxial compressive strengths of the basalt specimens. The Hualong WDW-600 electronic universal testing machine was employed; a total of five specimens were used. The test results showed that the average uniaxial compressive strength was 67.7 MPa and minimum strength was 56.7 MPa.

Fully coupled cyclic stress–temperature tests are difficult to conduct because the test technology is limited in performing the heating–cooling and loading–unloading processes synchronously. Therefore, this study designed and applied a simplified testing procedure. The combination of one loading–unloading process and one heating–cooling process for a rock specimen was regarded as a complete stress–temperature cycle. One stress process means stress loading and unloading. The peak stress of one cycle was set as 80% or 65% of the average uniaxial compressive strength and also less than the minimum uniaxial compressive strength based on the regular uniaxial compression results. The stress loading–unloading processes were set as follows: the rock specimens were loaded to 55 MPa (or 45 MPa) using the Hualong WDW-600 electronic universal testing machine, and the stress of each specimen was then unloaded to zero. One temperature process means heating and cooling the rock specimens. The specimens were heated to the prescribed temperature of 60 °C or 90 °C in a 101A electronic blast heating furnace, which controls temperature fluctuation to less than 1 °C and elevates temperature to 50 °C to 300 °C. Each specimen was kept at the prescribed temperature for 1 h to ensure even heating after the prescribed temperature was achieved. The specimens were then taken out of the heating furnace and fully air-cooled at room temperature (15 °C) for 2 h. The uniaxial stress loading–unloading and heating–cooling processes were repeated to subject the specimens to the effects of cyclic stress and temperature. A total of 10 specimens were used in the cyclic stress–temperature tests. Table 1 lists the sample numbers and temperature and stress conditions of each specimen used. It needs to be noted here that a purely thermal finite element analysis was performed before the tests to check the test procedure, especially the time setting. The numerical results showed little difference between the temperatures on the specimen surface and in the core region. This means a nearly spatially uniform temperature field in the rock specimens after the heating or cooling

Table 1
Maximum stress and temperature of rock specimens.

Sample number	Maximum temperature (°C)	Maximum stress (MPa)
T1S1-1, T1S1-2	90	45
T1S2-1, T1S2-2	90	55
T2S1-1, T2S1-2, T2S1-3	60	45
T2S2-1, T2S2-2, T2S2-3	60	55