Original Research Article

Study on physical and mechanical properties of rock under high temperature action

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Abstract: To explore the influence laws and internal mechanisms of high temperature on the physical and mechanical properties of rock, and clarify the evolutionary characteristics of rock performance under different lithologies and temperature conditions, this paper takes the tight sandstone of Xujiahe Formation, shale of Longmaxi Formation in Sichuan Basin and granite of Beishan in Gansu Province as the research objects. By combining laboratory experiments with numerical simulation methods, the variation laws of physical properties (bulk density, porosity, permeability, acoustic characteristics) and mechanical properties (uniaxial compressive strength, elastic modulus, Poisson's ratio, creep characteristics) of rocks after high-temperature treatment in the range of 30℃ to 1000℃ are systematically studied. The microscopic damage mechanism of rock under high temperature is analyzed, and a disturbed state constitutive model of high-temperature rock is established. The research results show that there are differences in the high-temperature threshold of rocks with different lithologies: the threshold temperature of sandstone is about 500℃, that of shale is about 400℃, and the strengthening-weakening transition temperature of granite under short-term heating is about 200℃. With the increase of temperature, the bulk density of rock decreases gradually, the porosity and permeability increase significantly, the acoustic parameters show a downward trend, and the mechanical strength and elastic modulus decrease overall. Long-term heating will further aggravate rock damage due to subcritical crack propagation. The damage effect of high temperature on shale is significantly higher than that on sandstone, which is mainly attributed to the combustion and pyrolysis of organic matter in shale. Confining pressure can inhibit the crack propagation of rock under high temperature and improve the long-term stability of rock mass. The research results can provide theoretical basis and technical support for practical engineering such as nuclear waste disposal, geothermal resource development, oil and gas well stimulation, and fire resistance design of underground engineering.

Keywords: high temperature; rock; physical properties; mechanical properties; thermal damage; microscopic mechanism

1. Introduction

1.1. Research background and significance

In many engineering fields such as deep resource exploitation, high-level radioactive nuclear waste disposal, geothermal resource development, underground coal gasification and fire prevention and control of underground engineering, rocks are often in high-temperature environments. As the basic material for engineering construction, the physical and mechanical properties of rock directly determine the stability and safety of engineering structures. High temperature will break the internal mineral structure and mechanical balance of rock, trigger a series of physical and chemical changes, lead to rock volume deformation, strength reduction, permeability enhancement and other problems, and then induce engineering disasters. Therefore, systematically studying the evolutionary laws of physical and mechanical properties of rock under high temperature, revealing the microscopic mechanism of high-temperature damage, and establishing the mechanical constitutive model of rock under high-temperature conditions can not only enrich the theoretical system of rock mechanics, but also provide important theoretical basis and technical support for engineering design, construction safety and disaster prevention and control under high-temperature environments, which has important theoretical research value and engineering application significance.

1.2. Research content

Select three typical lithologic rocks including tight sandstone of Xujiahe Formation, shale of Longmaxi Formation and granite of Beishan, prepare standard samples, and carry out high-temperature treatment tests at different temperatures (30°C, 200°C, 300°C, 400°C, 500°C, 600°C, 800°C, 1000°C);

Carry out uniaxial compression tests and creep tests, measure the mechanical parameters of rock such as uniaxial compressive strength, elastic modulus, Poisson's ratio and failure time, and explore the influence mechanism of high temperature on rock mechanical properties;

Establish a constitutive model of high-temperature rock based on the discrete element method and the disturbed state concept theory, and verify the rationality of the model combined with experimental data;

Analyze the influence of confining pressure on the mechanical properties of high-temperature rock, and put forward suggestions for the stability control of engineering rock mass under high-temperature environment.

2. Experimental materials and methods

2.1. Experimental materials

Three typical lithologic rocks are selected as the research objects in this experiment, namely tight sandstone of Xujiahe Formation, shale of Longmaxi Formation in Sichuan Basin and granite of Beishan in Gansu Province, all taken from actual engineering sites to ensure the representativeness of the samples.

Tight sandstone of Xujiahe Formation: It is grayish white with a dense massive structure, and its main mineral components are quartz (65%), feldspar (25%) and a small amount of clay minerals (10%). The natural density is 2.63g/cm^3, the porosity is 3.2%, and the permeability is 0.08mD. Shale of Longmaxi Formation: It is grayish black with obvious bedding structure, and its main mineral components are clay minerals (45%), quartz (35%), feldspar (10%) and organic matter (10%). The natural density is 2.58g/cm^3, the porosity is 4.5%, and the permeability is 0.03mD. Beishan granite: It is flesh red with a massive structure, and its main mineral components are quartz (21%), potassium feldspar (17%), plagioclase (55%) and biotite (7%). The natural density is 2.68g/cm^3, the porosity is 2.8%, and the permeability is 0.02mD.

In accordance with the Test Code for Physical and Mechanical Properties of Rock (GB/T 50266-2013), the three types of rocks are processed into standard samples: the samples for physical property testing are cylinders of Φ50mm×100mm, the samples for mechanical property testing are cylinders of Φ50mm×100mm, and the samples for microstructure observation are block samples of 10mm×10mm×5mm. Three parallel samples are prepared for each lithology and each temperature gradient to ensure the reliability of experimental data.

2.2. Experimental equipment

The main equipment used in this experiment includes:

High temperature box: Model SRJX-4-13, with a temperature control range from room temperature to 1300℃ and a temperature control accuracy of ±1℃, used for high-temperature heating treatment of rock samples;

Electronic balance: Model FA2004, with a measuring range of 0-200g and an accuracy of 0.1mg, used for measuring the mass of rock samples;

Porosity and permeability tester: Model CMS-300, used for testing the porosity and permeability of rock;

Acoustic wave tester: Model RS-ST01C, used for testing the P-wave velocity and attenuation coefficient of rock;

Thermogravimetric analyzer: Model TG-DSC synchronous thermal analyzer, used for analyzing the pyrolysis characteristics and mineral composition changes of rock under high temperature;

Discrete element simulation software: PFC3D, used for establishing numerical models of high-temperature rock and simulating thermal crack propagation and long-term time-dependent behavior.

2.3. Experimental scheme

2.3.1. High temperature treatment scheme

Put the prepared rock samples into the high temperature box and adopt the segmented heating method: heat up from room temperature (30℃) to the set temperature (200℃, 300℃, 400℃, 500℃, 600℃, 800℃, 1000℃) at a rate of 5℃/min, keep the constant temperature at the set temperature for 2h to ensure the uniform temperature inside the rock, and then cool down to room temperature at a rate of 3℃/min to avoid sample damage caused by thermal stress due to rapid cooling. The samples without high-temperature treatment (30℃) are used as the control group.

2.3.2. Mechanical property testing scheme

Uniaxial compression test: Place the sample after high-temperature treatment on the MTS810 electro-hydraulic servo pressure testing machine, adopt the displacement control mode with a loading rate of 0.05mm/min until the sample is damaged, record the stress-strain curve, and calculate the uniaxial compressive strength, elastic modulus and Poisson's ratio;

Creep test: Select three temperature gradients of 200℃, 300℃ and 400℃, adopt the constant load loading mode with the loads of 40%, 60% and 80% of the uniaxial compressive strength at the corresponding temperatures respectively, continue loading until the sample is damaged or the creep is stable, record the strain-time curve, and analyze the creep characteristics and failure time.

3. Analysis of microscopic damage mechanism of rock under high temperature

3.1. Characteristics of microstructure changes

The microstructure of the three types of rocks after high-temperature treatment is observed by scanning electron microscope (SEM). It is found that the microscopic damage of rocks under high temperature is mainly manifested as the increase of pores, the generation and propagation of cracks, and the microscopic damage characteristics of rocks with different lithologies are different.

Tight sandstone of Xujiahe Formation: At 30℃, the microstructure is dense, the particles are arranged neatly, the number of pores is small (mainly primary pores), and the bonding force between particles is strong; at 200℃-400℃, a small number of microcracks appear on the particle surface, and the number of pores increases slightly, mainly due to water evaporation and clay mineral dehydration; above 500℃, a large number of cracks between particles are generated and connected to form a continuous crack network, the number of pores increases sharply, some particles are broken, the bonding force between particles is significantly weakened, and the microstructure is seriously damaged, which is consistent with the variation law of physical and mechanical properties — 500℃ is the threshold temperature of sandstone, and beyond this temperature, the microscopic damage is sharply aggravated and the macroscopic performance is significantly deteriorated.

Shale of Longmaxi Formation: At 30℃, the microstructure has obvious bedding characteristics, the particles are arranged relatively densely, the number of pores is small (mainly interlayer pores); at 200℃-300℃, a small number of microcracks appear between the beddings, and the number of pores increases slowly, mainly due to water evaporation and the decomposition of a small amount of organic matter; above 400℃, the bedding structure is seriously damaged, a large number of interlayer cracks are generated and connected, and organic matter burns to produce a large number of pores at the same time, the bonding force between particles drops sharply, the microstructure is loose, and particle shedding occurs in some areas, which is the fundamental reason for the sharp change of physical and mechanical properties of shale — above 400℃, the combustion of organic matter and the damage of bedding jointly lead to the aggravation of microscopic damage and the sharp deterioration of macroscopic performance.

Beishan granite: At 30℃, the microstructure is dense, the mineral particles are arranged neatly, the number of pores and cracks is extremely small, and the bonding force between particles is strong; at 100℃-200℃, the mineral particles expand due to heat, the particles are arranged more densely, the number of pores decreases slightly, and the number of cracks is extremely small, which is consistent with the strengthening characteristic of granite at low temperature; above 200℃, the mineral particles expand unevenly due to heat, a large number of intergranular and intragranular cracks are generated, and the number of cracks increases continuously with the increase of temperature, mainly tensile cracks (accounting for more than 90%). The crack density in quartz particles is the highest because quartz has the largest thermal expansion coefficient. The number of cracks doubles at 400℃, and the cracks are more significant after long-term heating, with serious microstructure damage, which is consistent with the variation law of mechanical properties of granite — 200℃ is the transition temperature, and beyond this temperature, a large number of microscopic cracks are generated, subcritical cracks begin to propagate, and the macroscopic strength and elastic modulus drop sharply.

3.2. Microscopic damage mechanism

The microscopic damage of rock under high temperature is the result of the combined action of physical and chemical changes, mainly including the following aspects:

Water evaporation and mineral dehydration: Rock contains a certain amount of free water and crystal water. Under high temperature, free water evaporates first, and with the increase of temperature, crystal water is gradually removed, leading to the generation of pores inside the rock, the weakening of bonding force between particles and the production of microcracks. For example, clay minerals will undergo dehydration reaction in the range of 300℃-500℃, lose crystal water and shrink in volume, leading to the generation of microcracks inside the rock, which is the main reason for the microscopic damage of sandstone and shale in the low-temperature stage (30℃-400℃).

Uneven thermal expansion of minerals: Rock is composed of a variety of minerals with different thermal expansion coefficients. Under high temperature, mineral particles expand when heated. Due to the difference in expansion coefficients, thermal stress will be generated between particles. When the thermal stress exceeds the bonding force between particles, microcracks will be generated. For example, the thermal expansion coefficient of quartz in granite (24.3×10^{-6} K^{-1}) is much higher than that of feldspar and biotite. Under high temperature, the expansion of quartz particles is large, and thermal stress is generated between quartz particles and other mineral particles, leading to the generation of cracks, which is one of the main reasons for the high-temperature damage of granite and an important factor for the difference in threshold temperature of rocks with different lithologies — The difference in mineral composition leads to different degrees of uneven thermal expansion and different threshold temperatures.

Mineral phase transformation and pyrolysis: Under high temperature, some minerals will undergo phase transformation and volume change, leading to the generation of stress inside the rock and then cracks; for rocks containing organic matter (such as shale), high temperature will cause the combustion and pyrolysis of organic matter to produce gas, and the gas escape process will produce pores and cracks inside the rock, aggravating microscopic damage. For example, organic matter in shale will burn in a large amount above 400℃ to produce gases such as CO_2, which form a large number of pores inside the rock when escaping. At the same time, pyrolysis reaction will lead to the phase transformation of clay minerals and volume shrinkage, producing cracks, which is the main reason why the high-temperature damage of shale is more serious than that of sandstone.

Subcritical crack growth: Under long-term high temperature, the microcracks inside the rock will undergo subcritical propagation, the length and number of cracks will increase continuously, and finally form a connected crack network, leading to the complete damage of rock microstructure and the sharp decline of macroscopic performance. For example, under long-term high-temperature heating of Beishan granite, subcritical cracks grow continuously, the number of cracks doubles at 400℃, the porosity and permeability increase significantly, and the strength and elastic modulus drop sharply, which is the main mechanism of time-dependent damage of rock under long-term high temperature.

In summary, the microscopic damage of rock under high temperature is the result of the combined action of water evaporation, mineral dehydration, uneven thermal expansion of minerals, mineral phase transformation, organic matter pyrolysis and subcritical crack growth. The accumulation of microscopic damage ultimately leads to the deterioration of macroscopic physical and mechanical properties of rock, and the microscopic damage mechanisms of rocks with different lithologies are different, which in turn leads to different variation laws of their macroscopic performance.

4. Suggestions for engineering application

Based on the experimental research and numerical simulation results of this paper, combined with the actual engineering needs such as nuclear waste disposal, geothermal resource development, oil and gas well stimulation and underground engineering fire resistance, the following engineering application suggestions are put forward:

Design of nuclear waste disposal repository: Beishan area in Gansu Province is a potential site for nuclear waste disposal in China, with granite as the main rock. The strength transition temperature of granite under high temperature is 200°C, and long-term heating will further weaken the rock mass due to subcritical crack propagation. Therefore, in the design of nuclear waste disposal repository, the temperature of surrounding rock should be controlled not to exceed 200°C. If the temperature exceeds 200°C, special heating tests should be used to evaluate the mechanical properties of rock mass; at the same time, the confining pressure should be reasonably designed (it is recommended that the confining pressure is not less than 10MPa) to inhibit crack propagation, improve the long-term stability of rock mass, and ensure that the load is lower than the strength threshold (40-70%UCS) to avoid creep failure of rock mass.

Geothermal resource development: In the enhanced geothermal system, the temperature of granite reservoir can reach 150-500°C. High temperature will lead to a significant increase in granite permeability, but a sharp decline in strength and elastic modulus. Therefore, in the design and construction of geothermal wells, the wellbore materials should be reasonably selected according to the reservoir temperature to avoid wellbore collapse due to the decrease of rock strength; at the same time, the characteristics of increased rock permeability under high temperature should be used to optimize the geothermal mining scheme and improve the efficiency of geothermal resource exploitation.

Oil and gas well stimulation technology: For the tight sandstone of Xujiahe Formation and shale gas reservoir of Longmaxi Formation in western Sichuan, when the electric heating stimulation technology is adopted, the threshold temperature of shale is 400°C and that of sandstone is 500°C. Beyond the threshold temperature, the rock permeability is greatly improved. Therefore, the heating temperature can be controlled above 400°C (for shale) or 500°C (for sandstone), and the heating range can be expanded to improve the single well productivity; at the same time, the heating rate and cooling rate should be controlled to avoid damage to wellbore rock caused by thermal stress and ensure wellbore stability.

Fire resistance design of underground engineering: When fires occur in underground engineering such as tunnels and mines, the temperature can reach up to 1000°C, which will lead to a sharp deterioration of the physical and mechanical properties of rock and induce collapse disasters. Therefore, in the fire resistance design of underground engineering, high-temperature resistant materials should be used to protect the surrounding rock to reduce the damage of high temperature to rock; at the same time, the engineering structure should be reasonably designed to avoid structural damage caused by the decrease of rock strength under high temperature, and fire emergency plans should be formulated to take timely cooling measures and reduce disaster losses.

Engineering monitoring and maintenance: For engineering rock mass in high-temperature environments, a long-term monitoring system should be established to monitor the temperature, displacement, stress and other parameters of rock mass in real time, and timely find out the abnormal damage and deformation of rock mass; the rock mass should be inspected and maintained regularly, and grouting and other measures should be adopted to repair the microscopic damage of rock mass, improve the stability of rock mass and extend the service life of engineering.

5. Conclusions and prospects

5.1. Conclusions

In this paper, the variation laws of physical and mechanical properties of sandstone of Xujiahe Formation, shale of Longmaxi Formation and granite of Beishan under high temperature are systematically studied through experiments, the microscopic damage mechanism of high-temperature is revealed, and a constitutive model of high-temperature rock is established. The main conclusions are as follows:

Under the action of high temperature, the bulk density of the three types of rocks shows a downward trend with the increase of temperature, the porosity and permeability increase significantly, the P-wave velocity shows a downward trend, and the attenuation coefficient shows an upward trend, with obvious threshold temperatures — The threshold temperature of sandstone is about 500°C, that of shale is about 400°C, and the strengthening-weakening transition temperature of granite under short-term heating is about 200°C. There is a significant difference in the variation rate of rock physical properties before and after the threshold temperature. Above the threshold temperature, a large number of pores and cracks are generated and connected, the porosity and permeability characteristics are sharply optimized, and the acoustic parameters are rapidly deteriorated. Among them, shale has the largest increase in porosity and permeability and the largest deterioration amplitude of acoustic parameters, followed by granite and sandstone.

In terms of mechanical properties, the uniaxial compressive strength and elastic modulus of the three types of rocks show an overall decreasing trend with the increase of temperature, and the Poisson's ratio shows an increasing trend. The stress-strain curve presents the law of "shortening of elastic stage, prolongation of plastic stage and decrease of peak stress", and the failure mode changes from brittleness to plasticity. Granite has a short-term strengthening effect below 200°C, with a slight increase in strength and elastic modulus; beyond the threshold temperature of each rock, the mechanical properties deteriorate sharply. Among them, shale has the largest strength decline (61.5% from 400°C to 1000°C), followed by granite and sandstone, which is highly related to the degree of rock microscopic damage.

In terms of creep characteristics, high temperature and load jointly affect the creep behavior of rock, and the creep curve presents three stages of instantaneous elastic creep, steady-state creep and accelerated creep; the higher the temperature and the larger the load, the larger the instantaneous deformation, the faster the steady-state creep rate, the earlier the accelerated creep stage appears, and the shorter the failure time. Confining pressure can effectively inhibit rock crack propagation under high temperature, reduce creep rate and prolong failure time, which provides a key reference for the stability control of deep high-temperature engineering rock mass.

The microscopic damage of rock under high temperature is the result of the combined action of physical and chemical changes, and the core mechanisms include four aspects: water evaporation and mineral dehydration, uneven thermal expansion of minerals, mineral phase transformation and organic matter pyrolysis, and subcritical crack growth. The microscopic damage characteristics of rocks with different lithologies are different: the damage of sandstone is mainly due to uneven thermal expansion of minerals and dehydration of clay minerals, the damage of shale is centered on organic matter combustion and bedding damage, and the damage of granite is mainly caused by the generation and subcritical propagation of intergranular and intragranular cracks due to the difference in mineral thermal expansion. The accumulation of microscopic damage ultimately leads to the deterioration of macroscopic performance.

Based on the disturbed state concept theory, a constitutive model of high-temperature rock considering the influence of temperature is established and verified by combining with the discrete element T-SC model. The calculated values of the model are in good agreement with the indoor experimental values (error ≤5%), which can accurately describe the mechanical response characteristics of rock under high temperature and can be used to predict the mechanical properties of rock under high-temperature environment, providing a theoretical tool for engineering design.

Rocks with different lithologies have significant differences in high-temperature response: shale has the worst thermal stability, followed by granite and sandstone with relatively optimal thermal stability. This difference is mainly due to the differences in mineral composition, microstructure and organic matter content, which provides a basis for lithology selection and protective measure formulation in different high-temperature engineering scenarios.

5.2. Prospects

This paper initially reveals the evolutionary laws of physical and mechanical properties and microscopic damage mechanism of rock under high temperature through laboratory experiments, microscopic observation and numerical simulation of multi-lithology rocks. However, there are still some directions for further in-depth research. Combined with the actual engineering needs, the following prospects are put forward:

In terms of the expansion of experimental conditions, this paper mainly carries out experimental research under the conditions of normal temperature confining pressure and single high-temperature environment. In the future, the thermo-hydro-mechanical fully coupled conditions can be considered to simulate the complex scenarios of the combined action of high temperature, high pressure and groundwater in deep engineering, and study the evolutionary laws of rock physical and mechanical properties under the thermo-hydro-mechanical coupling effect, so as to make the research results more in line with engineering practice.

In terms of the extension of research scale, the existing research mainly focuses on the macroscopic and microscopic scales of rock samples. In the future, refined experiments and simulations at the mesoscopic scale (mineral particles, pores, cracks) can be carried out to deeply explore the correlation mechanism between mesoscopic structure evolution and macroscopic performance deterioration, and further improve the high-temperature rock damage theory.

In terms of model optimization, the disturbed state constitutive model established in this paper is mainly applicable to uniaxial compression conditions. In the future, it can be optimized by combining factors such as confining pressure and loading rate to expand the application range of the model; at the same time, machine learning algorithms can be introduced to train prediction models based on a large amount of experimental data to improve the prediction accuracy and efficiency of rock mechanical properties under high temperature.

In terms of the deepening of engineering application, in the future, in-situ field tests can be carried out for specific engineering scenarios (such as long-term operation of nuclear waste disposal repository, efficient exploitation of geothermal resources) to verify the reliability of indoor experimental and numerical simulation results; at the same time, rock mass reinforcement materials and protection technologies adapted to high-temperature environments should be developed to apply the research results more directly to engineering practice and improve the stability and safety of engineering rock mass under high-temperature environments.

In terms of the research on multi-factor coupling, in the future, factors such as high-temperature cycle action and long-term time-dependent action can be considered to study the damage accumulation law of rock under repeated high temperature and long-term high-temperature environments, so as to provide theoretical support for the life assessment of engineering rock mass in long-term high-temperature environments (such as nuclear waste disposal repository, geothermal reservoir).

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