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Mechanical Characteristics of Sandstone under High Temperature and Cyclic Loading in Underground Coal Gasification

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Abstract: In the process of underground gasification of coal, the top rock of coal seam will experience a certain high temperature action and be in a complex stress environment. Therefore, it is of great theoretical and engineering significance to study the effect of cyclic unloading and loading on mechanical properties of rocks under high temperature action. In this thesis, the stress–strain curves of sandstone under different high-temperature treatments are obtained by conducting graded loading and unloading tests on sandstone treated at room temperature and at 200 °C, 400 °C, 600 °C, and 800 °C, respectively. The research content of this paper is as follows: the peak stress, peak strain, elastic modulus, Poisson's ratio, internal friction angle, and cohesion of sandstone in the destruction stage of sandstone. The results show that the peak strain and cohesion of sandstone show an increasing trend with the increase of temperature from room temperature to 800 °C; the peak stress shows a decreasing trend with the increase of temperature from room temperature to 800 °C; the modulus of elasticity tends to increase from 200 °C to 400 °C and to decrease with temperature in the rest of the period; the Poisson's ratio tends to increase from 600 °C to 800 °C and to decrease with temperature in the rest of the period; the internal friction angle increases sharply within room temperature to 200 °C, decreases slowly within 200–600 °C, and decreases sharply when the temperature exceeds 600 °C. The results of the study will provide important reference significance for the design and engineering application of the gasifier of a coal-bed underground gasification project.

Keywords: mechanical characteristics; high temperature treatment; graded loading and unloading; stress–strain curve relationship; basic physical parameters

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1. Introduction

Rock engineering problems in complex stress environments in high temperature operations are a challenge for rock mechanics. In the process of underground coal gasification, the rock around the top of the coal seam will experience certain high temperature action and be under complex stress conditions. At this time, the strength and deformation characteristics of rocks under high temperature are needed to be considered, and the basic mechanical parameters are the basis for solving complex rock mechanics problems.

Over the years, many scholars have studied the subject of the effect of temperature on the properties of rocks by conducting impact compression tests or uniaxial compression tests to investigate the changes in the basic physical parameters and the energy of rocks after different temperatures [1–5]. He et al. [6] compared the changes in volume, ultrasonic velocity, and attenuation coefficient of rock samples before and after experiencing different temperatures. Gu et al. [7] studied the anisotropic characteristics of laminated rocks in terms of dynamic mechanics and fine structure. Xie [8] constructed a theoretical research system of deep rock mechanics and mining with the aim of providing theoretical basis and technical support for the future development of deep mineral resources in China.

Zhu et al. [9] used the extreme value method to determine the model parameters based on the concept of rock yielding, and compared them with the compression test results of granite at different temperatures. Zhang et al. [10] investigated the effect of temperature on the mechanical strength of granite by conducting compression experiments on granite specimens under real-time high temperature; analyzed the differences of physical and mechanical properties of granite under real-time high temperature and thermal shock conditions, and proposed the concept of thermal shock damage coefficient to reveal the mechanism of thermal shock damage to break the rock. Mambou et al. [11] modeled the rate equation for sandstone specimens under uniaxial mechanical loading and high temperatures based on Newton's second law. It was found that, as the temperature increased, the rigidity of the sandstone was lost, the mechanical properties of the sandstone were significantly reduced, and the nonlinear parameters of the material slowly affected the thermal damage to the sandstone. Deng et al. [12] studied the physical and mechanical properties of heated sandstone and examined the factors and mechanisms that influence them. Justo et al. [13] analyzed the main mechanical properties of four different types of isotropic rocks at different temperatures. Tian et al. [14,15] explored the mechanical properties of rocks at high temperatures. Zhang et al. [16] investigated the effect of envelope pressure and envelope temperature on the mechanical properties of the rock. Dorcas S.E Yinla [17] considered the effect of changes in the elastic properties of the material during fault injection on the magnitude of the seismic event. Siddig et al. [18] used the rig's sensor recordings to create a continuous Young's modulus curve and then used two different data sets, one to build and test the model and the other to hide it from the algorithm and later use it to validate the constructed model. Mao et al. [19] studied the mechanical properties of limestone under the effect of temperature from room temperature to 800 °C, such as stress–strain curves, variable properties of peak strength, and elastic modulus of limestone. Liu et al. [20] studied the macroscopic and microscopic mechanical properties of building sandstone under different thermal damage conditions and assessed its thermal stability. Zhang et al. [21] obtained the macroscopic response to the progressive process of thermal damage to sandstone, as well as its microscopic damage mechanism, by measuring the macroscopic physical and mechanical properties of red sandstone heated at different temperatures up to 800 degrees °C, deep in the rock mass.

At present, there are more studies on the physical properties and uniaxial compression tests under high temperature operation of rocks, but there are fewer studies on the change laws of mechanical properties of sandstone under the action of cyclic loading and unloading after high temperature. In this paper, several groups of sandstone specimens were heated at 200 °C, 400 °C, 600 °C, and 800 °C, and a group of normal temperature sandstone specimens were added for comparison tests, and graded loading–unloading tests were conducted on these sandstone specimens to analyze the stress–strain relationship of sandstone at different temperatures, and to study the change law of basic physical parameters of sandstone after high temperature, in order to provide a better understanding of the stability and safety of overlying rocks of coal seams during underground gasification of coal seams, as well as the stability of rocks under complex stress environments. This study will provide a scientific basis for the stability and safety of the overlying rocks in the process of underground coal bed gasification and the design and research of rock engineering under high temperature and complex stress environment.

2. High-Temperature Treatment and Mechanical Properties Test of Sandstone Specimens

2.1. Sampling and Processing of Sandstone Specimens

The sandstone used in this study was taken from coal mine sandstone, and the rocks with good integrity and no damage were selected for sampling. According to the "Rock Dynamic Properties Test Procedure", the rocks were cored, cut, ground, and polished perpendicular to the laminae direction, and the error of non-parallelism at both ends of the sandstone specimen was controlled within 0.05, and then processed into a standard rock specimen of 50 mm in diameter and 100 mm in height.

2.2. High-Temperature Treatment

High-temperature treatment of sandstone was carried out in a chamber-type high-temperature sintering furnace as shown in Figure 1. The sandstone was divided into four groups and heated in the furnace at a rate of 10 °C/min to four temperature levels of 200 °C, 400 °C, 600 °C, and 800 °C, respectively. After heated to the preheating temperature, the sample is held at a constant preheating temperature for 2 h to ensure that the sandstone specimen is heated more evenly inside and out, then the door is slowly opened, and the specimen is allowed to cool naturally to room temperature. Finally, the sandstone specimens after high-temperature treatment were sealed and stored in sample bags, and subsequent tests were carried out after all the preparation was completed.

Figure 1. Box-type high-temperature fritting furnace.

2.3. Mechanical Properties Test

Five sets of sandstone specimens treated at room temperature and high temperature were subjected to conventional uniaxial compression tests and cyclic loading and unloading tests using a graded loading and unloading tester. First, the unconfined compressive strengths of the sandstone specimens were measured by uniaxial compression tests at room temperature, 200 °C, 400 °C, 600 °C, and 800 °C to be approximately 90 MPa, 80 MPa, 70 MPa, 60 MPa, and 50 MPa, respectively, which provided the basis for the subsequent test parameters. The uniaxial compressive strengths of the sandstone at room temperature, 200 °C, 400 °C, 600 °C, and 800 °C were approximately 90 MPa, 80 MPa, 70 MPa, 60 MPa, and 50 MPa, respectively, so each set of specimens at different temperatures was tested at 7, 6, 5, 4, and 3 levels of addition and removal, respectively. The peak load stresses were about 30, 40, 50, 60, 70, 80, 90, and 100 MPa for sandstone at room temperature, 30, 40, 50, 60, 70, 80, and 90 MPa for sandstone at 200 °C, 30, 40, 50, 60, 70, and 80 MPa for sandstone at 400 °C, 30, 40, 50, 60, and 70 MPa for sandstone at 600 °C, and 30, 40, 50, and 60 MPa for sandstone at 800 °C. The specimens were damaged when the sandstone was loaded at room temperature, 200 °C, 400 °C, 600 °C, and 800 °C to the seventh, sixth, fifth, fourth, and third levels, respectively. The high-temperature treated white sandstone specimens are shown in Figure 2, Single-axis cyclic loading and unloading tester are shown in Figure 3.

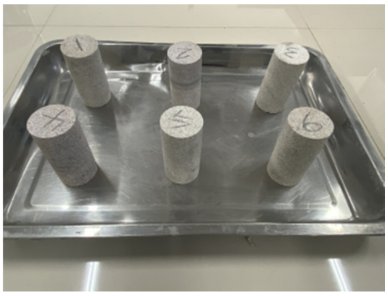

Figure 2. Sandstone specimens after high temperature treatment.

Figure 3. Single-axis cyclic loading and unloading tester.

3. Stress–Strain Curves of Sandstone under Thermal Damage and Cyclic Loading and Unloading Conditions

In order to analyze the evolution of axial stress and axial strain of sandstone under the action of graded unloading after high temperature, the stress–strain curves of sandstone under the action of graded unloading after experiencing different high temperatures are given in Figure 4.

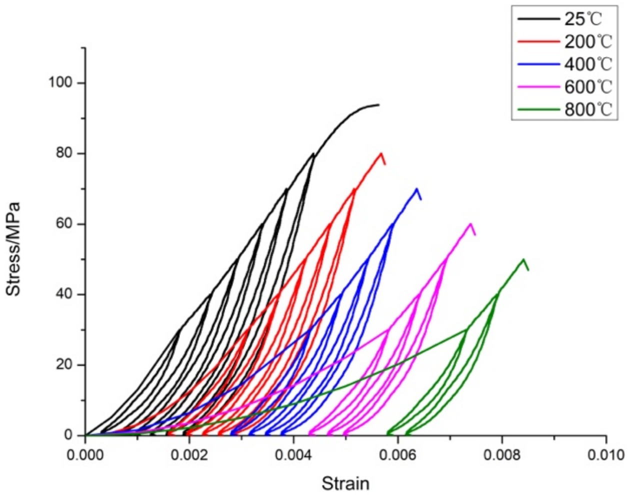

Figure 4. Stress–strain curves of sandstone after different high temperatures.

In the cyclic loading and unloading curve section, the stress and strain in the unloading section fall to the minimum value, but the curve cannot coincide with that of the loading section, thus forming a hysteresis loop, and the position of the hysteresis loop moves along the positive direction of strain, which is caused by the nonlinear characteristics of the rock itself. The residual strain is generated at each level of loading and unloading, resulting in the accumulation of damage within the rock. As the temperature increases, the strength of the rock decreases, the peak stress gradually decreases, the peak strain gradually increases, and the stress–strain curve shifts along the positive direction of strain.

The temperatures corresponding to this stress–strain curve graph from left to right are 25 °C, 200 °C, 400 °C, 600 °C, and 800 °C. The sandstone at 25 °C was damaged when the stress reached 95.6 MPa, the sandstone after 200 °C treatment was damaged when the stress reached 80.9 MPa, and the sandstone after 400 °C treatment was damaged when the stress reached 74.8 MPa. The sandstone treated at 600 °C was damaged when the stress reached 66.2 MPa, and the sandstone treated at 800 °C was damaged when the stress reached 49.5 MPa. It can be seen that, when the temperature is higher, the strength of the sandstone is less, and the brittleness is greater.

4. Mechanical Properties of Sandstone under the Action of High Temperature Cyclic Loading and Unloading

4.1. Peak Stress

The variation of peak stress with temperature in sandstone after experiencing different temperatures and complex graded loading and unloading is shown in Figure 5.

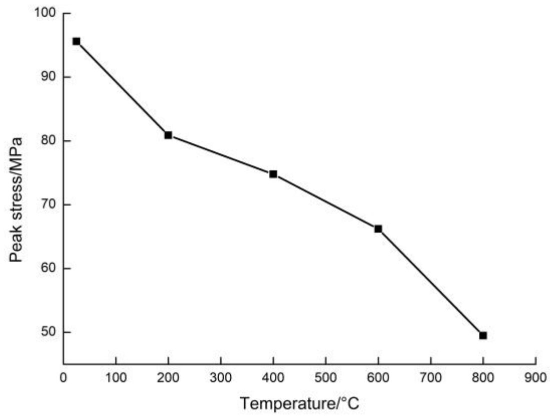

Figure 5. Peak stress in sandstone as a function of temperature.

From room temperature to 800 °C, the average peak stress of sandstone showed a general trend of gradual decrease with increasing temperature. From room temperature to 200 °C, the average peak stress of sandstone decreases from 95.6 MPa to 80.9 MPa, with a decrease of 15.4%. From 200 °C to 400 °C, the average peak stress of sandstone decreases from 80.9 MPa to 74.8 MPa, with a decrease of 7.5%. From 400 °C to 600 °C, the average peak stress of sandstone decreases from 74.8 MPa to 66.2 MPa, a decrease of 11.5%. From 600 °C to 800 °C, the average peak stress of sandstone decreases from 66.2 MPa to 49.5 MPa, with a decrease of 25.2%. It can be seen that the peak stress of sandstone decreases with the increase of temperature.

4.2. Modulus of Elasticity

The modulus of elasticity is the value of the stress required to produce unit elastic deformation of rock material under the action of external force, and it is an indicator of the ability of rock material to resist elastic deformation. The variation of modulus of elasticity of sandstone with temperature at room temperature and after the action of different temperatures is shown in Figure 6.

As can be seen from Figure 6, the average modulus of elasticity of sandstone decreases with increasing temperature until 200 °C. The average modulus of elasticity of sandstone increases from 200 °C to 400 °C, reaching 32.246 GPa, and basically decreases after 400 °C, reaching an average modulus of 12.696 GPa at 800 °C, which is only 33.46% at room temperature. The average modulus of elasticity at 800 °C is 12.696 GPa, which is only 33.46% at room temperature.

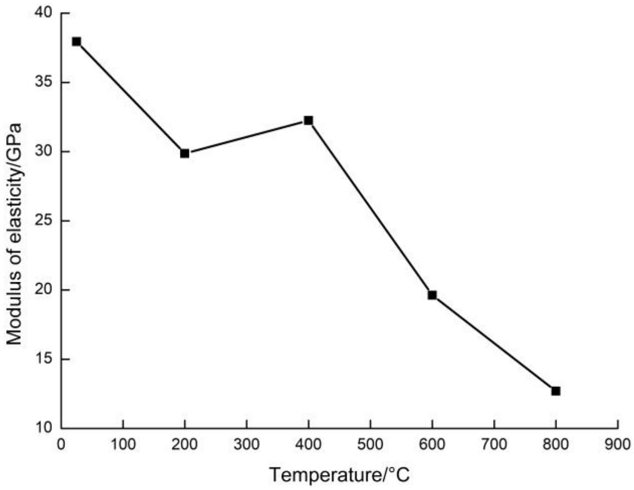

Figure 6. Modulus of elasticity of sandstone as a function of temperature.

4.3. Poisson's Ratio

Poisson's ratio is the ratio of transverse strain to longitudinal strain, which is the basic mechanical parameter of rock materials. Poisson's ratio of different rocks has its specific range of values. In this paper, the authors study the relationship between temperature and Poisson's ratio of sandstone, and the variation of Poisson's ratio of sandstone with temperature at room temperature and after the action of different temperatures, as shown in Figure 7.

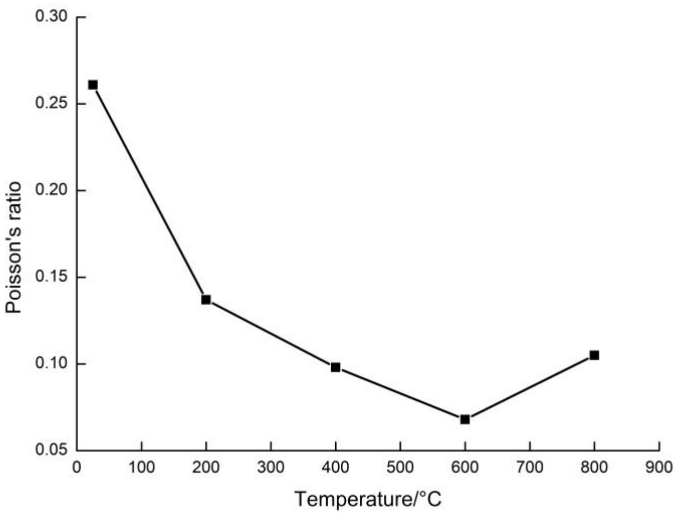

Figure 7. The relationship between Poisson's ratio and temperature for sandstone.

Before 600 °C, the Poisson's ratio of sandstone decreases with the increase of temperature, with the largest decrease of 47.5% before 200 °C. From 600 °C to 800 °C, its average Poisson's ratio shows an increasing trend with an increase of 34.62%.

4.4. Angle of Internal Friction

The internal friction angle refers to the friction characteristic formed by the mutual movement and gluing action between particles in the soil, and its value is the angle between the intensity envelope and the horizontal line. The variation of the internal friction angle of sandstone with temperature after the action of room temperature and different temperatures is shown in Figure 8.

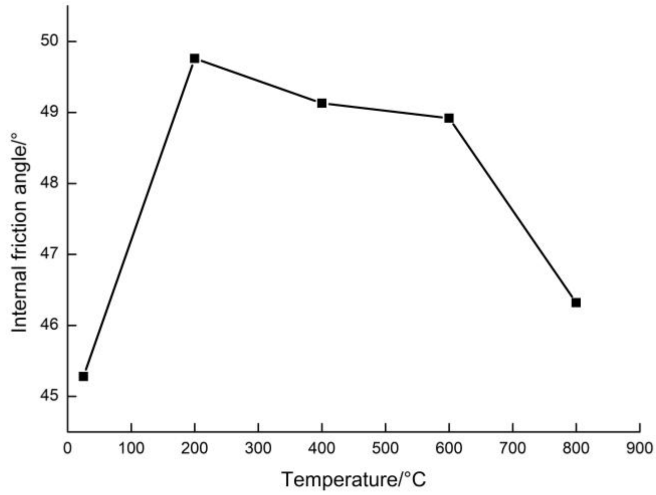

Figure 8. Relationship between internal friction angle and temperature in sandstone.

Before 200 °C, the internal friction angle of sandstone tends to increase with temperature, with an average angle of 49.76° at 200 °C, an increase of 9.89% compared to room temperature. The average angle of internal friction of sandstone is basically in a decreasing trend with increasing temperature from 200 °C to 800 °C.

4.5. Cohesion

The cohesion includes the original cohesion formed by the molecular gravitational force inside the sandstone and the solidified cohesion formed by the cementation of the compounds in the sandstone. The variation of sandstone cohesion with temperature at room temperature and after the action of different temperatures is shown in Figure 9.

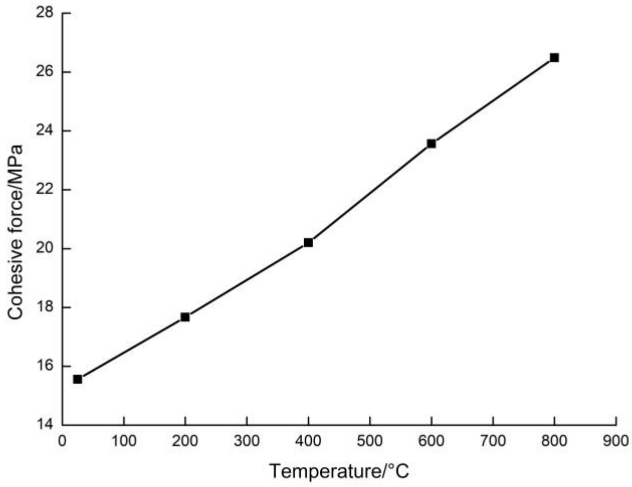

Figure 9. Relationship between sandstone cohesion and temperature.

With the increasing temperature, the cohesion of sandstone also increases, from 15.555 at room temperature to 26.485 at 800 °C, an increase of 70.27%.

The reasons for different basic physical parameters of sandstone under different temperature conditions: the temperature will cause cracks in the inner layers of sandstone to form microcracks due to anisotropy and mismatch of thermal expansion and water loss, increase porosity, decrease uniaxial compressive strength, decrease elastic modulus, decrease Poisson's ratio, and deteriorate the mechanical properties of sandstone; higher temperature will lead to increased sliding resistance between adjacent soil layers, increased shear strength, increased internal friction angle increase, and cohesion increase.

5. Analysis of the Destructive Process and Characteristics of the Rock

In this test, cyclic loading–unloading tests were carried out on four groups of sandstone experiencing high temperatures. By observing the rupture process of the rock and analyzing Figure 4, the whole process of the last load of the rock under the cyclic loading-unloading phase was divided into the following five stages:

(1) Initial crack closure stage: the stress–strain curve is a downward concave section, with the increase of the load, the native microfractures inside the rock under the load gradually close. When the stress value reaches a certain value, the strain of the cracked body no longer increases and the fracture can be considered to be completely closed.
(2) Elastic compression stage: The stress–strain curve is a straight line, and the rock basically does not have new cracks generated within this stage, which shows a straight line in the stress–strain curve, and the mineral particles of the rock body become denser with the increase of the load.
(3) Stable crack growth stage: new cracks are continuously generated and expanded inside the rock, and axial cracks mainly start to appear, and the lateral bulging of cracks produces a shear expansion effect.
(4) Crack accelerated growth stage: when the loading stress reaches the compressive strength of the rock, the stress–strain curve begins to exhibit nonlinear characteristics, and the macroscopic performance of the rock specimen shows macroscopic damage.
(5) Post-peak stage: The rock specimen is destabilized after the peak strength, and the corresponding lateral strain increases dramatically, and the test loading ends.

By observing the statistical analysis of sandstone damage patterns after the test, as shown in Figure 10, it was found that there were four types of fractures that led to the overall rupture of sandstones: (1) open fractures, (2) secondary coplanar fractures, (3) secondary inclined fractures, and (4) oblique fractures as shown in Figure 11.

Figure 10. 600 °C sandstone specimens after damage.

(1) Tension fracture: generally initiated in the middle of the specimen at the earliest, and then gradually extended to both ends under the action of compressive stress. The stress in the middle of the specimen will be concentrated, resulting in tensile stress. The fracture from the middle is gradually extended.
(2) Secondary coplanar fracture: initiated at the tip of the open fracture, after starting the fracture along with the open fracture direction coplanar or nearly coplanar direction stable expansion; after observation of the sandstone specimen after the damage, it can be found that the surface of secondary coplanar fracture shows a rough state.
(3) Secondary inclined fracture: initiated at the end of the open fracture or secondary coplanar fracture, along with the open fracture into a certain angle direction expansion.

Through the test, we can find that, around the secondary inclined fracture specimen fragmentation phenomenon, it is most obvious.

(4) Oblique fracture: initiated in a position in the middle of the open fracture, perpendicular to the direction of the open fracture, and may expand in the form of zigzag lines after developing to a certain stage.

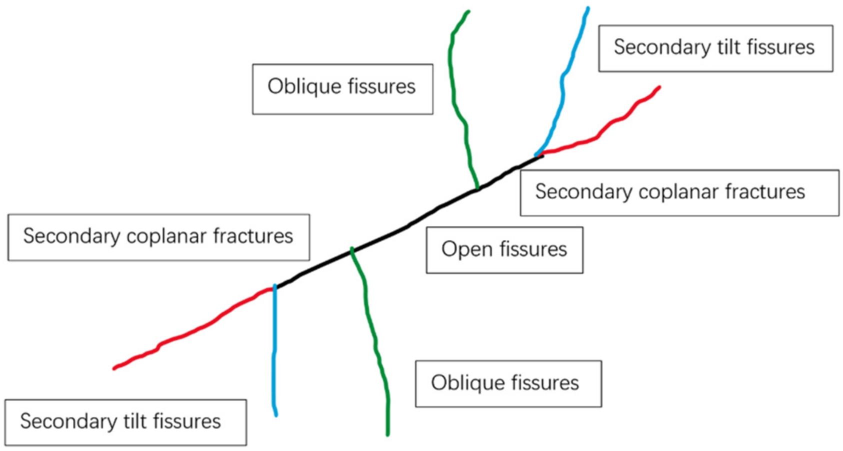

Figure 11. Fracture expansion mode.

6. Conclusions

(1) The peak strain and cohesion of sandstone show an increasing trend with the increase of temperature from room temperature to 800 °C; the peak stress shows a decreasing trend with the increase of temperature from room temperature to 800 °C; the elastic modulus and Poisson's ratio show an increasing trend from 200 °C to 400 °C and 600 °C to 800 °C, respectively, and a decreasing trend with the increase of temperature in the remaining stages; the internal friction angle increases sharply from room temperature to 200 °C. The internal friction angle increases sharply within room temperature to 200 °C, decreases slowly within 200–600 °C, and decreases sharply when the temperature exceeds 600 °C.

(2) Temperature will cause cracks in the inner layer of sandstone to form microcracks due to anisotropy and mismatch of thermal expansion and water loss, increase porosity, decrease uniaxial compressive strength, decrease modulus of elasticity, decrease Poisson's ratio, and deteriorate mechanical properties of sandstone; higher temperature will lead to increase sliding resistance between adjacent soil layers, increase shear strength, increase internal friction angle, and increase cohesion.

(3) As the temperature increases, the strength of the rock decreases, the peak stress gradually decreases, the peak strain gradually increases, and the stress–strain curve moves along the positive direction of strain. When the temperature is higher, the strength of the sandstone is less, and the brittleness is greater.

(4) There are four types of cracks that cause rock to break: open fractures, secondary coplanar fractures, secondary inclined fractures, and oblique fractures. The whole process of rock damage phase can be divided into five stages: initial crack closure stage, elastic compression stage, stable crack growth stage, accelerated crack growth stage, and post-peak stage.

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