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Abstract. Rocks often have certain bedding structures under long-term geological conditions, which leads to different performances. In this paper, ultrasonic analysis of horizontal bedding and vertical bedding is carried out by high temperature tests on anisotropic red sandstone samples to obtain data on mass, density, porosity and longitudinal wave velocity as a function of temperature. Then through the apparent morphology analysis of the sample, data processing and image analysis, the high temperature damage law of the anisotropic sandstone is finally obtained, which provides theoretical support for underground resource development and underground engineering construction.

1. Introduction

With the development of the national economy, the improvement of engineering technology, the construction of major projects and the need for energy exploitation, people began to focus on the development and utilization of underground space, which inevitably touched the high temperature characteristics of rocks. As a kind of aggregate under the action of rock, the internal composition of the rock is more complicated. The properties of different components in the rock are also different after being heated. Some mineral components and internal structures may change under high temperature, and there are many pores inside the rock, which will generate a lot of micro-cracks under the action of temperature. Also, under the action, a large number of micro-cracks will be generated, which will cause the deterioration of the internal structure of the rock and cause thermal damage deformation [1]. It can be seen that high temperature damage has a great impact on rock performance, and it is very important to study the high temperature damage of rock, which is helpful for the safe development and utilization of underground space. In 1976, Dougill [2] pioneered the introduction of damage mechanics into the study of rock-like materials. Since then, Dragon [3] and other scholars have studied the continuous damage of rock according to the theoretical method of damage mechanics, and constructed a damage model suitable for continuous media. Zhang Chuanhu et al [4] summarized the research status of rock physical properties, mechanical properties, damage and constitutive models under temperature. Xiong Liangzhu et al. [5] briefly described the research results of rock mechanics in high temperature and high temperature in China in the past 20 years. Moreover, it can be seen from the summary of the two scholars that the research on rock damage under high temperature in China is still in an immature stage, and the subject of high temperature damage of rock still has a large research space.

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At present, most of the researches on high temperature damage of rocks in China are directed at granite, sandstone, mudstone and marble. For example, Zhang Lianying et al [1] established a statistical constitutive model of marble damage under uniaxial compression, and studied the evolution law of thermal damage characteristics of marble under different temperatures. Xie Weihong et al [6] conducted a real-time experimental study on the mesostructure of limestone under uniaxial compression and uniaxial tension under high temperature, and analyzed the failure mechanism of limestone thermal damage deformation. While, sandstone has been studied by many scholars, as the most widely used stone in humans. Liu Xuyang et al [7] conducted a uniaxial compression test on the heat-treated white sandstone, and established a relationship between the damage variable of white sandstone and temperature. Zhao Hongbao et al [8] obtained the influence of temperature on sandstone damage by studying the ultrasonic velocity change and porosity change law of sandstone after high temperature. Li Chang et al [9] established a creep damage model considering temperature effects, and analyzed the influence of temperature on model parameters. However, compared with isotropic rocks, the mechanical properties of bedding rocks are more special. The existence of bedding has a non-uniform distribution of mechanical properties. The same type of rock regularly distributes the performance advantages and disadvantages. Anisotropic features often occur during loading, which makes the engineering mechanics more complex and directly affects the reliability of the engineering structure.

In this paper, high-temperature experiments were carried out on the anisotropic red sandstones of vertical and horizontal layers. The morphological, quality, density, porosity and longitudinal wave velocity of the different temperatures were investigated to obtain the internal damage at different temperatures, and then the high temperature damage law of the anisotropic red sandstone was obtained.

2. Test

2.1. Sample

The red sandstone used in this test has two layers of vertical and horizontal (shown in Figure 1), and the specification of the sample is $\Phi 96\mathrm{mm}\times 48\mathrm{mm}$. The sample has no obvious cracks and defects.

（a）Vertical bedding （b）Horizontal bedding

Figure 1. Sample

2.2. Test Instruments

2.2.1. Heating equipment. The test adopts RX3-20-12 box type resistance furnace with six built-in thermocouples. The designed maximum temperature is 1200 °C. The temperature of the furnace is controlled by the intelligent push-button temperature control box. The control precision is ±1 °C, as shown in Figure 2.

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（a）RX3-20-12 box type resistance furnace （b）Self-designed guide rail

Figure 2.Heating equipment

2.2.2. Drying device. The test adopts 101-2ASB type electric blast drying oven, and the temperature control precision can reach ±1 °C, as shown in Figure 3.

Figure 3. Blast drying oven

2.2.3. Non-metallic ultrasonic analyser. The test uses a NM-4A non-metal ultrasonic analyzer with a pulse width of 20 μm and a frequency of 50 kHz. Vaseline is used as a coupling agent and evenly applied to the surface of the transducer during testing to remove air between the transducer and the contact surface of the specimen.

Figure 4. Non-metallic ultrasonic analyzer

2.3. Experiment method.

The red sandstone is divided into six groups, with five pieces per group, placed in a box-type resistance furnace to 25 ° C (normal temperature), 200 ° C, 400 ° C, 600 ° C, 800 ° C, 1000 ° C .The control heating rate is 10 ° C / min. Keep warm for 3 h after reaching the preset temperature to ensure the samples are heated evenly inside and outside. Subsequently, in order to avoid the influence of air humidity, we placed the test piece in a blast drying oven and cooled to room temperature to prepare a sandstone sample after high temperature.

Finally, the non-metallic ultrasonic analyzer was used to analyze the prepared samples, to obtain the changes in mass, density, porosity and longitudinal wave velocity.

3. Test results and analysis

3.1. Apparent morphology analysis

（a）Horizontal bedding （b）Vertical bedding

Figure 5. Apparent characteristics of rock at normal temperature

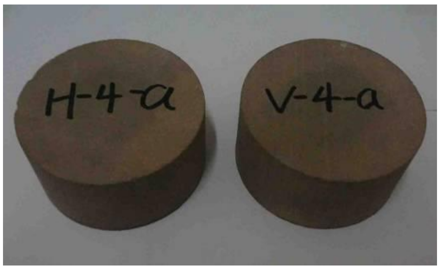
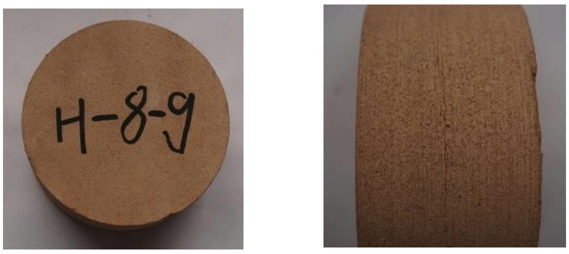
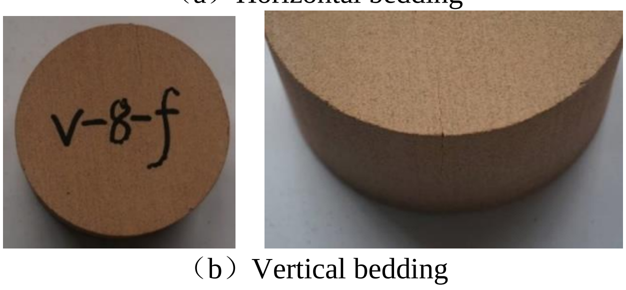


Figure 6. Apparent characteristics of rock at 400°C



（a）Horizontal bedding



（b）Vertical bedding

Figure 7. Apparent characteristics of rock at 800°C

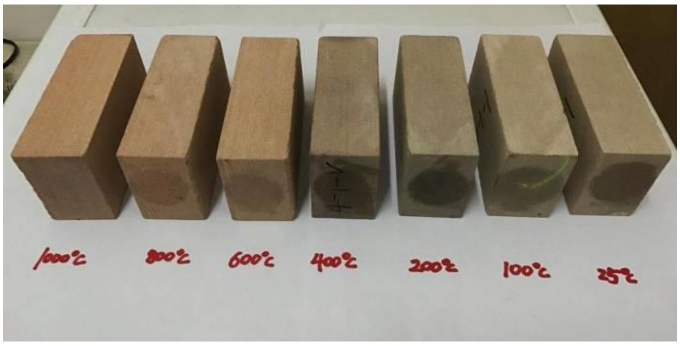


Figure 8. Color contrast of rock samples after different temperatures

The test piece was light gray at normal temperature and the surface condition was good. As the temperature rises, the color of the test piece deepens and tends to be blue-gray. After 600 °C, the color begins to turn yellow, and at 800 °C, apparent cracks appear in both horizontal and vertical bedding.

3.2. Quality change

Under the action of high temperature, different kinds of water inside the rock will evaporate after a certain temperature, and some minerals will also undergo physical and chemical reactions such as decomposition and dehydroxylation, resulting in changes in their quality. Considering that the overall quality of the test specimen is light and the mass change is relatively small, we use the mass loss rate to analyze the mass change characteristics of the rock specimen. The formula for calculating the mass loss rate is as shown in equation (1).

$$M_l = \frac{M_a - M_g}{M_g} \quad (1)$$

In the formula: M_1 is the relative loss rate of mass, which characterizes the loss of mass of rock material after high temperature action; M_a is the initial (before high temperature effect) mass; M_g is the mass after high temperature action.

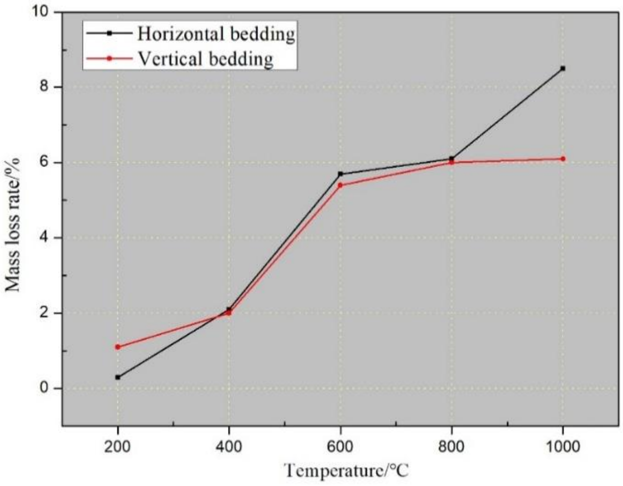


Figure 9. Mass loss rate of samples at different temperatures

As the temperature rises, the water inside the rock evaporates continuously and the physicochemical reaction progresses. The mass loss rate of the horizontal and vertical bedding of the sample generally increases with the increase of temperature, and growing speed of the mass loss rate of the horizontal bedding slows down at 600~800°C , and then continues to increase significantly after 800°C. While the mass loss rate of vertical bedding increases rapidly at 400~600°C, and the growth trend slows down after 600°C, and tends to be stable after 800°C at 6.1%.

3.3. *Density change*

The density of rock is related to internal mineral components, attached water and combined water. Some minerals decompose during high temperature, and some minerals expand, accompanied by water changes. Considering that the overall quality of the test sample is lighter and the density changes are relatively small, the density loss rate is used to characterize the change of density index at high temperature.

The calculation method of the density loss rate of anisotropic rock is as follows.

$$\rho_l = \frac{\rho_a - \rho_g}{\rho_g} \quad (2)$$

In the formula: ρ_l is the relative loss rate of density, which characterizes the degree of density loss of rock material after high temperature; ρ_a is the initial (before high temperature) density; ρ_g is the density after high temperature action.

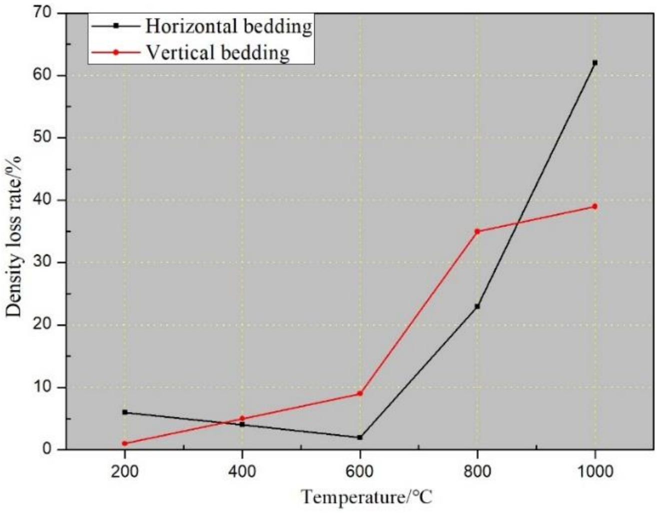


Figure 10. Density loss rate of samples at different temperatures

The density loss rate of the horizontal bedding of the sample at a high temperature is slowly decreased at 200-600 ° C, then rapidly increases after 600 ° C, and finally the density loss at 1000 ° C reaches 60%. The density loss rate of vertical bedding is generally slow, with a rapid increase at 600-800 °C and a growth value of 25%.

3.4. *Porosity change*

The rock sample porosity can be used to describe the changes in the internal composition of the rock and the development of the crack. It can be obtained by the quality of the sample in different states. The calculation method is as follows.

$$\phi_e = \frac{M_w - M_d}{M_s - M_{sw}} \times 100\% \quad (3)$$

$$\phi_t = \frac{M_s - M_d}{M_s - M_{sw}} \times 100\% \quad (4)$$

In the formula: ϕ_e is the effective porosity, which is the ratio of the open pore volume to the total volume of the sample, also known as the open porosity; ϕ_t is the total porosity, the ratio of the total pore volume to the total volume inside the sample is characterized; M_w is the mass of the rock sample after free water absorption; M_d is the mass of the rock sample after drying; M_s is the mass after the rock sample is saturated; M_{sw} is the mass of the saturated rock sample measured by water weighing.

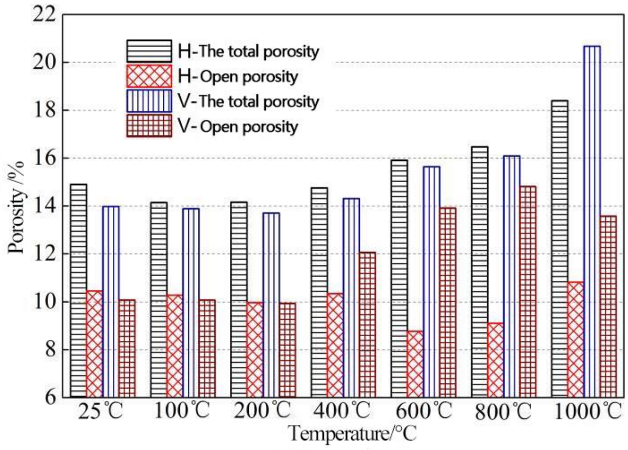


Figure 11. Porosity change of samples at different temperatures

In order to more intuitively observe and analyze the change of porosity with temperature, we define the relative value of porosity— δ , and the calculation formula is as follows.

$$\delta = \frac{\phi_g}{\phi_c} \quad (5)$$

In the formula: δ is the relative change of rock porosity to initial porosity after high temperature; ϕ_g is the porosity of rock sample after different high temperature action; ϕ_c is the initial porosity of rock sample (porosity under normal temperature condition). The calculation results are averaged.

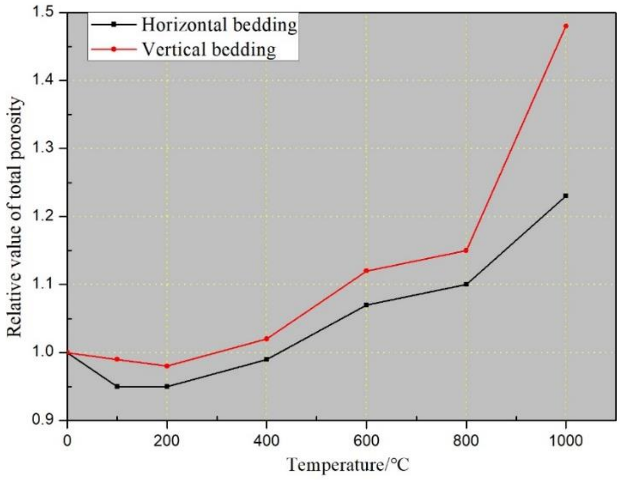


Figure 12. Relative porosity of samples at different temperatures

Generally speaking, the relative porosity of the horizontal and vertical bedding of the sample decreased first and then increased with the increase of temperature. The relative porosity of the horizontal bedding decreased first from 0 to 100 °C, and after 100 °C, it grows slowly and then grows rapidly at 800~1000°C, with a growth rate of (1.24-1.1)/1.1=12.7%; the relative porosity of vertical bedding decreases first at 0~200°C, and slowly increases after 200°C. The growth rate is faster at 800~1000 °C, and the growth rate is (1.48-1.15)/1.15=28.7%. The descending section is dominated by the expansion of the filler between the cracks, after which the crack develops and the porosity increases.

3.5. Analysis of longitudinal wave velocity changes

The use of wave velocity to study rock damage is a non-destructive test method. After high temperature action, physical and chemical reactions such as dehydration, crack development and mineral differential expansion inside the rock will lead to changes in the longitudinal wave velocity of the rock. In the following, according to the wave velocity measurement data of sandstone samples under different temperature effects, the curve of wave velocity with temperature is obtained.

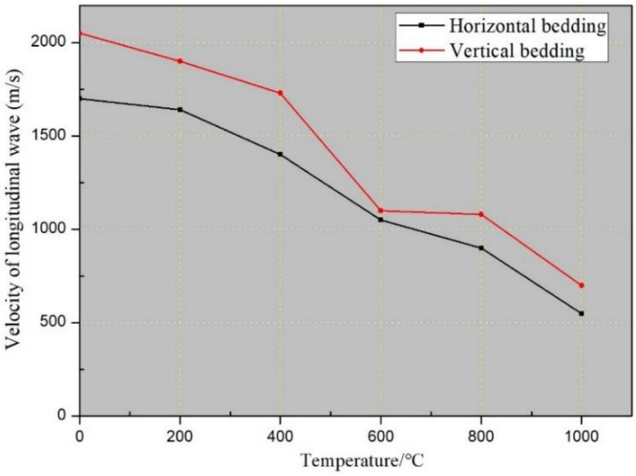


Figure 13. Longitudinal wave velocity changes of samples at different temperatures

With the increase of temperature, the internal cracks of the rock continue to develop and the porosity increases. The longitudinal wave velocity of the horizontal and vertical bedding of the sample generally decreases, and both decrease rapidly at 400~600 °C. In addition, the longitudinal wave velocity of the vertical bedding occurs at 600~800 °C due to the decomposition of some minerals and the continued expansion of some other minerals. The two effects mutually inhibit each other.

4. Conclusion

In this paper, the high temperature test of anisotropic red sandstone samples and the analysis of non-metallic ultrasonic analyzers are carried out to obtain the relevant data of mass, density, porosity and longitudinal wave velocity as a function of temperature. Then through the analysis of the apparent morphology of the sample, as well as the data processing and image analysis, the high temperature damage law of the anisotropic sandstone is finally obtained:

1. After the high temperature action, the red sandstone gradually changes from light gray to blue gray and finally turns yellow, and apparent cracks appear at 800 °C. The mass loss increases with the increase of temperature, and the horizontal bedding quality loss is greater. The density loss is mainly reflected after 600 °C, and the density loss of horizontal bedding is significantly higher than that of horizontal bedding. The porosity of both horizontal and vertical bedding decreases before 200 °C, and increases after 200 °C, and the porosity of vertical bedding is higher than horizontal bedding in the whole process. The longitudinal wave velocity is gradually reduced in the overall trend.

2. By analyzing the variation characteristics of each parameter with temperature, it can be obtained that the critical value of the stable development of the parameter trend is 400~600 °C. The reason is that before the rock at 600 °C, due to physical and chemical changes of some mineral components, crack development, water evaporation and participation in chemical reactions, the internal conditions of the rock are complicated, and the parameter curve may rise or fall. While, after 600 °C, the parameter change law is more obvious, and there is no mutation.

3. Through the combination of apparent morphology, mass, density, porosity and wave velocity, it can be used as a physical method to quickly and effectively identify high temperature damage of rocks. Apparent morphology, as the most intuitive form of thermal damage of rock, can qualitatively determine the degree of thermal damage of rock by virtue of the observed color change and apparent crack development; then, through the changes in mass, density, and porosity, the internal damage

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condition is further judged; finally, the wave velocity, the more sensitive parameter are used to evaluate the detailed damage of the rock, so as to obtain the most accurate high temperature damage of the rock.

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