Study on physical and dynamic splitting mechanical properties of temperature-water coupled sandstone

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Abstract: Temperature and water are important factors to induce the mechanical properties of rock mass, the deformation and failure of rock under dynamic load such as blasting depends on its tensile strength. In order to study the influence of temperature and water coupling on the mechanical properties of rock dynamic splitting, the basic physical parameters of sandstone specimens were measured at room temperature and after 45 ℃ water bath treatment, and the dynamic splitting tensile tests at 8 loading rates were carried out using the Hopkinson pressure bar (SHPB) test apparatus. The results show that the mass and volume of sandstone specimen increased slightly after water bath, but the increase of density was small, and the increase of longitudinal wave velocity was obvious. The dynamic tensile strength and radial dynamic strain of the specimen have a quadratic function relationship with the loading rate, and the positive correlation is obvious, the dynamic tensile strength and radial dynamic strain show strong strain rate effect. The dynamic tensile strength of sandstone specimens after water bath is lower than that under natural condition, but the radial dynamic strain of the specimen after water bath is higher than its natural state. The strain rate increases as a power function of the loading rate, the strain rate of the specimen after water bath is higher than that under...
natural condition. The failure mode of the specimen after water bath satisfies the condition of validity of Brazilian disc.

Key words: rock dynamics; temperature-water coupling; Brazilian disc; dynamic splitting; strain rate effect; SHPB

1. Introduction

Mineral resources are an essential part of human life, but shallow resources have become increasingly unable to meet human needs, so the development of deep mineral resources has become an inevitable trend. High temperature and groundwater have adverse effects on the safety of rock engineering[1-2]. Therefore, it is of great engineering significance to study rock physical and dynamic mechanical properties under temperature-water coupling.

Because the tensile strength of rock is far less than the compressive strength, the failure of rock often depends on its tensile mechanical properties. In order to solve the problem that direct tensile test of rock material is difficult, scholars of China and abroad usually use indirect method to measure tensile properties. For example, the Brazilian disc test (splitting tensile test)[3]. In recent years, more and more scholars have used SHPB device to conduct dynamic fracture tensile test of rock. Ping [4-5] studied the dynamic tensile strength, radial strain, average strain rate and fracture type of sandstone at different temperatures through SHPB splitting tensile test. The failure modes, average strain rate effect and dynamic tensile stress intensity of sandstone specimens are analyzed. Scholars of China and abroad have carried out a large number of studies on the influence of temperature and water on rocks[6]. Gao[7] studied the dynamic compression characteristics of temperature-damaged marble under different water content conditions; Deng[8] conducted splitting tests on layered sandstone with different water content, and concluded that the tensile strength of sandstone decreased with the increase of water content; Yuan [9] concluded that the dynamic uniaxial compressive strength and longitudinal wave velocity of sandstone both increased exponentially with the increase of water content.

It can be seen that China and abroad scholars seldom study the mechanical properties of rocks under the combined action of temperature and water, and most of their studies focus on the static load test, while less on the dynamic load. Therefore, the temperature-water coupling method is adopted in this test to study the dynamic splitting mechanical properties of sandstone specimens.

The sandstone test specimens in this paper are selected from Gubei Coal Mine in Huainan City, Anhui Province. The depth of the mine can reach more than 700 meters. Combined with the local annual average temperature, the temperature at the bottom of the mine is about 45 °C; Therefore, the test scheme in this paper adopts 45 °C for coupled temperature-water treatment of rock. In order to study the change law of physical and dynamic splitting mechanical properties of sandstone under different loading rates. The physical properties of sandstone before and after water bath were measured, and the changes of volume, mass, density and wave velocity were analyzed. The specimens were divided into eight experimental groups with four parallel specimens in each group. Each experimental group was corresponding to eight different impact pressure (0.3MPa–0.475MPa), shock experiments (SHPB) were performed at these pressures[10-15]. At the same time, the time of the bullet passing through the laser source was recorded and the loading rate was calculated. The dynamic characteristics of dynamic compression stress-strain curve, dynamic
compressive strength, dynamic strain and strain rate and their variation rule were analyzed.

2. Experimental research

2.1. Processing and preparation of sandstone specimens

The specimen was processed in accordance with the test specification and requirements[16]. The size of the specimen was Φ50mm×25mm. Using rock coring machine, cutting machine, grinding machine on the specimen processing. In order to reduce the test error, the test specimens are taken from the same rock mass. The end face roughness is required to be within the range of ±0.05mm, the end face is perpendicular to the axis, and the error is controlled within ±0.25°. Ensure the machining accuracy and meet the requirements of the test specification[17]. The average density and longitudinal wave velocity of natural specimens are 2.65 g/cm³ and 3044 m/s.

2.2. Test scheme

The sandstone specimen was evenly placed in the water bath box, and then heated to 45°C at a heating rate of 1.6°C per minute, which took about 25min and kept the temperature constant for 48 hours. When the temperature rises, the temperature of the water bath box per minute is recorded. The temperature of the water bath box rises linearly with time, and the heating rate slows down when approaching 45°C. After the water bath was kept at a constant temperature for 48 hours, the specimen was taken out of the water bath, dried with a dry towel, and its mass, diameter, thickness, longitudinal wave velocity and other basic physical parameters were measured. Then SHPB splitting tensile test was carried out to analyze the dynamic splitting mechanical properties of sandstone. In addition, a control group of normal temperature sandstone specimens was set and SHPB impact splitting test was carried out. Thus, the dynamic mechanical properties of unbathed and bathed sandstone are compared and analyzed.

2.3. SHPB experimental apparatus

Using the stress wave signals collected from the strain gauge on the incident and transmission bars, based on the one-dimensional stress wave theory and the assumption of stress uniformity, as well as Newton's third law, the experimental loads P(t), strain $\varepsilon_s$ and mean strain rate $\dot{\varepsilon}_s$ were given to the specimens in the process of splitting impact. The calculation principle is shown in Formula (1).

$$
\begin{align*}
P(t) &= E_0A_0[\varepsilon_i(t) - \varepsilon_R(t)] = E_0A_0\varepsilon_T(t) \\
\varepsilon(t) &= \frac{2C_0}{D} \int_0^t [\varepsilon_i(t) - \varepsilon_T(t)] dt = \frac{2C_0}{D} \int_0^t \varepsilon_R(t) dt \\
\dot{\varepsilon}(t) &= -\frac{2C_0}{D} [\varepsilon_i(t) - \varepsilon_T(t)] = -\frac{2C_0}{D} \varepsilon_R(t)
\end{align*}
$$

Where, $E_0$ and $A_0$ are the elastic modulus and cross-sectional area of the compression bar material respectively; $\varepsilon_i$, $\varepsilon_R$, $\varepsilon_T$ are incident, reflection and projection strains respectively. $C_0$ is the longitudinal wave velocity of the compression bar, $C_0 = \sqrt{E_0/\rho_0}$, $\rho_0$ is the density of the press bar material; D is the diameter of the specimen; $\tau$ is the duration of stress wave.
The static and dynamic stress distribution of rock is basically consistent in the dynamic splitting tensile test. Therefore, the dynamic tensile stress $\sigma_{dt}(t)$ of specimens in the SHPB tensile test can be calculated by using the elastic mechanics method, and the calculation formula is shown in Formula (2).

$$\sigma_{dt}(t) = \frac{2P(t)}{\pi DB} = \frac{2E_0A_0\varepsilon(t)}{\pi DB} \quad (2)$$

Where: $B$ is the thickness of the disc specimen.

3. Test data analysis

3.1. Analysis of physical properties

The color and apparent morphology changes of sandstone before and after 45 $^\circ$C water bath are shown in Fig. 1. Before and after the water bath, the color of the specimen can be found to change. The color of the original specimen was gray and white. After 48 hours of water bath, the color was deepened by the infiltration of warm water.

(a) before water bath  (b) after water bath

Figure 1. Apparent morphology of sandstone before and after water bath

According to the relevant test standards of engineering rock mass, the physical parameters of the specimen at 45 $^\circ$C before and after treatment were measured to calculate its volume and density. The C61 type non-metallic ultrasonic detector was used to measure the time taken for a longitudinal wave to propagate at both end faces and calculate the longitudinal wave velocity.

Compared with before the water bath, the wave velocity of the specimen increased after the water bath, with an increase rate of 2.9%. The mass increases by 0.56% in step with the volume, and the density remains basically the same. Because the sandstone itself is unsaturated rock mass, after 48 hours at 45 $^\circ$C constant temperature treatment, water will immerse into the void, making its mass increase. At the same time, after 45 $^\circ$C water bath heating, the volume of sandstone will expand slightly.

3.2. Dynamic property analysis

The specimens without water bath and after water bath were subjected to splitting impact using SHPB test apparatus. In order to reduce the friction and the influence of the end face constraints on the stress distribution in the specimen, Vaseline was applied to the contact area between the end face of the specimen and the pressure bar during splitting test. The time taken for the bullet to pass through the light controller was recorded to calculate the loading rate. In order to reduce the test error generated in the test process, two test data with small dispersion were selected for each group.

3.2.1. Relationship between dynamic tensile strength and impact rate

After SHPB test device carried out splitting impact on the specimen, the specimen was
damaged when it reached the peak stress. The peak stress was the dynamic compressive strength, which was the maximum stress value in the stress-strain diagram of rock mass shear test. By analyzing the reasons, as the impact pressure increases, the loading rate gradually increases, and the cracks in the rock fail to cut-through in time, resulting in deformation hysteresis, thus increasing the tensile stress of the specimen, which is also known as the rock strain rate effect. The relationship between impact rate and dynamic tensile strength is shown in Figure 2. The correlation coefficient $R^2$ reached 0.9794 and 0.9781, and this curve had a good fitting effect.

![Figure 2. Relationship between dynamic tensile strength and loading rate](image)

3.2.2. Relationship between different loading rates and average strain rates

The average strain rate of specimens without water bath and after 45°C water bath varies with the loading rate and the fitting curve is shown in Figure 3.

![Figure 3. Relationship between different loading rates and strain rates](image)

According to the fitting curve, the average strain rate and impact rate satisfy the power function relationship. The $R^2$ reached 0.9823 and 0.9721, which had a strong correlation. It shows a strong strain rate effect. With the increase of impact rate, the power function of strain rate increases, and the sandstone is more likely to be damaged. The average strain rate of the specimen after water bath is obviously higher than that without water bath. Therefore, after water bath and heating treatment, sandstone is more prone to damage, and the degree of damage will be greater.

3.2.3. Relationship between peak strain and different loading rates

![Figure 2. Relationship between dynamic tensile strength and loading rate](image)

![Figure 3. Relationship between different loading rates and strain rates](image)
In SHPB impact test, the dynamic peak strain can reflect the maximum fracture degree of the specimen. The study of peak strain is helpful to analyze the strength and breaking degree of the test piece, and obtain the dynamic properties of the test piece.

The variation law of peak strain with impact rate and the fitting curve of specimens after and without water bath are shown in Figure 4.

![Figure 4. Relationship between different loading rates and peak strain](image)

According to the fitting curve obtained, the correlation coefficient $R^2$ between the peak strain and the impact rate of the specimen both reached 0.9862 and 0.9746, which proved that the fitting curve had a good fitting effect. According to the fitting curve, the relationship between peak strain and impact rate is a quadratic function. At the same time, it can also be concluded that with the increase of impact rate, the damage degree of sandstone is gradually increasing. By comparing the specimens after water bath with those without water bath, it can be found that the sandstone specimens after 45°C water bath have higher peak strain and are more likely to be damaged.

### 3.4. Failure mode analysis

After the impact of the SHPB device, fragments of sandstone specimens with and without water bath were obtained, as shown in Figure 5 and Figure 6.

![Figure 5. Fragments of specimens without water bath (Impact pressure: MPa)](image)

![Figure 6. The specimen is broken after the water bath (Impact pressure: MPa)](image)

It can be seen that the dynamic fracture failure pattern of the specimen is mainly divided into two parts along the radial loading direction, which is consistent with the theoretical analysis and meets the validity condition of the Brazilian disc test. At the same temperature, with the increase of loading rate, the area of local crushing area of the specimen becomes larger and larger. The
extent of the damage is also increasing. By comparing the failure modes of the specimens after water bath with those before water bath, the local crushing area of the specimens after water bath is larger, and the damage degree is greater than that of the specimens without water bath. The reason for the analysis is that at 45 °C, thermal expansion occurred in the cracks inside the sandstone, accompanied by water immersion, which gradually increased the cracks, softened the specimen and reduced its integrity. In this way, in the impact test, the test block will be more prone to damage after the water bath, and the damage degree is greater.

4. Conclusion

The physical parameters of sandstone specimens before and after 45 °C water bath were measured to analyze the physical properties of sandstone. At the same time, the SHPB impact test was carried out on eight groups of specimens with eight pressures ranging from 0.300MPa to 0.475MPa to analyze the relationship between the dynamic tensile strength, peak strain and average strain rate of sandstone and the loading rate.

(1) After temperature-water coupling action, the color of sandstone darkens slightly. The longitudinal wave velocity increases by 2.69%. The dynamic tensile strength and dynamic strain of the specimen are positively correlated with the loading rate as a quadratic function, and showing a strong correlation.

(2) The SHPB test data were compared between the two groups without water bath and after water bath: After the water bath, the peak strain and average strain rate of the specimen increased obviously, while the dynamic tensile strength decreased. Therefore, the temperature-water coupling effect reduces the dynamic properties of sandstone and makes it more prone to damage.

(3) With the increase of loading rate, the area of local crushing area increases and the damage degree becomes larger and larger. The failure mode is mainly split into two parts along the radial loading direction, which meets the validity condition of the Brazilian disc test.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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