Determination of Parameters of Johnson-Holmquist-II (JH-2) Constitutive Model for Red Sandstone

Hongxin Huang*, Wenbin Li and Zhenyu Lu
College of Mechanical Engineering, NJUST, Nanjing 210094, China
Email: huanghongxin@njust.edu.cn

Abstract. In this paper, the parameters of Johnson-Holmquist II (JH-2) model of red sandstone are determined. Firstly, some mechanical properties of red sandstone specimens are tested, including quasi-static compression, SHPB dynamic compression test and Brazilian disk splitting test, and the basic mechanical parameters are obtained. Then, according to the theoretical model of JH-2 and other supplementary literature, some material parameters are preliminarily determined. Finally, by comparing the numerical simulation results with the experimental results, satisfactory parameters are obtained, which can effectively and accurately describe the mechanical response of red sandstone at various stages.

Keywords: Red sandstone; JH-2; Mechanics test; Numerical simulation

1. Introduction

As a natural medium [1], rock has a wide range of applications in many fields, especially in the field of protection engineering, in which the impact of projectiles on rocks has always been a hot topic for researchers [2-6]. The diversity of rock materials and the discreteness and complexity of mechanical properties make the test of the same type of rock have different results.

In the past ten years, due to the rapid development of computers and large-scale calculation programs, more and more researchers have devoted themselves to the study of numerical simulation methods for rock impact and collision problems. Many researchers have developed many material constitutive models of rock [7-13] for accurately describing the mechanical properties of rock materials under different loads.

In the existing constitutive models, the JH-2 model takes into account the factors of pressure, volume, and strain rate, and at the same time has been softened, making this model widely used in the nonlinear dynamics of explosion and impact phenomena. This model parameters of many rocks have been basically determined [14-16], but parameters of red sandstone have not been estimated. Therefore, this paper will determine the JH-2 constitutive parameters of the red sandstone based on the mechanical performance experiment of the red sandstone and combined with the numerical simulation.

2. The description of JH-2 model

2.1. Strength Description

The strength model of JH-2 includes three states of material intact, damage, and fracture (figure 1(a)). For a intact material, its normalized complete strength is described by the following formula [10,13,17-18]:

$$\sigma_i^* = A(P^* + T^*)^N \left(1 + C \ln \dot{\varepsilon}^* \right)$$  

(1)
Where $\sigma_i^* = \sigma_i / \sigma_{HEL}$ is the normalized complete strength; $A$ and $N$ are the complete material constants; $C$ is the strain rate coefficient; $P^* = P / P_{HEL}$ is the normalized hydrostatic pressure; $T^* = T / T_{HEL}$ is the normalized maximum tensile hydrostatic pressure; $\dot{\varepsilon}^* = \dot{\varepsilon} / \dot{\varepsilon}_0$ is the dimensionless strain rate.

For fractured materials, the normalized fracture strength is defined as follows [10,13,17-18]:

$$\sigma_f^* = B(P^*)^M \cdot (1 + C \ln \dot{\varepsilon}^*)$$  \hspace{1cm} (2)

Where $B$ and $M$ are the parameters of the fracture material; $P^*$, $C$ and $\dot{\varepsilon}^*$ are already defined in Eq. (1). Normalized fracture strength $\sigma_f^* \leq \mathrm{SFMAX}$. 

For damaged materials, the normalized strength is defined as [10,13,17-18]:

$$\sigma_D^* = \sigma_i^* - D(\sigma_i^* - \sigma_f^*)$$  \hspace{1cm} (3)

Where $D$ is the damage factor ($0 \leq D \leq 1$).

The above formula describes the material from complete to damage to complete fracture at the end.

![Diagram](image_url)

(a) The intact, damage and fractured strength.

(b) Equation of state.

(c) The damage model.

**Figure 1.** Description of JH-2.

### 2.2. Equation of State

When the material is intact, the relation (figure 1(b)) between hydrostatic pressure $P$ and volumetric strain $\mu$ is [10,13,17-18]:

$$P = K_1\mu + K_2\mu^2 + K_3\mu^3$$  \hspace{1cm} (4)
As material damage accumulates, Eq.(4) will add a $\Delta P$. When $D = 0$, $\Delta P = 0$; when $D = 1$, $\Delta P = \Delta P_{\text{max}}$.

The polynomial equation of state for increasing pressure is as follows [10,13,17-18]:

$$P = K_1 \mu + K_2 \mu^2 + K_3 \mu^3 + \Delta P$$

When the material is under tension, the polynomial equation of state becomes

$$P = K_1 \mu$$

Where $K_1$, $K_2$, $K_3$ are the constants of the equation of state; $\mu = \rho / \rho_0 - 1$ is the volumetric strain ($\rho$ and $\rho_0$ correspond to the initial and current density of the material, respectively).

2.3. Damage Description

The material damage curve is shown in figure 1(c). As the pressure on the material increases, the plastic strain $\varepsilon_f^P$ at fracture is [10,13,17-18]

$$\varepsilon_f^P = D_1 (P^f + T^f)^{D_2}$$

Where $D_1$ and $D_2$ are the damage parameters of the material.

With the increase of plastic deformation $\varepsilon_f^P$, the damage value $D$ also increases. It can be calculated as follows [10,13,17-18]:

$$D = \sum \frac{\Delta \varepsilon_p}{\varepsilon_f^P}$$

3. Mechanical Test

3.1. Quasi-static Compression Test

Quasi-static compression tests on Φ40×80mm red sandstone specimens (figure 2(a)) at two strain rates ($2 \times 10^{-4}$ and $2 \times 10^{-3}$) is completed by the CSS44300 electronic universal material testing machine. The process of rock breaking is recorded by a high-speed camera. The test layout is shown in figure 2(b).

Figure 2. Specimen and test layout

Suppose $L$ is the length of red sandstone specimen, $\dot{\varepsilon}$ is the strain rate, and $v$ is the compression speed of the beam of the testing machine, then

$$\dot{\varepsilon} = \frac{v}{L}$$

Where $v$ is 0.96mm/min and 9.60mm/min respectively, and $\dot{\varepsilon}$ is calculated as $2 \times 10^{-4}$s$^{-1}$ and $2 \times 10^{-3}$s$^{-1}$.
respectively. The test results are in Table 1 and Figure 3.

Table 1. Quasi-static compression test results.

| Test no. | Compression speed (mm/min) | Strain rates (s⁻¹) | Compressive strength (MPa) |
|----------|---------------------------|--------------------|---------------------------|
| 1        | 0.96                      | 2×10⁻⁴             | 59.12                     |
| 2        | 0.96                      | 2×10⁻⁴             | 58.28                     |
| 3        | 9.60                      | 2×10⁻³             | 50.89                     |

Figure 3. Quasi-static compression curve.

3.2. SHPB Dynamic Compression Test

According to some researches [19,20] and considering the diameter of the pressure rod, the size of the specimen is determined to be Φ40×20mm as shown in Figure 4(a). Due to the relatively large size of the rock specimen, it is difficult to ensure that the stress wave reaches equilibrium before reaching the peak when the cylindrical bullet with the same cross-section as the incident rod is used. In order to ensure the consistency of multiple tests as much as possible, the spindle-shaped bullet as shown in Figure 4(b) is selected.

(a) Red sandstone specimen for SHPB test.

(b) Spindle bullet.

Figure 4. Specimen and bullet.

The dynamic compression test groupings are shown in Table 2. According to the assumption of one-dimensional elastic stress wave [21], the following formula is given:
\[ \sigma_i(t) = \frac{AE}{2A_s} \left[ \varepsilon_i(X_{G1}, t) + \varepsilon_i(X_{G2}, t) \right] \]  \hspace{1cm} (10) \\
\[ \varepsilon_i(t) = \frac{C_0}{l_s} \int_0^t \left[ \varepsilon_i(X_{G1}, t) - \varepsilon_i(X_{G2}, t) - \varepsilon_i(X_{G1}, t) \right] dt \]  \hspace{1cm} (11)

Where \( A \) is the cross-sectional area of the specimen and transmission rod is 1256mm\(^2\); \( E \) is the elastic modulus of the rod material high-duralumin is 71GPa; \( C_0 \) is the longitudinal wave velocity of the rod material 5100m/s; \( A_s \) is the cross-sectional area of the rock specimen 1256mm\(^2\); \( t \) is the stress wave loading time during the dynamic compression test; \( \varepsilon_i(X_{G1}, t) \) is the incident strain; \( \varepsilon_r(X_{G1}, t) \) is the reflected strain; \( \varepsilon_t(X_{G2}, t) \) is the transmission strain. Combined with the data read by the super dynamic strain gauge, the calculated stress-strain curve of red sandstone at high strain rate is shown in figure 5.

| Table 2. Red sandstone SHPB test. |
|-----------------------------------|
| Test no. | Bullet speed(m/s) | Strain rate(s\(^{-1}\)) |
| 1        | 14.8              | 312                   |
| 2        | 16.5              | 484                   |

![Figure 5. Dynamic compression curve.](image)

### 3.3. Brazilian Disc Test

The Brazilian disc test [22,23] is the most commonly used test method at home and abroad. In 1987 and 1999, China listed it in the industry standard and the national standard respectively. According to the International Society of Rock Mechanics (ISRM) standard, when the rock is subjected to static tensile test, the rock is made into a disc-shaped standard specimen. During the test, a pair of equal linear loads are applied to the test piece in the radial direction through the upper and lower indenters of the testing machine, as shown in figure 6(a).
The fixture as shown in figure 6(b) is designed to fix the position of the specimen. The size of the test piece was Φ50×25mm. The upper part of the fixture is fixedly connected with the press as a whole to restrain the rock specimen, ensuring that the rock specimen is preloaded by the press no slippage occurs, which ensures that the press can generate a radial line load across the center of the specimen, and can make the tensile failure fracture surface of the specimen start from the center of the rock specimen as much as possible, improving the rock disc splitting test Success rate and credibility. The test results are shown in table 3 and figure 7.

| Test no. | Compression speed(mm/min) | Static tensile strength (MPa) |
|----------|---------------------------|-------------------------------|
| 1        | 0.012                     | 1.51                          |
| 2        | 0.012                     | 1.11                          |
| 3        | 0.012                     | 1.83                          |

Figure 7. Red sandstone static tensile strength curve.

4. Parameter Determination

4.1. EOS Parameters

The elastic modulus $E$ is 18.81 GPa, the density $\rho_0$ is 2460 kg/m$^3$, and the Poisson's ratio $\nu$ is 0.2. $K_1 = E/(3(1-2\nu))$ and $G = E/(2(1+\nu))$. $K_1$ is 10.45 GPa and $G$ is 7.84 GPa. According to the Hugoniot relationship

$$ u_s = S \cdot u_p + C $$

(12)

Where $u_s$ is the shock wave velocity, $u_p$ is the particle velocity, $S$ is the fitting slope of the straight line, and $C$ is the volume sound velocity of the material. According to the flyer impact test by Liu Chuang
et al. [24], the volumetric sound velocity $C$ of general sandstone is 2060 m/s and $S$ is 1.51.

The Hugoniot equation for conservation of mass and momentum can be expressed as [25]

Conservation of mass

$$\rho_s u_s = \rho (u_s - u_p)$$

(13)

Conservation of momentum

$$P = \rho u_p (u_s - u_p) = \rho_s u_s u_p$$

(14)

Combining Eq. (12) with Hugoniot Eq. (13) for conservation of mass and Hugoniot Eq. (14) for conservation of momentum, the shock wave Hugoniot on the plane $P - \mu$ is determined as

$$P = \frac{\rho_0 C^2 \mu (1+\mu)}{(1-(S-1)\mu)^2}$$

(15)

Where $P$ is the pressure, $\rho_0$ is the density of red sandstone, $\mu$ is the volumetric strain, and $S$ and $C$ are consistent with Eq. (12).

Finally, Eq. (15) can be written as

$$P = \frac{2.46 \times 2.06^2 \times \mu (1+\mu)}{(1-(1.51-1)\mu)^2}$$

(16)

Suppose $\mu = 0.0-0.13$, and then calculate the value of $P$ according to Eq. (16), and use the value shown in figure 9 to fit the value of $K_2$ and $K_3$ when $D=0$ in Eq. (4). The fitting values obtained are $K_2=20.78$GPa, $K_3=22.69$GPa, and the fitting curve is shown in figure 8.

![Figure 8](image)

(a) Red sandstone $P - \mu$ curve. (b) Linear relationship between equivalent stress - pressure.

**Figure 8.** Red sandstone $P - \mu$ curve and the fitting of the coefficient $C$.

### 4.2. Determination of EOS Parameters

Firstly, determine the parameters of Eq. (1) when the material is complete. Obtaining the values of $HEL$, $\sigma_{HEL}$ and $P_{HEL}$ is the first task. The $HEL$ of a rock material is usually determined by a flyer impact test. For the flyer impact test of red sandstone, Liu Chuang, Tobias Hoerth and Q. B. Zhang etc [24,26-30] found that the $HEL$ of general sandstone is about 2.5GPa. The following formula [17]

$$HEL = K_1 \mu_{HEL} + K_2 \mu_{HEL}^2 + K_3 \mu_{HEL}^3 + \frac{4}{3} G \frac{\mu_{HEL}}{1 + \mu_{HEL}}$$

(17)

Where $\mu_{HEL}$ is the volumetric strain at $HEL$, $HEL$, $K_1$, $K_2$, $K_3$ and $G$ are all known parameters, and $\mu_{HEL} = 0.11135$ can be obtained.
Then

\[ P_{\text{HEL}} = \text{HEL} - \frac{4}{3} G \left( \frac{\mu_{\text{HEL}}}{1 + \mu_{\text{HEL}}} \right) \]  \hspace{1cm} (18)

\[ \sigma_{\text{HEL}} = \frac{3}{2} \left( \text{HEL} - P_{\text{HEL}} \right) \]  \hspace{1cm} (19)

Finally \( P_{\text{HEL}} = 1.45 \text{GPa}, \ \sigma_{\text{HEL}} = 1.575 \text{GPa}. \)

In addition, according to the one-dimensional strain elastic equation [31]

\[ P_{\text{spall}} = \frac{T_{\text{spall}}}{1 - \nu} \left( 1 + \nu \right) \]  \hspace{1cm} (20)

\[ \sigma_{\text{spall}} = T_{\text{spall}} \left( 1 - 2\nu \right) \]  \hspace{1cm} (21)

Where \( \sigma_{\text{spall}} \) is the spall stress, \( P_{\text{spall}} \) is the spall pressure, \( T_{\text{spall}} \) is the spall strength, \( \nu \) is the Poisson's ratio. Han D B [32] conducted a dynamic tensile strength test on sandstone, and obtained the dynamic tensile strength \( T_{\text{spall}} = 0.15 \text{GPa} \) of sandstone under high strain rate, then \( P_{\text{spall}} = 0.075 \text{GPa} \) and \( \sigma_{\text{spall}} = 0.1125 \text{GPa} \). The normalized value is \( P^{*}_{\text{spall}} = P_{\text{spall}}/P_{\text{HEL}} = 0.074, \sigma^{*}_{\text{spall}} = \sigma_{\text{spall}}/\sigma_{\text{HEL}} = 0.095. \)

The value can be determined by the method of Johnson and Holmquist [33]. This method is to take three points on the intact material curve, the strength at HEL, the tensile spall strength and the strength at a high strain rate, and the \( T^{*} = 0.0103 \) and \( T = T^{*} \times P_{\text{HEL}} = 0.015 \text{GPa} \) calculated by this method.

It can be seen from figure 3 and figure 5 that red sandstone has obvious strain rate effect. The equivalent stress value at the same pressure of 39.79MPa under different strain rates (\( 2 \times 10^{-4} \text{s}^{-1} \) and 484 \text{s}^{-1} ) is shown in table 4.

**Table 4. Uniaxial compression results of red sandstone.**

| No. | Strain rate(\text{s}^{-1}) | Uniaxial compressive strength (MPa) |
|-----|-----------------------------|-----------------------------------|
| 1   | 0.0002                      | 37.20                             |
| 2   | 484                         | 39.23                             |

Linear relationship between equivalent stress and pressure under two different strain rates are shown in figure 8(b). From Eq. (1), we can get

\[ \frac{A(P' + T')^N (1 + C \times \ln \dot{\varepsilon}_i)}{A(P'^* + T'^*)^N (1 + C \times \ln \dot{\varepsilon}_i)} = \frac{1 + C \times \ln 484}{1 + C \times \ln 0.0002} = 1.051 \]  \hspace{1cm} (22)

Then, the strain rate constant \( C \) is 0.00337.

There are two methods to determine the value of \( A \) and \( N \) in the complete strength of the material. The first method [10,13,17-18,33] is to obtain normalized experimental data through quasi-static compression and dynamic tests. The second method [34-36] is to use the Hoek-Brown criterion [37] to estimate the hard rock mass. In this paper, the first method will be used to fit the parameters \( A \) and \( N \) using the quasi-static compression and dynamic experimental data in Section 3, and finally \( A = 0.88, N = 0.64 \), as shown in figure 9, including three different strain rates are 0.0002 \text{s}^{-1}, 0.002 \text{s}^{-1}, and 484 \text{s}^{-1}.
It is difficult to determine the parameters of material fracture strength Eq. (2) and damage constant Eq. (7). Through searching related studies, $B$ is considered to be $1/3$ of $A$. The constant $M$ is assumed to be the same as the constant $N$ is equal [23]. SFMAX is 25% of $\sigma_{HEL}$. Therefore $B = 0.293$, $M = 0.64$ and SFMAX = 0.39. $D_1$ and $D_2$ will be determined by a combination of test results and numerical simulation results, temporarily $D_1 = 0.005$, $D_2 = 0.7$.

5. JH-2 Numerical Simulation Results and Comparison

A numerical simulation model with the same conditions as the SHPB dynamic compression test was established, and the red sandstone was simulated and calculated at strain rates of $312 \text{ s}^{-1}$ and $484 \text{ s}^{-1}$. The mesh model is shown in the figure 10(a), and the simulated stress-strain curve As shown in the figure 10(b), it can be seen from the curve that as the strain gradually increases, the material is in the elastic stage before the maximum compressive strength is reached. At this time, it is controlled by Eq. (1). When the material reaches the maximum resistance When compressive strength, the material slowly starts to be damaged. This stage is controlled by Eq. (3). As the strain continues to increase, the material breaks, and the stress no longer decreases and tends to a constant value. The description of the JH-2 constitutive model is completely consistent.

The uncertainty of the material parameters $D_1$ and $D_2$, the fracture behavior of the numerical simulation and the test results are quite different. In order to make the numerical simulation results consistent with the test results, after repeated simulation and comparison, it is finally determined that $D_1 = 0.05$, $D_2 = 1.5$ Under the action of the impact load, the side of the rock specimen clamped between the incident rod and the transmission rod first appeared axial penetration cracks. With the continuous action of the impact load, the number of axial cracks increased and expanded to the fracture surface until the entire The rock specimen was broken and finally appeared powdery.
Figure 11. Comparison of experimental results and numerical simulation results (strain rate is 484 s⁻¹).

6. Conclusion
This paper takes red sandstone as the research object. Firstly, it conducts mechanical performance tests. Then, using the test results and theoretical derivation, the values of some parameters are initially obtained. Finally, the value of the red sandstone JH-2 is determined by comparing the numerical simulation results with the test results. The parameters of the structural model are shown in Table 5. The obtained parameters can well describe the mechanical response of red sandstone at various stages, and the parameters are considered effective and accurate.

Table 5. Red sandstone JH-2 constitutive model parameters.

| ρ/kg/m³ | v   | $K_1$/GPa | $K_2$/GPa | $K_3$/GPa |
|---------|------|------------|------------|------------|
| 2460    | 0.2  | 10.45      | 20.78      | 22.69      |
| HEL/GPa | $P_{HI3}$/GPa | $T$/GPa | $A$ | $B$ |
| 2.5     | 1.45 | 0.015      | 0.88       | 0.293      |
| C       | M    | N          | $D_1$      | $D_2$      |
| 0.00337 | 0.64 | 0.64       | 0.05       | 1.5        |
| SFMAX   |      |            |            |            |
| 0.39    |      |            |            |            |
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