Analysis of the Dynamic Mechanical Properties and Energy Dissipation of Water-Saturated Fissured Sandstone Specimens

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Abstract: To investigate the dynamic mechanical properties of water-saturated fissure rock at different strain rates, prefabricated sandstone specimens with a 45° dip angle were treated with water saturation and the impact compression test was performed with a Split Hopkinson Pressure Bar (SHPB) test device at different impact pressures. The results show that the clusters of dynamic stress–strain curves of water-saturated and natural sandstone specimens with a 45° dip angle of prefabricated fissures are basically similar under different impact air pressures. A distinct strain rate effect was observed for dynamic strain and dynamic compressive strength, both of which increased with increasing strain rate. From the failure pattern of the specimen, it can be seen that cracks appeared from the tip of the prefabricated fissure under axial stress, spreading to both ends and forming wing cracks and anti-wing cracks associated with shear cracks. As the strain rate increased, the energy dissipation density of the specimen gradually increased, and the macroscopic cracks cross-expanded with each other. The fracture form of the specimen showed a small block distribution, and the average particle size of the specimen gradually decreased. The specimen crushing energy dissipation density was negatively correlated with fracture size, reflecting a certain rate correlation. The sandstone fragments’ fractal dimension increases with the increase in crushing energy dissipation density, and the fractal dimension may be applied as a quantitative index to characterize sandstone crushing.

Keywords: rock dynamics; strain rate; water-saturated fissured sandstone; shock compression; SHPB device

1. Introduction

In underground rock engineering and geohazard prevention and control, fissured sandstone, as a common rock type, has dynamic mechanical properties that are crucial to the assessment of engineering stability and geologic risk [1,2]. However, in practical engineering, fissured sandstones are often subject to a variety of complex groundwater effects, which can result in large uncertainties in their dynamic response [3,4]. Among them, strain rate is one of the key factors effecting rock response. Hence, the dynamic mechanical properties of water-saturated fissure rocks under various strain rates are of great importance for stability assessment and disaster prediction in deep rock engineering [5].

In past studies, many scholars have focused on the static and dynamic mechanical properties of fissure-bearing and water-bearing rocks. Ping et al. [6] performed impact compression tests on seven groups of fissured sandstones of different dips using the Split Hopkinson Pressure Bar (SHPB) device (State Key Laboratory of Mining Response and Disaster Prevention and Control in Deep Coal Mines, Anhui, China). The results of the
dynamic parameters of the specimens show that a 45° fissure angle is the optimal brittleness angle, and the differences in the damage patterns of the specimens are attributed to the presence of fissures with different dip angles. Yang et al. [7] tested single-cleavage granite specimens under uniaxial compression and found that the rock mechanical parameters were highly correlated with fissure angle and temperature. Du et al. [8] studied the impact of crack length on sandstone’s mechanical properties using the SHPB device under different impact air pressure conditions. The results of the study show that sandstone with the presence of fissures has an increased proportion of plastic deformation in the stress–strain curve. Feng et al. [9] examined the mechanical properties of symmetric and asymmetric fissured rocks with static and dynamic loading at varying dynamic strain rates. The results indicate that the dynamic strength increases significantly with strain rate, whereas the dynamic modulus of elasticity is independent of strain rate. Li et al. [10] conducted dynamic impact experiments on rectangular marble specimens with cracks to investigate the impact of fissure angle and ligament angle on the dynamic mechanical characteristics and rupture behavior of rocks. Wang et al. [11] performed triaxial compression experiments on specimens with monoclinic joints under different loading rates. It was concluded that the competition between mechanical damping and inertial forces led to the strain rate effect, and the peak strength of the specimens increased with the increase in loading rate. Feng et al. [12] found that strain rate significantly affects the mechanics and rupture behavior of rocky specimens with two non-parallel fissures at different dip angles. Li et al. [13] examined the impact of preexisting defects with different angles and lengths on the dynamic mechanical properties of prismatic marble specimens with a single defect in the SHPB device. Eunhye K et al. [14], Zhou et al. [15], Zhu et al. [16], and Feng et al. [17] explored the comprehensive effects of water and strain rate from dynamic compression experiments on both dry and water-saturated rocks for the mechanical properties and crack growth behavior of rocks. Liu et al. [18] examined the impact of wet and dry cycles on the strength, damage pattern, and energy evolution of single-fracture carbonaceous shale. There is certainly a significant relationship between fissured rock energy dissipation and fragmentation patterns. Vivek P et al. [19] conducted Brazilian disk experiments on four rocks at different strain rates using the SHPB device. Characteristic strain rates were applied to evaluate the extent of fragmentation and these were compared to existing theoretical tensile fragmentation models. Zhao et al. [20] studied the mechanical properties, damage behavior, energy dissipation characteristics, and damage mechanisms of fissured rock specimens with different prefabricated fissure angles. You et al. [21] carried out triaxial dynamic tests on sandstone containing prefabricated cracks at different strain rates and concluded that the dynamic strength and energy dissipation density of sandstones increased with increasing strain rate. Malachi Ozoji et al. [22] investigated the increase in strain rate under dynamic uniaxial compression leading to an increase in fissure surface area and specific fracture energy during rock fragmentation. By translating into engineering dimensional parameters, this can be used to optimize rock destruction and reduce ore loss and energy wastage. Yin et al. [23] studied the characteristics of fluid transport properties and permeability evolution in heat-treated rock samples containing single fractures. After high-temperature exposure, the roughness of the fracture surface increased, and the fracture flow was affected by the temperature and surrounding pressure. Yan et al. [24] researched the effect of strain rate on the dynamic response of fractured rock using high-speed loading. The results show that an increase in strain rate leads to increased rupture, increased energy dissipation density, and the insignificant effect of crack strength on some properties. Yin et al. [25] tested dynamic impacts on rocks with different bridge lengths and water contents and found that the moisture status and bridge length significantly affected the dynamic compressive strength, elastic modulus, and energy dissipation density.

It should be noted that there are fewer studies concerning the dynamic mechanical properties of water-saturated fissured sandstones under different strain rates; studies are mostly focused on intact rock specimens under static loading conditions. Further exploration is necessary to fully understand the effects of fissure-containing and water-
saturated conditions. Therefore, in this paper, the SHPB device was used to conduct dynamic impact compression tests on prefabricated fractured 45° dip angle water-saturated sandstone specimens using different air pressures to analyze the effects of strain rate on the dynamic mechanical properties, crushing patterns, and energy dissipation. The results of this study indicated that water-saturated fissured sandstone fragmentation is more obvious at high strain rates, and these findings are helpful for specific areas of rock engineering involving high strain rates, such as mine blasting, underground tunneling and geotechnical engineering, dam and levee design, and military protective structures. For mine and mining engineering, the cracking behavior of rocks directly affects blast design, risk of rock failure, and mining efficiency. For dams and hydraulic engineering, understanding the mechanical properties of rocks under different strain rates can guide the design and maintenance of dam structures. The increase in rock strength under dynamic loading is a factor that influences the design of underground protective structures and the placement of blast holes. By analyzing the response mechanisms of water-saturated fissured sandstones under dynamic loading, we can better predict and respond to the complex engineering geological problems that may be encountered in underground projects, thus enhancing the overall performance and sustainability of underground projects.

2. Processing and Preparation of Water-Saturated Fissured Sandstone Specimens and SHPB Test Device

2.1. Processing of Water-Saturated Fissured Sandstone Specimens

The sandstone was provided by Pan Er Coal Mine, Huainan City, Anhui Province, China. It was treated according to the International Society for Rock Mechanics (ISRM) recommended test protocol [26] and China Technical Specification for Testing Method of Rock Dynamic Properties [27]. By coring, cutting, and polishing, cylindrical specimens with a diameter (D) and height (H) both measuring 50 mm were fabricated. A full cross-section through fissure measuring 20 mm in length (l) and 2 mm in width (h) with a 45° dip angle was machined along the side of the cylinder using water jet technology. The location of the prefabricated fissures in the sandstone specimen is shown in Figure 1.

![Figure 1. Precast fracture location diagram of sandstone specimen.](image)

Referring to the Rock Testing Procedure for Water Conservancy and Hydroelectric Engineering [28], the fissured sandstone specimens were put into water for 48 h of natural saturation to achieve the saturated state. The specimen preparation process is presented in Figure 2. The Smartlab SE X-ray diffractometer (XRD) (Anhui University of Science and Technology, Huainan, China) was used to analyze the compositions of the specimens after the water saturation of the prefabricated fissured sandstone, and the XRD patterns were measured as shown in Figure 3. By comparing the obtained XRD spectra with the standard PDF cards, it can be seen that the water-saturated fissured sandstone is mainly composed of quartz ([SiO2]) and gismondine ([CaAlSi2O8-4H2O]).
Figure 2. Flow chart of preparation of water-saturated fractured sandstone specimen.

Figure 3. XRD patterns of water-saturated fissured sandstone specimen.

2.2. SHPB Test Device and Principle

The test was conducted using the Split Hopkinson Pressure Bar (SHPB) test device of the State Key Laboratory of Deep Coal Mine Mining Response and Disaster Prevention and Control (as shown in Figure 4). The device consists of an impact loading system, a data acquisition system, and a speed measuring device system. The bars in this device are machined from 40Cr high-strength alloy steel with a modulus of elasticity of up to 210 GPa, and the diameter of the press bars is 50 mm. To apply dynamic shock loads, we utilize a high-pressure nitrogen gas cylinder as a pulse source to form a shock wave by rapidly releasing the gas. Specifically, we generated a high-speed shock wave by introducing a compressed gas inside the shock rod, followed by a rapid opening of the release valve, which caused the gas to expand rapidly. The impulse load thus generated acts on the specimen, triggering the dynamic response of the rock under high strain rate conditions. The entire test process was monitored by a high-speed data acquisition system to record and analyze the strain waveform of the specimen.

Figure 4. SHPB test device sandstone specimen placement diagram.

Based on the basic assumptions of the SHPB test principle [29,30], three important dynamic mechanical parameters of rock specimens, namely stress $\sigma(t)$, strain $\varepsilon(t)$, and strain rate $\dot{\varepsilon}(t)$, can be calculated as shown in Equation (1).

$$
\begin{align*}
\sigma(t) & = \frac{E_0 A_0}{2A_S} \left[ \varepsilon_L(t) + \varepsilon_R(t) + \varepsilon_T(t) \right] \\
\varepsilon(t) & = - \int_0^t \left[ \varepsilon_L(t) + \varepsilon_R(t) - \varepsilon_T(t) \right] dt \\
\dot{\varepsilon}(t) & = - \frac{C_0}{L} \left[ \varepsilon_L(t) + \varepsilon_R(t) - \varepsilon_T(t) \right]
\end{align*}
$$

(1)
where \( A_0, A_S \) is the cross-sectional area of compression bar and specimen; \( E_0, C_0 \) is the modulus of elasticity of compression bar material and longitudinal wave velocity; \( L_S \) is the length of the specimen; \( \varepsilon_I(t), \varepsilon_R(t), \varepsilon_T(t) \) is the incident, reflected, and transmitted strains; and the compressive stress and strain are taken as the positive direction.

3. Results of SHPB Tests

3.1. Dynamic Mechanical Parameters of Water-Saturated Fissured Sandstone

Tests of SHPB impact compression were carried out on specimens of water-saturated fissured sandstone and natural fissured sandstone, and the dynamic mechanical parameters measured are shown in Tables 1 and 2.

Table 1. Dynamic mechanical parameters of water-saturated sandstone specimens with precast fissure.

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Dynamic Compressive Strength /MPa</th>
<th>Dynamic Modulus of Elasticity /GPa</th>
<th>Dynamic Strain ( \times 10^{-3} )</th>
<th>Strain Rate /s(^{-1} )</th>
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Table 2. Dynamic mechanical parameters of natural sandstone specimens with precast fissure.

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<th>Specimen Number</th>
<th>Dynamic Compressive Strength /MPa</th>
<th>Dynamic Modulus of Elasticity /GPa</th>
<th>Dynamic Strain ( \times 10^{-3} )</th>
<th>Strain Rate /s(^{-1} )</th>
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<td>44.10</td>
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</table>

3.2. Dynamic Stress–Strain Curve Analysis

The SHPB dynamic compression test was carried out on the water-saturated fissured sandstone specimen and natural fissured sandstone specimen, and the typical dynamic stress–strain curve was obtained, as shown in Figures 5 and 6.

Figures 5 and 6 show that, under different impact air pressures, the dynamic stress–strain curve clusters of water-saturated fissured sandstone and natural fissured sandstone specimens are basically similar, which are approximately divided into four stages: the elastic stage, crack extension stage, plastic yielding stage, and destruction stage. During the initial elastic phase, the stress tends to increase with strain and the cluster of dynamic stress–strain curves is nearly straight. The internal crack of the specimen starts to sprout and expand under the impact load, plastic deformation occurs after the elastic ultimate stress is reached, and the curve clusters are concave. The specimen starts to soften after the
stress reaches the peak value; with the increase in strain, the stress decreases rapidly, the specimen is damaged, and the curve cluster shows a decreasing trend.

![Figure 5](image)

**Figure 5.** Dynamic stress–strain curves of water-saturated fissured sandstone specimens.

![Figure 6](image)

**Figure 6.** Dynamic stress–strain curves of natural fissured sandstone specimens.

### 3.3. Dynamic Compressive Strength

The dynamic compressive strength of the water-saturated and natural fissured sandstone specimens varies with strain rate $\dot{\varepsilon}$, as shown in Figure 7.

![Figure 7](image)

**Figure 7.** Variation in dynamic compressive strength with strain rate in sandstone specimens.

Figure 7 shows that the dynamic compressive strengths of water-saturated fissured sandstone and natural fissured sandstone specimens increase with increasing strain rate, which were fitted and found to increase exponentially; the fitted relationship is shown in Equation (2). The correlation coefficients are 0.9831 and 0.9957, and the fit is significant. With the increase in impact air pressure, the difference between the dynamic compressive
strength of the water-saturated sandstone specimen and natural sandstone specimen gradually increases from 0.62 MPa to 10.11 MPa, which is due to the tension effect and Stefan effect [31] of the free and bound water inside the water-saturated sandstone specimen under the dynamic impact loading, which impedes the further expansion of cracks and thus reduces the brittle microfracture activity of the rock, leading to the rock’s brittle microfracture and undergoing damage at higher strengths. A clear rate correlation can be seen for the dynamic compressive strength of water-saturated fissured sandstones.

\[
\begin{align*}
\sigma_{d1} &= 22.055e^{0.0121\varepsilon} (R^2 = 0.9831) \\
\sigma_{d2} &= 26.449e^{0.0092\varepsilon} (R^2 = 0.9957)
\end{align*}
\]  

(2)

where \(\sigma_{d1}\) is the dynamic compressive strength of water-saturated fissured sandstone, MPa; \(\sigma_{d2}\) is the dynamic compressive strength of natural fissured sandstone, MPa; and \(\varepsilon\) is the strain rate, s\(^{-1}\).

3.4. Dynamic Strain

The variation in dynamic strain with strain rate for the water-saturated fissured sandstone and natural fissured sandstone specimens is shown in Figure 8.

Figure 8. Variation in dynamic strain with strain rate in sandstone specimens.

For the water-saturated fissured sandstone and natural fissured sandstone specimen, the dynamic strain increases with strain rate in a quadratic trend, and the fitting relationship is expressed in Equation (3), with correlation coefficients of 0.9918 and 0.9947, which are significant fitting effects. The results of this test indicate that the dynamic strain of the natural fissured sandstone specimen is slightly larger than that of the water-saturated sandstone specimens, both of which have strain rate effects.

\[
\begin{align*}
\varepsilon_{d1} &= 0.0001\varepsilon^2 - 0.016\varepsilon + 2.485 (R^2 = 0.9918) \\
\varepsilon_{d2} &= 0.0009\varepsilon^2 - 0.005\varepsilon + 2.043 (R^2 = 0.9947)
\end{align*}
\]

(3)

where \(\varepsilon_{d1}\) is the dynamic strain of water-saturated fissured sandstone; \(\varepsilon_{d2}\) is the dynamic strain of natural fissured sandstone; and \(\varepsilon\) is the strain rate, s\(^{-1}\).

3.5. Dynamic Elastic Modulus

The variation in the dynamic modulus of elasticity with strain rate for the water-saturated fissured sandstone and natural fissured sandstone specimens is shown in Figure 9.
As shown in Figure 9, the dynamic modulus of elasticity of the water-saturated fissured sandstone and natural fissured sandstone specimen increases slowly with the increase in strain rate. The dynamic modulus of elasticity of water-saturated fissured sandstone specimens is generally greater than that of natural sandstone specimens, and the difference between the two ranges from 1.1 GPa to 2.9 GPa, with a relatively small change. The dynamic modulus of elasticity is related to the type of material, whereas sandstone is relatively dense, thus the strain rate effect of the modulus of elasticity is not significant at different strain rates. When the dynamic elastic moduli are fitted, they are found to increase linearly with the increase in strain rate. The fitting relationship is expressed in Equation (4), which indicates a reasonable fitting relationship.

\[
\begin{align*}
E_{d1} &= 0.3628\bar{\varepsilon} + 9.0354(R^2 = 0.9934) \\
E_{d2} &= 0.3051\bar{\varepsilon} + 11.360(R^2 = 0.9843)
\end{align*}
\]

where \(E_{d1}\) is the dynamic modulus of elasticity of water-saturated fissured sandstone, GPa; \(E_{d2}\) is the dynamic modulus of elasticity of natural fissured sandstone, GPa; and \(\bar{\varepsilon}\) is the strain rate, s\(^{-1}\).

4. Failure Pattern and Analysis of the Energy Consumption

4.1. Failure Pattern of Specimen

The sandstone specimens containing prefabricated fissures with a 45° dip angle were destabilized under dynamic loading because of the stress concentration at the end of the fissures, and the severe fragmentation of the localized area dominated by the sprouting wing cracks, counter-wing cracks, and secondary cracks around the prefabricated fissures. At this time, the rock microcracks rapidly undergo unstable expansion, part of the microcracks is large due to the expansion of the deformation, and its surrounding cracks occur through each other, so it can be assumed that this takes place in the dynamic loading of the rock crack instability expansion and through the simultaneous occurrence of the cracks. The specimen was tensile and shear composite damage, and the number of cracks is dense. Consistent with previous dynamic impact test studies on fissured rock specimens [32], the crack distribution under dynamic loading conditions mainly originated from the top of the prefabricated fissure or its vicinity, and the crack extension trajectories were not completely smooth, but rather jagged. The crack extension is schematically presented in Figure 10. The final crushing morphology of the water-saturated fissured sandstone specimen is presented in Figure 11. With the increasing impact air pressure, the crushing block size decreased obviously.
$ER = \frac{t_E}{C_0 A_0}$

$ET = \frac{t_T}{C_0 A_0}$

$ED = \frac{t_D}{C_0 A_0}$

where $E_I(t)$, $E_R(t)$, $E_T(t)$, $E_D(t)$ are the incident, reflected, transmitted, and absorbed energies, respectively; $\varepsilon_I$, $\varepsilon_R$, $\varepsilon_T$ are the incident, reflected, and transmitted strains, respectively; $E_0$ is the elastic modulus of the compression bar; $C_0$ is the longitudinal wave velocity of the compression bar; and $A_0$ is the cross-sectional area of the compression bar.

The energy values of the water-saturated fissured sandstone specimens during the test at different impact air pressures are shown in Table 3. It can be seen that the incident, reflected, transmitted, and absorbed energies of the specimen change as the impact air pressure and strain rate increase.

### Table 3. Energy values of water-saturated fissured sandstone specimens.

<table>
<thead>
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</table>

Figure 10. Crack propagation diagram.

Figure 11. Failure patterns of specimen at different strain rates.

4.2. Analysis of the Energy Dissipation

The incident, reflected, transmitted, and absorbed energies of the rock specimen during the impact test using the SHPB test device can be calculated using Equation (5) [33]:

$$
\begin{align*}
E_I(t) &= E_0 C_0 A_0 \int_0^t \varepsilon_I^2(t) dt \\
E_R(t) &= E_0 C_0 A_0 \int_0^t \varepsilon_R^2(t) dt \\
E_T(t) &= E_0 C_0 A_0 \int_0^t \varepsilon_T^2(t) dt \\
E_D(t) &= E_I(t) - E_R(t) - E_T(t)
\end{align*}
$$

where $E_I(t)$, $E_R(t)$, $E_T(t)$, $E_D(t)$ are the incident, reflected, transmitted, and absorbed energies, respectively; $\varepsilon_I$, $\varepsilon_R$, $\varepsilon_T$ are the incident, reflected, and transmitted strains, respectively; $E_0$ is the elastic modulus of the compression bar; $C_0$ is the longitudinal wave velocity of the compression bar; and $A_0$ is the cross-sectional area of the compression bar.
To minimize the influence of specimen scale in energy dissipation, the crushing energy dissipation density is considered to reflect the amount of energy absorbed by the specimen, that is, the amount of energy dissipated per unit volume of rock absorbed due to crushing, as shown in Equation (6).

$$E_V = \frac{E_D}{V_S}$$  \hspace{1cm} (6)

where $E_V$ is the energy dissipation density of the specimen, J·cm$^{-3}$ and $E_D$ is the energy dissipation of the specimen, J. $V_S$ is the effective volume of the specimen, cm$^3$.

The relationship between the crushing energy dissipation density and the strain rate for the water-saturated fissured sandstone specimens is shown in Figure 12.

![Figure 12. Variation in energy dissipation density with strain rate in water-saturated fissured sandstone specimens.](image)

From Figure 12, it is clear that the crushing energy dissipation density of the water-saturated fissured sandstone specimens basically tends to increase quadratically with increasing strain rate. As the air pressure is raised, the incident energy increases and the sandstone specimen gradually transitions from the larger block state to the broken and crushed state. In this process, more energy needs to be absorbed for the germination, expansion and penetration of cracks inside the specimen, so the crushing energy dissipation density shows a gradual increase as the strain rate rises. Equation (7) displays the correlation between the crushing energy dissipation density of the specimen and the strain rate with a positive correlation coefficient of 0.9942.

$$E_V = -5 \times 10^{-5} \dot{\varepsilon}^2 + 0.0157 \dot{\varepsilon} - 0.5473 (R^2 = 0.9942)$$  \hspace{1cm} (7)

where $E_V$ is energy dissipation density of the specimen, J·cm$^{-3}$ and $\dot{\varepsilon}$ is the strain rate, s$^{-1}$.

4.3. Fragment Size Distributions and Crushing Energy Dissipation of Specimens

The above sections explain the effect of rock crushing only from the perspective of energy release, while, in practical mining engineering, the problem of the particle size of crushed rock is a fundamental issue. Therefore, investigating the relationship between crushing size and energy dissipation has great significance. Representative specimens were selected from each group of crushed sandstone, and then the water-saturated fissured sandstone fragments under different strain rate impact loads were sieved by STSJ-4 digital high-frequency vibrating sieve machine according to 0.15, 0.3, 0.6, 1.18, 2.36, 4.75, 9.5, and 13.2 mm standard square hole gravel sieves. The crushed pieces were moved up and down the sieve and passed through the corresponding sieve holes according to their size. Subsequently, the retained fragments were weighed in each class of aperture sieve using a high-sensitivity electronic balance. The average particle size of the crushed sandstone was
calculated, which can aid in visualizing the degree of sandstone crushing; Equation (8), for the average particle size of the specimen crushing, is as follows:

\[ d_s = \frac{\sum r_i d_i}{\sum r_i} \]  (8)

where \( d_s \) denotes the average crushed particle size of the specimen, \( d_i \) denotes the average size of the rock fragments retained in the different sizes of the vacuolar sieve, and \( r_i \) denotes the percentage of mass of the rock fragments corresponding to \( d_i \).

The results of the fragment sieving tests after impact damage of the sandstone specimens are shown in Table 4:

Table 4. Measurement value of the screening test of fragments.

<table>
<thead>
<tr>
<th>Impact Air Pressure/MPa</th>
<th>Size of Screen Mesh/mm</th>
<th>Gross Mass /g</th>
<th>Average Particle Size of Fragments/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.300</td>
<td>0.0.20 0.11 0.39 0.52 1.43 3.77 7.42 7.52 230.80</td>
<td>252.16</td>
<td>23.49</td>
</tr>
<tr>
<td>0.325</td>
<td>0.42 1.27 1.72 1.93 3.80 10.46 19.14 20.41 194.62</td>
<td>253.77</td>
<td>20.80</td>
</tr>
<tr>
<td>0.350</td>
<td>0.83 1.40 2.22 2.53 3.89 16.00 36.30 51.59 140.75</td>
<td>255.51</td>
<td>17.33</td>
</tr>
<tr>
<td>0.375</td>
<td>1.42 1.19 2.70 3.06 5.15 22.01 45.88 60.45 114.62</td>
<td>256.48</td>
<td>15.47</td>
</tr>
<tr>
<td>0.400</td>
<td>1.83 3.40 3.22 4.53 6.89 26.10 51.30 75.59 83.83</td>
<td>256.69</td>
<td>13.36</td>
</tr>
<tr>
<td>0.425</td>
<td>2.03 4.42 4.23 5.72 7.39 30.00 54.27 77.90 69.73</td>
<td>255.69</td>
<td>12.28</td>
</tr>
</tbody>
</table>

The relationship between the crushing average grain size of water-saturated fissured sandstone and the crushing energy dissipation density is presented in Figure 13.

Figure 13 clearly shows that the crushing average particle size of water-saturated fissured sandstone after dynamic impact decreases gradually as the crushing energy dissipation density increases. This implies that the higher the energy absorption of the rock specimen, the higher the crushing energy dissipation during the deformation and destruction of the specimen, which leads to the formation of more cracks interacting with each other and cross-expanding, resulting in the rock specimen being broken into small fragments or even powder form. The smaller the crushing block scale of the sandstone specimen, the larger the crushing surface area per unit volume of rock, the larger the required specimen crushing energy dissipation, and, therefore, the more drastic the degree of crushing. The average particle size of specimen crushing is linearly and negatively correlated with the crushing energy dissipation density, reflecting a certain rate correlation; the fitting relationship is shown in Equation (9) with a positive correlation coefficient of 0.9981.

\[ d_s = 10.593E_V^2 - 49.83E_V + 36.3(R^2 = 0.9981) \]  (9)
where $d_s$ is the crushing average particle size of water-saturated fissured sandstone, mm and $E_I$ is energy dissipation density of the specimen, J·cm$^{-3}$.

### 4.4. Fractal Dimension and Energy Dissipation Density of Fragments

Water-saturated fissured sandstone specimens were damaged under different impact air pressures to generate fragments of different sizes, which were analyzed using sieve tests in conjunction with relevant fractal theory [34–36]. The fractal dimension analysis of the tested fragments was carried out, and the fractal dimension equation for the mass-equivalent size of the specimen fragments is shown in Equation (10).

\[
\begin{align*}
\left\{ \begin{array}{l}
 b = \frac{\ln(M_r/M)}{\ln r} \\
 D = 3 - b
\end{array} \right.
\]

where $b$ is the slope of the linear function in double log $\ln(M_r/M) - \ln r$ coordinates; $M_r$ is the mass of the corresponding fragments under the characteristic size $r$; $M$ is the total mass of the specimen fragments; and $D$ is the fractal dimension of the sandstone fragments.

The double logarithmic curve for a typical sandstone is shown in Figure 14.

![Figure 14. $\ln(M_r/M) - \ln r$ curve of a typical specimen with different strain rates.](image)

Figure 14 shows that, when the strain rate is low, the cumulative mass percentage of sandstone fragments at each grain size is low, and with increasing strain rate, the mass percentage of sandstone fragments increases significantly, and the fragmentation gradient of sandstone fragments is more obvious. This implies that, with low strain rate, the sandstone is under low impact load and the energy absorption by the rock specimens is not sufficient to support the complete fracturing of the rock specimens, leading to no apparent crushing of the sandstone. However, when the strain rate increases, the energy absorbed by the rock sample increases, exceeding the bearing capacity of the sandstone and leading to an increase in the extent of rock fragmentation. Furthermore, the cumulative fragment mass and grain size data at each grain size of the sandstone were linearly fitted in double logarithmic coordinates to obtain the slopes of their linear fit functions to calculate the fractal dimensions of the sandstone fragments, as shown in Table 5. The variation in the fractal dimension of sandstone clasts under different strain rates is presented in Figure 15.

Figure 15 illustrates the increase in the fractal dimension of sandstone fragments as the density of crushing energy dissipation increases. Combined with the crushing macroscopic morphology of typical sandstone under different strain rates, this indicates that a larger crushing energy dissipation density of the rock means that more energy is used for the rock crushing action; with deeper crushing of the rock, the number of fine-grained fragments will be larger, and the fractal dimension will be bigger as well. The fractal dimension of specimen fragments and the crushing energy consumption density satisfy the multiplicative power function relationship, and the fitting relationship is presented in Equation (11) with a positive correlation coefficient of 0.9981. Thus, the fractal dimension is suitable as a
quantitative index to characterize sandstone fragmentation, which can reflect the degree of sandstone fragmentation.

\[ D = 2.6882E_V^{0.2745} (R^2 = 0.9344) \]  

(11)

where \( D \) is the fractal dimension of sandstone fragments and \( E_V \) is the energy dissipation density of the specimen, J·cm\(^{-3}\).

**Table 5.** Calculation results of fractal dimension of water-saturated fissured sandstone specimens with different strain rates.

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Slope</th>
<th>Correlation Coefficient</th>
<th>Fractal Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>PJ42-01</td>
<td>1.1448</td>
<td>0.8627</td>
<td>1.8552</td>
</tr>
<tr>
<td>PJ42-04</td>
<td>0.9357</td>
<td>0.9286</td>
<td>2.0643</td>
</tr>
<tr>
<td>PJ42-08</td>
<td>0.9147</td>
<td>0.9437</td>
<td>2.0853</td>
</tr>
<tr>
<td>PJ42-10</td>
<td>0.8694</td>
<td>0.9281</td>
<td>2.1306</td>
</tr>
<tr>
<td>PJ42-13</td>
<td>0.7526</td>
<td>0.9266</td>
<td>2.2474</td>
</tr>
<tr>
<td>PJ42-17</td>
<td>0.6986</td>
<td>0.9199</td>
<td>2.3014</td>
</tr>
</tbody>
</table>

*Figure 15.* Variation in fractal dimension of fragments with crushing energy dissipation density.

**5. Conclusions**

The dynamic stress–strain curve, dynamic compressive strength, dynamic strain, dynamic modulus of elasticity, specimen crushing pattern, energy dissipation density, and specimen crushing average size and fractal dimension were obtained from SHPB impact compression tests on prefabricated fractured 45° dip angle water-saturated sandstone specimens at different impact air pressures. The main conclusions are as follows:

1. The dynamic stress–strain curve clusters of water-saturated fissured sandstone and natural fissured sandstone specimens are basically similar, which can be approximately divided into four stages, including the elastic stage, the crack extension stage, the plastic yielding stage, and the damage stage.

2. The dynamic compressive strength of the water-saturated fractured sandstone specimens is higher than that of the natural sandstone specimens. This is mainly due to the surface tension generated by the free water at the fissure tip of the water-saturated specimen, which hinders the instantaneous expansion of cracks and generates the Stefan effect. The dynamic strain of the water-saturated fissured sandstone specimen is slightly lower than that of the natural sandstone specimen. Both of them have a strain rate effect.

3. In the case of increasing impact air pressure, the specimen undergoes tensile and shear composite damage, the number of cracks is dense, and the size of the broken block is obviously reduced.

4. The energy-consuming density of crushing a water-saturated fissured sandstone specimen tends to increase quadratically with strain rate, and more energy needs to
be absorbed in the process for the germination, extension, and penetration of cracks within the specimen.

(5) The average particle size of specimen crushing gradually decreases with the increase in crushing energy dissipation density; the higher the energy absorption of the rock specimen, the higher the energy dissipation in the deformation and destruction process of the specimen, which leads to the formation of more cracks, and the rock specimen will be crushed into small fragments or even powder form. As the crushing energy dissipation density increases, the fractal dimension of sandstone fragments also increases, which satisfies the multiplicative power function relationship. The fractal dimension is suitable as a quantitative index to characterize sandstone crushing.

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