Influence of the Number of Parallel Joints on the Dynamic Mechanical Properties of Rock-Like Features

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The number and distribution of joints in rock are closely related to their physical and mechanical properties. In this paper, given the propagation law of explosive stress waves in jointed rock during rock blasting and the influence of joints on dynamic mechanical properties and crushing energy dissipation of rock, parallel joints are simulated in the construction of concrete specimens using a mica sheet. The discrete Hopkinson test device is used to perform the impact test, which is based on the three-wave and fractal theory. Under dynamic load, the fluctuation characteristics, failure mode, fractal dimension, and energy dissipation transfer law of rock-like specimens with various parallel joints are studied in detail. The results show that the overall failure of the specimen becomes more severe with the increase of parallel joints, and the failure mode is changed from the conjugate shear failure of the complete specimen to the edge collapse failure with joints. Thus, as the number of joints increases, the static strength decreases, and the degree of reduction is positively related to the number of joints. With the number of joints, the changing trend of enhancement factor increases first and then slows down. Compared with nonjointed specimens, the transmission coefficient of 1-3 jointed specimens is decreased by 0.22, 0.05, and 0.17, respectively. The dimension of the specimen $D_0$ is positively correlated. Under the synonymous impact pressure of 0.35 MPa, the corresponding fractal dimension is increased from 2.27 to 2.42. The crushing energy consumption density, transmission coefficient, and dynamic compressive strength $\sigma_d$ of the specimen are significantly negatively correlated, and the crushing energy consumption density of the specimen decreased from 0.82 J/cm$^3$ to 0.28 J/cm$^3$.

1. Introduction

The mechanical properties and deformation of rock and soil have always been the focus of scholars [1, 2]. Rock mass quality and its classification are of great significance in geotechnical engineering such as road and bridge, building foundations, large hydropower, and mining. The number and distribution of joints are some of the critical factors in rock mass quality evaluation. When dynamic loads such as earthquakes and blasting excavation act on the stress wave, the reflection, absorption, and transmission of the stress wave on the joint surface directly affect the dynamic mechanical properties of the rock mass. In the process of dynamic damage and fracture of jointed rock, the research on the stability, fracture, and energy dissipation of the structure with and without the joint is one of the hotspots of fracture damage mechanics. The findings have not been unified, making it difficult to be applied to practical engineering design and construction [3–8].

The mechanical properties and deformation of rock and soil have always been the focus of scholars. Some scholars have carried out dynamic uniaxial compression tests based on the split Hopkinson pressure bar (SHPB) system to study the mechanical behavior, failure mechanism, and stress wave propagation characteristics of jointed rocks and rock-like rocks [9–13] Yufei et al. [14] used a split Hopkinson
pressure bar to test rock samples with rough joints and quantitatively study the damage characteristics of the joint surface under multiple low amplitudes with a 3D scanner. It was found that some damage of rock blocks under multiple impact loads was weak, and the damage of joint surface was more severe. By using a split Hopkinson pressure bar with a diameter of 50 mm, Yong et al. [15] conducted impact tests on seven kinds of sandstones with penetrating joints with different dip angles; besides, they used a high-speed camera to capture the process of crack propagation and failure. The results showed that the peak strain and dynamic compressive strength of sandstone decreased first and then increased with the joint dip angle. Based on the basic theory of damage mechanics, Yexue et al. [16] deduced the analytical solution of the propagation velocity of stress wave in jointed rock and established the relationship between fractal dimension of jointed surface image and wave velocity. Yatao et al. [17] carried out impact compression tests on jointed rock samples with different roughness. By using a high-speed camera and image correlation method to explore the failure process of jointed rock mass, it was found that joint roughness and whether it was consistent were closely related to the properties and failure mode of the jointed rock mass. With the SHPB experimental system, Hongyan et al. [18] explored the dynamic mechanical properties of rock under different strain rates and joint inclination angles. The experiments showed that the strain rate had a significant impact on the energy dissipation and failure mode of jointed rock with different inclination angles. The fluctuation characteristics and energy dissipation of stress waves passing through the joint surface were studied under a similar impact velocity, and the expression of energy dissipation ratio with the joint inclination angle was given. Yang [19] studied the blasting response of a jointed rock mass under high-stress conditions using a model specimen and analyzed the crack initiation pattern and the initiation angle at the joint and the stress intensity factor and crack velocity. The blasting stress wave increased the stress concentration at the joints and promoted crack initiation and expansion. Some scholars [20–24] conducted impact compression tests on the dynamic strength and failure mode of jointed rock mass with different joint dip angles, joint penetration, joint filling thickness, and the joint filling type and found that the joint structural morphology was closely related to the properties and failure mode of the jointed rock mass. Based on the 75 mm large diameter split Hopkinson pressure bar (SHPB) dynamic load experimental apparatus, Wenke et al. [25] conducted a comparison experiment on the dynamic mechanical characteristics of impact damage of laminated raw coal specimens (vertically laminated and horizontally laminated samples) and sandstone specimens with good homogeneity and studied the influence law of lamination on the dynamic mechanical damage characteristics of coal rocks.

According to the findings of the preceding study, research on the influence of joint numbers on dynamic rock characteristics is uncommon. Aiming at the actual working condition of jointed and fissured surrounding rock of middle 253 section of Dahongshan Copper Mine, in order to solve the dynamic mechanical influence of blasting excavation on jointed surrounding rock, in this paper, similar materials are used to simulate rock-like specimens containing different numbers of joints, and impact tests are carried out on rock-like specimens containing different numbers of joints with the help of separated Hopkinson compression bars to study the dynamic response characteristics of the number of joints on rock-like specimens. The research results can provide certain reference for the dynamic characteristics of jointed rock.

2. Materials and Methods

2.1. Test Equipment and Principle

2.1.1. Test Equipment. The test employs split Hopkinson pressure bar (SHPB) system equipment, as shown in Figure 1, which consists primarily of the power system, pressure bar system, and data acquisition system. The incident rod, the projection rod, and the bullet are all made of high-strength Cr40. During the test, the bullet, the incident rod, and the transmission rod must be coaxial. The end face of the specimen is fully contacted with the rod to ensure that no scattering occurs during the impact process.

2.1.2. SHPB Principle. The theory is based on the three-dimensional elastic wave and stress uniformity hypothesis. The stress-strain and average strain rate of the specimen were estimated by the two-wave method according to the signal measured by the strain gauge [26]. The calculation formula is shown in

\[
\sigma(t) = \frac{E_A}{A_S} \varepsilon_r(t),
\]

\[
\dot{\varepsilon}(t) = \frac{2C}{L_S} \varepsilon_r(t),
\]

\[
\varepsilon(t) = \frac{2C}{L_S} \int_0^t \varepsilon_r(t) dt,
\]

where \(E_A\) is the elastic modulus of the strut; \(A_S\) is the cross-sectional area of the strut; \(C\) is the elastic wave velocity in the compression bar; \(L_S\) is the initial thickness of the specimen; \(\varepsilon_r(t)\) is the reflected wave strain; and \(\varepsilon(t)\) is the transmitted wave strain.

2.1.3. Calculation of Fractal Dimension. According to the fractal theory [27], the functional relationship between the number of broken bodies with particle size \(r\) after rock breaking and the total number of broken bodies \(N\) greater than or equal to the particle size is expressed as follows:

\[
N(r) = C_0 r^{-D_f},
\]

where \(C_0\) is a dimensional constant and \(D_f\) is the fractal dimension of the broken body.

Therefore, the percentage of the number of broken bodies with particle size less than \(r\) to the total number of
broken bodies is

$$P(r) = 1 - \left( \frac{r_{\text{min}}}{r} \right)^{D_f}. \quad (3)$$

Because the sample size is small, assuming the shape of the broken body is spherical particles, the expression of the number of broken bodies and the total volume $V$ under impact load can be expressed as

$$V = \int_{r_{\text{min}}}^{r_{\text{max}}} N_i \left( \frac{4}{3} \pi r^3 \right) dp(r), \quad (4)$$

where $N_i$ is the total number of broken bodies, whereas $r_{\text{max}}$ and $r_{\text{min}}$ are the maximum particle size and the minimum particle size of the crushed body, respectively.

Substituting (3) into formula (4), the expression of the total volume $V$ of the broken body can be obtained:

$$V = \frac{4}{3} \pi N_i \frac{D_f}{3 - D_f} \frac{r_{\text{min}}^{3-D_f} r_{\text{max}}^{3-D_f}}{D_f}. \quad (5)$$

According to formula (5), the cumulative mass of any fragment with particle size less than $r_0$ should have the following relationship:

$$M(r < r_0) = \frac{4}{3} \pi N_i \rho \frac{D_f}{3 - D_f} \frac{r_{\text{min}}^{3-D_f} r_{\text{max}}^{3-D_f}}{D_f}, \quad (6)$$

where $M(r < r_0)$ is the total mass of broken body with particle size less than $r_0$ and $\rho$ is the density of variable jointed rock mass. Equation (6) shows that the percentage of the accumulated mass with particle size less than $r_0$ in the totals of mass of broken body $y_i$ is expressed as follows:

$$y_i = \frac{M(r < r_0)}{M(r < r_{\text{max}})} = \left( \frac{r_0}{r_{\text{max}}} \right)^{3-D_f}, \quad (7)$$

where $M(r < r_{\text{max}})$ is the total mass of the broken body.

After taking logarithms on both sides of Equation (7) at the same time, we can obtain

$$\ln y_i = (3 - D_f) \ln \left( \frac{r_0}{r_{\text{max}}} \right), \quad (8)$$

$$d_m = \frac{\sum (y_0 \cdot r_0)}{\sum y_0}, \quad (9)$$

where $r_0$ is the particle size of any fragment size, whiles $y_0$ is the percentage of the particle size.

2.1.4. Rock Energy Transfer. During the SHPB test, the process of rock deformation and damage is accompanied by the transformation of internal energy, which is calculated by the following equation [28].

$$W_I = \frac{A_0}{c_0 p_0} \int_{t_0}^{t_f} \sigma_1^2(t') dt', \quad (10)$$

$$W_R = \frac{A_0}{c_0 p_0} \int_{t_0}^{t_f} \sigma_2^2(t') dt', \quad (10)$$

$$W_T = \frac{A_0}{c_0 p_0} \int_{t_0}^{t_f} \sigma_3^2(t') dt', \quad (10)$$

where $W_I$, $W_R$, and $W_T$ are the incident, reflected, and transmitted waves energies. Also, $c_0$, $A_0$, and $p_0$ are the longitudinal wave velocity, cross-sectional area, and density of the
elastic rod independently. Again, $\sigma_{I(t)}$, $\sigma_{R(t)}$, and $\sigma_{T(t)}$ are the incident, the reflected, and the transmitted stress, respectively. When the energy loss between the compression bar and the specimen is taken into account, the absorbed energy of the specimen can be expressed as

$$W_D = W_I - W_R - W_T.$$  \hfill (11)

Defining crushing energy consumption density $\varphi$ [29, 30],

$$\varphi = \frac{W_D}{V},$$  \hfill (12)

where $V$ is the volume of the specimen.

Define transmission coefficient $\delta$ [31],

$$\delta = \frac{W_D}{W_I}. \quad (13)$$

The transmission coefficient and crushing energy density reflect the specimen’s ability to absorb energy and destroy the absorbed energy to do work.

2.2 Specimen Preparation and Program

2.2.1. Test Material and Specimen Preparation. Based on the principle of material similarity, a cylindrical specimen with a diameter of $\Phi 50 \times 50$ mm was constructed. According to the methods used in the relevant literature [32], the cement, sand, and water were mixed in the ratio of 1 : 2 : 0.45 thoroughly and then moulded and remoulded after 24 h. The specimens were kept at a constant temperature in the maintenance room for 28 days to produce cement mortar samples that resembled rock materials. In this paper, four specimens with a different number of joints were made to investigate the dynamic mechanical properties of rock-like specimens with different numbers of joints under different impact loads, and the related literature revealed that mica flakes with 1 mm thickness were chosen as the simulated joints with good effect [33]. There are 16 groups of specimens, 3 specimens in each group making it 48 specimens in total. The specimens are shown in Figure 2. The test data were averaged to reduce the error. Figure 1 depicts some of the prepared specimens.

2.2.2. Test Scheme. The parameters of the SHPB test system are as follows: the bullet, incident rod, and transmission rod are made of 40Cr alloy steel with a density of 7800 kg/m$^3$, elastic modulus of 210GPa, and longitudinal wave speed of 5100 m/s. The length and diameter of the incident rod and
transmission rod are both 2 m and 50 mm. When the incident pulse reaches the contact interface with the specimen, part of it is reflected at the interface to form the reflected pulse, and the rest of it passes through the specimen into the transmission rod to become the transmitted pulse. The incident, the reflected, and the transmitted signals can be measured simultaneously by strain gauges attached to the incident and transmitted rods at equal distances. A high-precision dynamic test analyzer processes the pulse signals to measure the bullet’s velocity during the experiment using a velocimetric system. The study shows that the sinusoidal compression pulse at a constant strain rate can be obtained by using spindle bullet loading.

2.2.3. Test Rationality Verification. Based on the one-dimensional stress propagation theory, the rationality of the SHPB test exists if the specimen can reach stress equilibrium before it is damaged [34]. As shown in Figure 3, the transmitted waveform roughly coincides with the incident and reflected waveforms after translation and superposition, which indicates that the magnitude of the axial forces acting on the two ends of the rock specimen is basically the same in the dynamic impact compression stage, whereby the axial inertia effect is considered to have no effect on the test system, indicating that the stress at both ends of the specimen has reached equilibrium before the damage, and the test results have some reliability.

3. Results and Discussion

SHPB uniaxial impact tests were conducted on specimens with a different number of joints, and the impact air pressure gradient was set to 0.2 MPa, 0.25 MPa, 0.3 MPa, and 0.35 MPa for each group of specimens to obtain the stress-strain curves under the different number of joints.

Figure 4 depicts the original waveform at an average strain rate of 33.03 s⁻¹. Here, it can be seen that after the stress pulse generated by the impact load passes through the specimens, there is an obvious reflection platform in the original waveform, which indicates that the loading process occurs at a constant strain rate; the transmittance ability of the nodeless specimens is significantly larger than that of the nodular specimens, and the transmittance wave amplitude gradually decreases with the increase of the number of nodules, which reveals that the number of nodules has the effect of the number of joints on the transmittance of

### Table 1: The static and dynamic comparative analysis.

<table>
<thead>
<tr>
<th>Group number</th>
<th>Impact speed (m/s)</th>
<th>Average strain rate (s⁻¹)</th>
<th>Dynamic compressive strength (MPa)</th>
<th>Static compressive strength (MPa)</th>
<th>Enhancement factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0-1</td>
<td>3.23</td>
<td>23.26</td>
<td>28.26</td>
<td>27.52</td>
<td>1.03</td>
</tr>
<tr>
<td>J0-2</td>
<td>3.74</td>
<td>33.03</td>
<td>36.29</td>
<td>31.71</td>
<td>1.18</td>
</tr>
<tr>
<td>J0-3</td>
<td>4.56</td>
<td>44.65</td>
<td>49.81</td>
<td>45.13</td>
<td>1.07</td>
</tr>
<tr>
<td>J0-4</td>
<td>5.98</td>
<td>69.92</td>
<td>53.09</td>
<td>19.73</td>
<td>2.86</td>
</tr>
<tr>
<td>J1-1</td>
<td>3.38</td>
<td>26.26</td>
<td>20.89</td>
<td>21.46</td>
<td>1.15</td>
</tr>
<tr>
<td>J1-2</td>
<td>4.12</td>
<td>37.59</td>
<td>31.17</td>
<td>18.45</td>
<td>1.70</td>
</tr>
<tr>
<td>J1-3</td>
<td>4.96</td>
<td>45.38</td>
<td>45.13</td>
<td>21.62</td>
<td>2.10</td>
</tr>
<tr>
<td>J1-4</td>
<td>5.51</td>
<td>66.56</td>
<td>47.58</td>
<td>31.34</td>
<td>1.49</td>
</tr>
<tr>
<td>J2-1</td>
<td>3.39</td>
<td>26.44</td>
<td>19.91</td>
<td>16.33</td>
<td>1.18</td>
</tr>
<tr>
<td>J2-2</td>
<td>4.55</td>
<td>48.51</td>
<td>21.46</td>
<td>13.24</td>
<td>1.62</td>
</tr>
<tr>
<td>J2-3</td>
<td>5.01</td>
<td>57.09</td>
<td>36.62</td>
<td>22.34</td>
<td>1.67</td>
</tr>
<tr>
<td>J2-4</td>
<td>5.69</td>
<td>62.83</td>
<td>38.68</td>
<td>26.52</td>
<td>1.46</td>
</tr>
<tr>
<td>J3-1</td>
<td>3.43</td>
<td>27.29</td>
<td>13.95</td>
<td>14.23</td>
<td>1.04</td>
</tr>
<tr>
<td>J3-2</td>
<td>4.26</td>
<td>42.82</td>
<td>16.33</td>
<td>12.11</td>
<td>1.35</td>
</tr>
<tr>
<td>J3-3</td>
<td>5.25</td>
<td>61.64</td>
<td>23.34</td>
<td>12.11</td>
<td>1.93</td>
</tr>
<tr>
<td>J3-4</td>
<td>6.14</td>
<td>72.18</td>
<td>31.86</td>
<td>2.63</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 6: Dynamic strength changes with the number of rock-like joints.](image)

![Figure 6: Dynamic strength changes with the number of rock-like joints.](image)

\[ \sigma = -0.33e^2 - 6.28e + 53.36 \]

\[ \sigma = -0.33e^2 - 6.28e + 53.36 \]

\[ \sigma = -0.33e^2 - 6.28e + 53.36 \]

\[ \sigma = -0.003e^2 - 6.95e + 36.75 \]

\[ \sigma = -0.003e^2 - 6.95e + 36.75 \]

\[ \sigma = -2.15e^2 - 2.34e + 49.76 \]

\[ \sigma = -2.15e^2 - 2.34e + 49.76 \]

\[ \sigma = 0.35e^2 - 5.44e + 27.69 \]

\[ \sigma = 0.35e^2 - 5.44e + 27.69 \]
the specimen is more significant. This is because when the stress wave reaches the nodes of the specimen, the reflection occurs continuously, resulting in partial loss of energy of the stress wave, which causes the attenuation of the transmitted wave amplitude.

Figure 5 shows that when the strain rate is 33.03 s\(^{-1}\), the stress-strain curve of the specimen undergoes three different stages, namely, the linear elastic stage and plastic stage and failure stage; different from static stress-strain curve of no pressure dense phase, microcracks under transient impact, the linear elastic stages of all specimens coincide roughly, indicating that the initial strain rate effect of jointed specimen is not significant. In the linear elastic stage, the linear elastic stages of the specimens roughly overlapped, indicating that the initial strain rate effect of the nodal specimen was not significant. In the plastic stage, the slope of the curve in this stage decreases continuously, and the microfractures develop rapidly under the action of dynamic load and penetrate. The damaged area and the microscopic damage area inside the specimen continue to expand, and the fractures gradually converge and intersect to form multiple macroscopic damage surfaces, and finally, the specimen is “cut” into multiple pieces of uneven size. When the number of joints increased from 0 to 3, the dynamic strength peaks were 36.29, 31.17, 21.46, and 16.33 MPa, respectively.

The decreases were 14.11%, 40.87%, and 55.00%, respectively. It can be seen that the peak strength of the specimens decayed nearly linearly with the number of joints. In the damage stage, the decline of the curves of different specimens is different, and the nonnodular specimens have the phenomenon of “stress drop” out of the peak stress, showing more obvious brittle damage characteristics. The nodal specimens showed a certain plasticity characteristic as the slope of decline gradually slowed down, indicating that the presence of nodal joints transformed the specimens from brittle to plastic flow [35].

3.1. SHPB Test Results. To characterize the change in rock strength under impact loading, a dynamic strength growth factor \( K \) was introduced in Equation (14) to quantitatively describe the increase in dynamic compressive strength of rock comparing to static compressive strength under different impact loads. The results of the impact tests are shown in Table 1.

\[
K = \frac{\sigma_d}{\sigma_c},
\]

where \( K \) is the dynamic strength growth factor and \( \sigma_d \) and \( \sigma_c \) are the dynamic and static compressive strength of rock sample, MPa.

Table 1 shows that the enhancement factor increased from 1.06 to 2.41 as the average strain rate increased from 26.26 s\(^{-1}\) to 65.56 s\(^{-1}\), while the number of joints remained constant at one. Also, it depicts that the enhancement factors of the specimens were increasing with the increase of the average strain rate, and the strain rate had a significant effect on the enhancement factor. However, the variation of the enhancement factor is mainly affected by two aspects, one of which is that the specimens are rate-sensitive materials, and the enhancement factor increases continuously with the increase of the average strain rate. In addition, the bonding force of the mica sheet between the specimens has a certain restraining effect on the lateral deformation of the specimen, and the lateral restraining effect of the bonding surface is strengthened as the strain rate of the specimen increases, which makes the enhancement factor of the specimen increase with the increase of the number of joints [36].

Figure 6 depicts the relationship between the peak strength of the specimen and the number of nodules. It is easy to see that the dynamic compressive strength of the specimen reveals a decreasing trend with the increase of the number of nodules at the same strain rate. The compressive strength of the specimen without nodules is the largest at a strain rate of about 35 s\(^{-1}\), which is about 40 MPa, whereas the single nodule is about 34 MPa. The double nodule is about 28 MPa and the triple nodule is about 14 MPa. The dynamic compressive strength of the specimens is closely related to the number of nodules, and the
compressive strength exhibits a linear decay as the number of nodules increases.

### 3.2. Damage Analysis

The damage forms of the specimens under different strain rates are different. Table 2 shows the damage pattern of the specimens under different strain rates. When IP = 0.2 MPa, the damage of nonjointed specimens is mainly in the form of conjugate shear damage, and most of the damaged specimens are in the form of conical blocks, with two macroscopic cracks and a small amount of debris.

![Figure 7: Distribution of fragmentation of variable jointed rock-like mass under 0.35 MPa impact pressure.](image)

The damage of single-jointed specimens is mainly in the form of edge spalling, with a lot of debris. The damage of double-nodular specimens is mainly in the middle layer, which may be due to the failure to mix uniformly when making, resulting in the lower strength of the middle layer. When a jointed specimen is damaged, the front end of the specimen is damaged due to energy absorption, the stress wave at the joint attenuation, and the end cannot provide sufficient crushing energy. When IP = 0.25 MPa, there is no jointed specimen overall destabilization, accompanied by many large pieces. The average diameter of the large pieces is around 4.2 cm, single jointed specimen edge damage, only the middle part of the residual strength, and the average diameter of the large pieces is about 3.5 cm, double nodular.

When IP = 0.3, the whole of the nonnodular specimen loses its strength. When IP = 0.3, the overall destabilization of the nonnodular specimen occurs, the block size is significantly reduced, accompanied by powder generation, and the diameter of the large block is about 3.4 cm, and the overall destabilization of the single-nodular specimen is about 3.4 cm.

The average diameter of the double-nodular specimens was 3.0 cm, but the diameter was smaller than that of the single-nodular specimens. When IP = 0.35, the specimens were transformed from large pieces to small pieces or even powder, but with the increase of the number of nodules, the block size of the specimens decreased, and the average block size value decreased from 2.5 cm when there were no nodules to 2.1 cm and also when there were double nodules. As the percentage of powder increases, so does the amount of powder. This is because as the strain rate increases, the specimens must increase their stress to resist external deformation. Due to nodular defects, nodular specimens have a lower ability to transfer load, so the damage is more serious [37].

### Table 3: Screening results of jointed Specimen under different impact pressures.

<table>
<thead>
<tr>
<th>Number of joint</th>
<th>Impact air pressure (MPa)</th>
<th>Cumulative mass percentage of crushed body at different screening apertures (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 mm</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0.1</td>
<td>1.16</td>
</tr>
<tr>
<td>2</td>
<td>0.6</td>
<td>2.13</td>
</tr>
<tr>
<td>3</td>
<td>1.6</td>
<td>3.4</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>2.1</td>
<td>2.56</td>
</tr>
<tr>
<td>2</td>
<td>2.8</td>
<td>2.37</td>
</tr>
<tr>
<td>3</td>
<td>2.93</td>
<td>7.58</td>
</tr>
<tr>
<td>0</td>
<td>1.74</td>
<td>2.43</td>
</tr>
<tr>
<td>1</td>
<td>2.9</td>
<td>3.98</td>
</tr>
<tr>
<td>2</td>
<td>3.76</td>
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</tr>
<tr>
<td>3</td>
<td>3.92</td>
<td>9.5</td>
</tr>
<tr>
<td>0</td>
<td>2.1</td>
<td>2.37</td>
</tr>
<tr>
<td>1</td>
<td>3.5</td>
<td>4.8</td>
</tr>
<tr>
<td>2</td>
<td>3.96</td>
<td>5.9</td>
</tr>
<tr>
<td>3</td>
<td>4.01</td>
<td>10.9</td>
</tr>
</tbody>
</table>
Table 4: Calculation results of fractal dimension and particle size of Specimen fragmentation under 0.35 MPa.

<table>
<thead>
<tr>
<th>Joint</th>
<th>Impact air pressure (MPa)</th>
<th>Correlation coefficient ($R^2$)</th>
<th>Average particle sized (mm)</th>
<th>$D_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No joint</td>
<td></td>
<td>96.29</td>
<td>26.23</td>
<td>2.27</td>
</tr>
<tr>
<td>Single joint</td>
<td>0.35 MPa</td>
<td>95.23</td>
<td>24.74</td>
<td>2.36</td>
</tr>
<tr>
<td>Two joints</td>
<td></td>
<td>95.29</td>
<td>23.41</td>
<td>2.39</td>
</tr>
<tr>
<td>Three joints</td>
<td></td>
<td>96.76</td>
<td>16.07</td>
<td>2.42</td>
</tr>
</tbody>
</table>

Figure 8: Relationship between transmission coefficient and joint number.

3.3. Rock-Like Fractal Study. The graded standard sieve aperture sizes used for sieving the crushed rock-like were 0.3 mm, 0.5 mm, 1.0 mm, 2.0 mm, 5.0 mm, 10.0 mm, 15.0 mm, 20.0 mm, and 25.0 mm in order. The results are shown in Table 2, and only the distribution of crushing mass of specimen bodies containing the different number of joints at a similar impact air pressure of about 0.35 MPa is plotted for analysis.

The sieving results of crushed bodies of different nodular rock-like masses under different impact air pressures listed in Table 3 are calculated according to Equation (8), and the linear regression equation of crushed body particle size distribution under different impact air pressures is obtained. Then, the distribution curves of crushed bodies with different nodular quantities at similar impact air pressures of about 0.35 MPa with better regularity are employed to analyze the influence of nodular quantities on rock-like crushing as shown in Figure 6. From the figure, it can be seen that the correlation of the block size particle size distribution of the crushed body of variable nodular rock-like mass under impact loading is high, and the correlation coefficient of the straight line is good, which indicates that the distribution trend of the crushed body of the rock-like specimen has good fractal characteristics after the damage occurred by the impact loading.

According to the slope of the linear regression equation in Figure 7, the fractal dimension of the nodular rock-like specimens under different impact pressure can be obtained, and the average particle size of the crushed body mass under different conditions can be calculated according to Equation (9). The calculation results are shown in Table 4. Combined with Table 4 and Figure 6, it was observed that under similar impact loading, with the increasing number of nodules, the number of crushed bodies of rock-like specimens increases with the fractal dimension of rock-like, which has a good positive correlation, while the average particle size of crushed bodies changes negatively with the number of nodules. Accordingly, the fractal dimension can be used to describe the degree of rock-like fragmentation quantitatively, and the larger the corresponding fractal dimension is, the higher the degree of rock-like fragmentation is.

From the perspective of microscopic crack expansion, there are many randomly distributed microcracks and microdefects inside the nodular specimen; more number of nodules represents more microcracks and microdefects. Under the impact of external dynamic load, the end of the crack in an unfavourable orientation is prone to stress concentration so that the stress reaches tens or even hundreds of times of the applied axial pressure, and the crack begins to expand along the axial direction. When the incident energy is small, the specimen with more microdefects, such as the specimen with more number of joint cracks, is prone to expansion, and the microfissures penetrate each other; then, when the high incident energy acts on the microfissures, the three-jointed specimen is damaged first, prompting the microfissures to expand, penetrate, and converge to form the main crack; then, more main cracks inside the rock-like were generated, leading to more internal free surface and greater damage of the specimen.

3.4. Analysis of Energy Transfer Law. The relationship between the transmission coefficient and the number of joints is depicted in Figure 8. From the figure, it can be seen that the transmission coefficient decreases by 0.22, 0.05, and 0.17, respectively, when the number of joints increases from 1 to 3, which means that the transmission coefficient of the specimen shows a decreasing trend as the number of joints increases. This indicates that the presence of nodules weakened the energy carried by stress waves, resulting in a gradual decrease of transmission coefficient [38].

Figure 9 shows the relationship between the incident energy of the specimen and the crushing energy consumption density. It is easy to see that the crushing energy density of the specimen is positively correlated with the increase of the incident energy and combined with the crushing morphology of the specimen. It can be seen that the macroscopic damage of the specimen is more significant when the crushing energy density of the specimen is 0.51 J/cm² as an example. With the increase of strain rate, more energy acts on the internal microcrack sprouting; expansion of the specimen is
gradually transformed from a more complete state to a broken state. Therefore, the crushing energy density of the specimens gradually increases with the increase of incident energy. Comparing four different nodular specimens at the same time, it can be seen that when the incident energy is 75 J and the number of nodules increases from 0 to 3, the crushing energy density of the specimens are 0.82 J/cm³, 0.69 J/cm³, 0.61 J/cm³, and 0.28 J/cm³, representing the smallest crushing energy density of the three-nodular specimens and the largest crushing energy density of the nodular specimens, respectively. The existence of nodules makes the value of crushing energy density of specimens smaller than that of intact specimens, which indicates that the existence of nodules affects the transmission of stress waves, and when the incident energy is equal, the more the number of nodules, the less the transmitted energy.

4. Conclusions

Through similar model tests and SHPB experimental setup, impact tests were conducted on artificially simulated rock specimens with different numbers of joints to investigate the stress-strain characteristics, damage characteristics, and energy consumption laws of jointed rock-like specimens under dynamic loading, and the following conclusions were obtained.

(1) The stress-strain curve of the specimens is closely related to the number of joints. When the number of joints increased from 0 to 3, the peak dynamic strengths were 36.29, 31.17, 21.46, and 16.33 MPa at a strain rate of about 35 s⁻¹. The decrease values were 14.11%, 40.87%, and 55.00%, respectively. The more the number of joints, the more the peak strength tends to decay, and the specimen transforms from brittle to plastic in the postpeak stage.

(2) The presence of nodules affects the damage mode of the specimens. Under the same impact load, the damage of intact specimens is mainly compression-shear damage. Under the same impact load, the damage of intact specimens is mainly compression-shear damage, whereas the damage mode of nodular specimens is mainly reflected by edge collapse damage.

(3) By sieving the broken rock-like masses of specimens with the different number of joints, the mass percentages of broken rock-like masses under different dimensions were obtained. The number of joints has a certain influence on the fractal characteristics of the broken masses of rock-like specimens, and the corresponding fractal dimensions were 2.27, 2.36, 2.39, and 2.42 which increases the number of joints when the similar impact load was about 0.35 MPa.

(4) The presence of nodules attenuates the energy carried by stress waves. When the number of nodules increases from 0 to 3, the crushing energy density of the specimen at the same strain rate is 0.82 J/cm³, 0.69 J/cm³, 0.61 J/cm³, and 0.28 J/cm³ independently, and the transmittance of the specimen gradually decreases with the increase of the number of nodules.

Data Availability

All data included in this study are available upon request by contact with the corresponding author.

Conflicts of Interest

The authors declare no conflict of interest.

Authors’ Contributions

Zhang Zhiyu and Li Zhuo contributed equally to this manuscript.

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