Study on the Dynamic Mechanical Properties of Metamorphic Limestone under Impact Loading

Zhiyu Zhang, Qingyun Qian, Hao Wang, Yonghui Huang, Jianguo Wang, and Haoshan Liu

1Faculty of Land Resources Engineering, Kunming University of Science and Technology, Yunnan 650093, China
2Yunnan Key Laboratory of Sino-German Blue Mining and Utilization of Special Underground Space, Kunming University of Science and Technology, Yunnan 650093, China
3State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Sichuan 610500, China
4Faculty of Electric Power Engineering, Kunming University of Science and Technology, Yunnan 650500, China

Correspondence should be addressed to Yonghui Huang; 8176309@qq.com and Jianguo Wang; wangjg0831@163.com

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To study the dynamic damage and fracture of metamorphic limestone under explosive load and the stability of the surrounding rock, the stress-strain curve, fracture morphology, and energy dissipation characteristics of metamorphic limestone in the Dahongshan mining area under different strain rates were studied by the Hopkinson pressure bar (SHPB), stress wave analysis, and fractal theory. The experimental results show that the crushing form and degree are significantly affected by the loading strain rate. There are several typical failure modes. When the strain rate is 17.56 s\(^{-1}\), there is no obvious failure except corner cracks. When the strain rate is between 26.92 s\(^{-1}\) and 56.18 s\(^{-1}\), the failure mode of the specimen is axial splitting failure, and when the strain rate is 67.34 s\(^{-1}\), splitting and shearing failure occur. With the increase of the strain rate, the growth rate of the dynamic compressive strength slows down. Compared with static compressive strength, the strength factor increases from 1.15 to 4.19. Also, the fractal dimension shows a gentle increase. When \(D_f\) is in the range of 1.82–2.24, there is a sudden change in fragmentation when the strain rate is in the range of 34.70 s\(^{-1}\)–56.18 s\(^{-1}\). Energy dissipation density increases logarithmically with the strain rate. The results reveal the dynamic breaking and energy consumption laws of metamorphic limestone under impact loads with different strain rates and could provide some reference value for the safe and efficient construction in the Dahongshan mining area and similar engineering projects.

1. Introduction

During the engineering activity of tunnel excavation, mining, water conservancy, and hydropower station construction, the involving blasting and mechanical vibration have a great impact on the behavior of the surrounding rock mass. During the process, the dynamic mechanical properties, deformation, and failure characteristics of the ore and rock show significant strain rate effects; also, dynamic disasters such as face collapse and surrounding rock collapse are more likely to occur [1]. The efficient and safe drilling and blasting construction must be based on the premise that the surrounding rock and slope are as small as possible by the blasting disturbance, and the efficiency of blasting rock is systematically studied. Rock stability, damage, and fragmentation under explosive load are dynamic processes. However, traditional design methods are mostly based on rock static mechanical parameters and there are obvious deficiencies in the entire process from the rock breaking mechanism to engineering guidance.

At present, scholars at home and abroad have carried out a lot of research on ore rock under impact load. Ping et al. [2] used the SHPB test device to carry out impact tests on limestone at room temperature and between 100°C and 800°C to study the influence of temperature changes on the stress-strain curve and strength parameters. Zhang et al. [3–10] used the improved Hopkinson test equipment to conduct conventional uniaxial impact tests on dolomite, granite, phyllite, and marble; the dynamic mechanical
properties of ore and rock were studied from the stress-strain curve, failure morphology, energy distribution, and fractal dimension. Ma et al. [11–13] conducted dynamic impact tests on artificially frozen sand and shale under active confining pressure, and the changes of stress-strain curves and strength parameters with confining pressure and strain rate were studied. Ji et al. [14–16] conducted dynamic impact tests on granite and sandstone and analyzed the relationship between the fracture degree, strength parameters, energy dissipation, and strain rate of the two materials under different strain rates. Liu et al. [17–22] analyzed shales under complex geological conditions; simulation software pEDFM was used to construct analytical models for controlling the connection and optimization between volumes. Zhang et al. [23–29] carried out SHPB tests on sandstone under different impact conditions and obtained stress-strain curves and rock fragmentation, and the peak strain, particle size distribution, and energy dissipation of sandstone were further analyzed. Metamorphic limestone is one of the main lithologies in the Dahongshan mining area in Yuxi city, Yunnan province; the existing static parameters cannot meet the needs of mine production and scientific research modeling. Also, research on the failure pattern, stress-strain curve, fractal dimension, and energy consumption of metamorphic limestone under different rates is rarely reported.

The paper took samples from the Dahongshan mining area, and the SHPB impact test system of Kunming University of Science and Technology was applied to carry out low-speed impact load deformation and fracture tests. The failure mode of rock samples under impact load and the stress under different strain rate-strain relationship was systematically studied. Analysis of the particle size distribution law and strength parameters, fractal dimension, and energy dissipation change law with the strain rate of specimens provides a certain scientific basis for safe and efficient mining of ore in the Dahongshan mining area.

2. Test Equipment and Principle

2.1. Test Equipment. The rock dynamics standard test tool recommended by the International Society of Rock Mechanics—Split Hopkinson pressure bar (SHPB) [30]—is selected. The SHPB test system of Kunming University of Science and Technology is shown in Figure 1. The system consists of several parts, such as a nitrogen cylinder, Hopkinson compression bar test bench, acceleration chamber, spindle-shaped bullet, elastic compression bar system, energy absorption device, LK2019 dynamic signal collector, optical signal velocimeter, oscilloscope main, and computer.

In the impact test, the diameter of the elastic rod is 50 mm, the material is 40Cr high-strength alloy steel, the length is 2000 mm, the density is 7784 kg/m3, the elastic modulus is 250 GPa, the longitudinal wave velocity of the elastic rod is 5667 m/s, and the bullet is a spindle-shaped special-shaped bullet, with a length of 400 mm. The bullet can generate an approximate constant strain rate half-sine loading wave to avoid the Pochhammer-Chree oscillation problem [31]; a schematic map of the test system setup is shown in Figure 2. In order to ensure that the two ends of the sample are in full contact with the incident rod and the transmission rod, Vaseline is applied to both ends of the specimen to eliminate the effect of end friction [32]. In this experiment, the high-frequency oscillations were filtered out by pasting a thin circular aluminum sheet as a waveform shaper on the impacting end of the incident rod to obtain a better waveform.

2.2. Principles of SHPB Technology. The SHPB test is mainly based on the assumption of one-dimensional elastic wave and stress uniformity. The stress pulse is regarded as a distortion-free one-dimensional elastic wave in the compression bar, ignoring the strain rate effect of the compression bar material. The axial strain measured by the strain gauge on the surface of the compression bar in the one-dimensional stress state can replace the axial strain at each point of the whole section. Under the assumption of stress uniformity, the stress wave effect of the specimen can be ignored because the specimen is very short and the average stress and strain of the specimen obtained from the deformation of the end face of the compression bar can reflect the real mechanical properties of the specimen. In the impact test, the bullet impacts the test piece at different speeds and the stress \( \sigma(t) \), strain \( \varepsilon(t) \), and strain rate \( \dot{\varepsilon}(t) \), of the test piece are obtained using the “three-wave method” calculation formula [33]; the formula is as follows:

\[
\sigma(t) = \frac{A_s E_0}{2 A_t} \left[ \varepsilon_1(t) + \varepsilon_R(t) + \varepsilon_T(t) \right],
\]

\[
\varepsilon(t) = \frac{C_0}{L_s} \int_0^t \left[ \varepsilon_1(t) - \varepsilon_R(t) - \varepsilon_T(t) \right] dt,
\]

\[
\dot{\varepsilon}(t) = \frac{C_0}{L_s} [\varepsilon_1(t) - \varepsilon_R(t) - \varepsilon_T(t)],
\]
where $A_0$, $E_0$, and $C_0$ are the cross-sectional area of the incident rod, elastic modulus, and longitudinal wave velocity, $L_9$ is the length of the incident rod, $e_i(t)$, $e_R(t)$, and $e_f(t)$ are the strain signals of the incident wave, reflected wave and transmitted wave, respectively, and $A_3$ is the cross-sectional area of the specimen.

### 2.3. Calculation Method of Fractal Dimension.

According to the fractal theory [34], there is a functional relationship as shown in formula (4) between the number of broken bodies and the particle size $r$. After the rock is broken, the total number $N$ of broken bodies larger than or equal to this particle size is as follows:

$$N(r) = C_0 r^{-D_f},$$  \hspace{1cm} (4)

where $C_0$ is the dimensional constant and $D_f$ is the fractal dimension of the broken body.

Therefore, the percentage of the number of broken bodies whose particle size is smaller than $r$ to the total number of broken bodies is as follows:

$$P(r) = 1 - \left( \frac{r_{\text{min}}}{r} \right)^{D_f}.$$  \hspace{1cm} (5)

Due to the small size of the sample this time, it can be assumed that the shape of the crushed body is spherical and the expression of the number of crushed bodies and the total volume $V$ under impact load can be obtained as follows:

$$V = \int_{r_{\text{min}}}^{r_{\text{max}}} N_t \left( \frac{4}{3} \pi r^3 \right) \, dp(r),$$  \hspace{1cm} (6)

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

Incorporating formula (5) into (6), the total volume $V$ of the crushed body is obtained as follows:

$$V = \frac{4}{3} \pi N_t \frac{D_f}{3 - D_f} r_{\text{min}}^{3-D_f} r_{\text{max}}^{3-D_f}.$$  \hspace{1cm} (7)

In formula (7), it can be seen that the cumulative mass of any crushed body with a particle size smaller than $r_0$ in the crushed body can be expressed as follows:

$$M(r < r_0) = \frac{4}{3} \pi N_t \rho \frac{D_f}{3 - D_f} r_{\text{min}}^{3-D_f} r_0^{3-D_f},$$  \hspace{1cm} (8)

where $M(r < r_0)$ is the total mass of crushed bodies with lumpiness and particle size smaller than $r_0$ and $\rho$ is the density of metamorphic limestone.

According to formula (8), the percentage $y_i$ of the cumulative mass of the crushed body, whose lumpiness particle size is less than $r_0$, to the total mass of the crushed body can be expressed as follows [35]:

$$y_i = \frac{M(r < r_0)}{M(r < r_{\text{max}})} = \left( \frac{r_0}{r_{\text{max}}} \right)^{3-D_f},$$  \hspace{1cm} (9)

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

After taking the logarithms of both sides of formula (9), we can get

$$\ln y_i = (3 - D_f) \ln \left( \frac{r_0}{r_{\text{max}}} \right).$$  \hspace{1cm} (10)

According to formula (10), the slope of the regression formula $k = 3 - D_f$ in this coordinate system; thus, the fractal dimension $D_f$ of rock fragmentation can be obtained.

In order to characterize the size of the crushing degree of the rock specimen, as well as to avoid the errors brought about by experimental chance on the experimental results, the crushing degree and block size distribution of the rock under a single impact test are analyzed by defining the average block size of the crushing degree and the average block size $d_m$ can be expressed as follows:

$$d_m = \frac{\sum (y_0 \cdot r_0)}{\sum y_0},$$  \hspace{1cm} (11)

where $r_0$ is the particle size of any crushed body and $y_0$ is the percentage of the particle size of the fragment.

### 2.4. Calculation of Energy Consumption for Rock Crushing.

The SHPB device is used to conduct the dynamic impact test of petroleum jelly on the rock sample. The calculation formulas of incident energy $W_i$, reflected energy $W_R$, and transmission energy $W_T$ on the rod are as follows:

$$W_i(t) = A_0 E_0 C_0 \int_0^t e_i^2(t) \, dt,$$  \hspace{1cm} (12)

$$W_R(t) = A_0 E_0 C_0 \int_0^t e_R^2(t) \, dt,$$  \hspace{1cm} (13)

$$W_T(t) = A_0 E_0 C_0 \int_0^t e_T^2(t) \, dt.$$  \hspace{1cm} (14)

Since petroleum jelly is applied to both ends of the rock sample, the energy consumed by the stress wave propagating in the rock sample and rods in the impact test can be ignored and the energy consumed by rock failure can be calculated as follows:

$$W_D = W_i - W_R - W_T.$$  \hspace{1cm} (15)

In order to express the strength of the energy dissipation of the rock sample under different strain rates, the ratio of the dissipated energy to the incident energy is introduced as the energy dissipation rate $\eta$, namely,
η = \frac{W_D}{W_I} \times 100\% \quad (16)

3. Rock Sample Preparation and Test Plan

3.1. Rock Sample Preparation. The rock sample used in the test is the metamorphic limestone from the Dahongshan Iron Mine of Yuxi Mining Co. Ltd. The sample was processed into a cylinder of \( \Phi 50 \times 50 \text{ mm} \) with a length-to-diameter ratio of 1.0 [38]. The coring machine, cutting machine, double-end grinder, and sandpaper were used to core, cut, and polish the rock sample. To meet the requirements of the impact test, the nonparallelism between the upper and lower ends and the nonperpendicularity of the circumferential surface and the end face of the specimen are controlled within 0.02 mm. The processed rock sample is shown in Figure 3.

3.2. Test Plan. In order to study the dynamic mechanical properties of metamorphic limestone under different strain rates, a reasonable impact air pressure must be determined before the impact test. Different impact air pressures are used to achieve different impact speeds of bullets to analyze the failure of rock specimens under different strain loading rates. To avoid the situation that the sample with too small impact air pressure is not damaged or the sample with too large air pressure is powdery damage, the test impact air pressure levels are set to 0.2 MPa, 0.3 MPa, 0.4 MPa, 0.5 MPa, and 0.6 MPa and the test specimens are divided into 5 groups, with 3 specimens in each group.

3.3. Test Reliability Verification. The rationality of the SHPB test is based on the one-dimensional stress propagation theory. An important prerequisite that must be followed is that the sample can reach stress balance before failure [39]. As shown in Figure 4, the transmitted wave, the translated and superimposed incident wave, and the reflected wave basically coincide. This indicates that the magnitude of the axial force on the two end faces of the rock sample is basically the same at the dynamic shock compression stage. As a result, the influence of the axial inertia effect on the test system can be ignored. It is believed that stress equilibrium of both ends has been achieved before sample failure and the experimental results are reliable.

4. Test Results and Analysis

4.1. SHPB Test Results. In the SHPB test, the voltage signals collected by the strain gauges attached to the incident rod and the transmission rod are converted by the conversion factor \( K \) to obtain the incident stress amplitude. The stress, strain, and strain rate of the rock sample under different impact loads are calculated by formulas (1)–(3). In order to characterize the change of rock strength under impact loads, the dynamic strength increase factor (DIF) \( K \) is used to quantitatively describe the increase of rock dynamic compressive strength relative to static compressive strength under different impact loads, as shown in formula (17). The impact test results are shown in Table 1.

\[ K = \frac{\sigma_d}{\sigma_s}, \quad (17) \]
while $K$ is the dynamic strength growth factor and $\sigma_d$ and $\sigma_c$ are the dynamic and static compressive strengths of the rock sample, in MPa.

4.2. Stress-Strain Curve and Strength Analysis. As shown in Figure 5, the stress-strain curve can be roughly divided into the linear elastic phase, the microcrack evolution phase, the microcrack unsteady expansion phase, the postfailure phase, and the plastic rebound phase. The curve trend is basically the same under different strain rates, but the rock samples still show certain differences under different strain rates.

Table 1: Test parameters of rock samples under impact load.

| Specimen number | Impact air pressure (MPa) | Impact velocity (m/s) | Strain rate (s^-1) | Incident stress (MPa) | Dynamic compressive strength (MPa) | Dynamic strength growth factor |
|-----------------|---------------------------|------------------------|---------------------|-----------------------|-----------------------------------|-----------------------------|
| #1              | 3.68                      | 17.60                  | 53.38               | 45.66                 | 1.17                              |                             |
| #2              | 3.52                      | 17.24                  | 48.71               | 46.22                 | 1.11                              | 1.15                        |
| #3              | 3.74                      | 17.85                  | 51.67               | 44.48                 | 1.16                              |                             |
| #4              | 7.42                      | 27.55                  | 114.65              | 82.41                 | 1.98                              |                             |
| #5              | 7.05                      | 26.48                  | 108.49              | 84.69                 | 1.96                              | 1.99                        |
| #6              | 7.28                      | 26.74                  | 110.44              | 83.94                 | 2.02                              |                             |
| #7              | 9.26                      | 34.70                  | 150.16              | 108.78                | 2.91                              |                             |
| #8              | 9.08                      | 34.24                  | 148.35              | 106.40                | 2.97                              | 2.94                        |
| #9              | 10.02                     | 35.16                  | 154.63              | 106.82                | 2.95                              |                             |
| #10             | 12.78                     | 56.47                  | 184.72              | 140.43                | 3.23                              |                             |
| #11             | 12.14                     | 55.80                  | 182.34              | 136.56                | 3.29                              | 3.27                        |
| #12             | 12.69                     | 56.28                  | 183.67              | 137.89                | 3.29                              |                             |
| #13             | 14.98                     | 67.24                  | 215.78              | 160.78                | 4.12                              |                             |
| #14             | 15.24                     | 67.90                  | 218.42              | 163.93                | 4.19                              | 4.20                        |
| #15             | 14.24                     | 66.89                  | 210.27              | 165.80                | 4.28                              |                             |

Figure 5: Stress-strain curves under different strain rates.

Figure 6: Curves of dynamic compressive strength and elastic modulus versus strain rate.

As the strain rate increases, the peak stress (dynamic compressive strength) and slope (dynamic modulus of elasticity) of the stress-strain curve also increase and the dynamic compressive strength and elastic modulus of the rock are obviously positive with the loading strain rate [40]. The fitting results are shown in Figure 6. When the strain rate is 17.56 s^-1, the peak stress is 45.45 MPa and the sample remains intact. When the strain rate increases to 26.92 s^-1 and 34.70 s^-1, the peak stress of the sample increases to 83.68 MPa and 107.33 MPa, respectively, and sample gradually breaks. With the increase of the strain rate, the maximum strain amplitude during the descending stage
of the stress-strain curve also increases and the ability of the rock sample to resist load deformation increases with the increase of the strain rate.

4.3. Failure Analysis. Uniaxial impact tests under different strain rates are conducted on metamorphic limestone to study the failure mode of the rock samples under the condition that the incident energy is basically the same under the impact pressure [41]. Figure 7 shows the failure morphology of metamorphic limestone under different strain rates. The directions of macrocracks and minor cracks are marked with a white dashed line and a red dashed line, respectively.

According to the failure morphology and cracks of the rock, it can be found that with the increase of strain rate, the number of broken bodies after the failure of the rock sample also increases significantly, showing a strong positive correlation with the strain rate [42, 43]. When the strain rate is 17.56 s$^{-1}$, the damage degree of the rock sample is relatively low and the cracks are mostly macroscopic cracks [44]. When the strain rate is 26.92 s$^{-1}$–34.70 s$^{-1}$, the damage degree of the rock increases, the broken bodies are mostly the block split structure and lamellar spall structure, and the number and length of cracks increase significantly. When the strain rate is 56.18 s$^{-1}$, there are more and more small-volume crushed bodies when the rock is broken. The crushed bodies are mostly a lamellar spall structure, columnar split structure, and cone structure. At this time, the crack penetrates the entire specimen [45]. When the strain rate

### Table 2: Rock screening results under different impact pressures.

| Specimen number | Impact air pressure (MPa) | Cumulative mass percentage of broken body under different sieving apertures (%) |
|-----------------|---------------------------|--------------------------------------------------------------------------------|
|                 |                           | 0.3 mm | 0.5 mm | 1 mm | 2 mm | 5 mm | 10 mm | 15 mm | 20 mm | 25 mm | >32.8 mm |
| #1              | 0.2                       | 0.0   | 0.55  | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 100   |
| #2              | 0.3                       | 0.22  | 0.57  | 1.86 | 3.74 | 6.52 | 14.70| 25.44| 57.68 | 66.58 | 100     |
| #3              | 0.4                       | 0.23  | 0.52  | 1.94 | 7.48 | 14.31| 23.18| 30.64| 55.28 | 74.89 | 100     |
| #4              | 0.5                       | 0.25  | 0.59  | 2.10 | 7.86 | 14.94| 23.78| 31.25| 56.78 | 73.20 | 100     |
| #5              | 0.6                       | 0.20  | 0.55  | 1.98 | 7.94 | 15.28| 25.20| 30.78| 55.94 | 73.95 | 100     |
| #6              | 0.7                       | 2.78  | 4.82  | 9.47 | 12.78| 23.17| 32.22| 53.29| 74.48 | 83.20 | 100     |
| #7              | 0.8                       | 3.20  | 4.91  | 9.28 | 11.28| 23.08| 31.95| 53.94| 74.91 | 81.62 | 100     |
| #8              | 0.9                       | 2.98  | 4.65  | 8.25 | 14.82| 21.89| 31.28| 52.82| 75.62 | 83.62 | 100     |
| #9              | 1.0                       | 2.49  | 5.21  | 10.78| 15.84| 24.69| 38.74| 66.50| 78.25 | 85.47 | 100     |
| #10             | 1.1                       | 2.72  | 5.62  | 12.24| 16.77| 25.20| 38.61| 68.25| 77.41 | 85.92 | 100     |
| #11             | 1.2                       | 2.69  | 6.08  | 11.68| 16.89| 24.85| 40.25| 65.12| 77.68 | 87.16 | 100     |

![Figure 7: Failure modes of metamorphic limestone under different strain rates.](image)

![Figure 8: The mass percentage and the particle size distribution curve of the block size.](image)
increases to 67.34 s$^{-1}$, the number of cone-shaped broken bodies increases significantly after the rock sample is broken and the quality of the silty broken body increases significantly and the rock sample is seriously damaged. With the increase of the strain rate, the specimen gradually transits from split failure to shear failure under the action of uniaxial impact load. When the loading strain rate is high enough, silty failure would occur.

5. Fractal Research on Rock Fragmentation

5.1. Crushing Body Screening. The standard sieve apertures for this screening are 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. The cumulative mass percentage of the crushed body under different sieve sizes is presented in Table 2.

The sieving results of rock crushed bodies under different impact air pressures are provided in Table 2, and the linear regression formula of particle size distribution of crushed bodies under different impact air pressures is obtained. Since no clear damage of the rock sample under 0.2 MPa occurs and the linear regression conditions are not met, only the broken body distribution curve in the range of 0.3 MPa to 0.6 MPa is drawn, as shown in Figure 8. It can be seen that the particle size distribution of the metamorphic limestone crushed body under impact load is highly correlated and the linear correlation coefficient is good, indicating that the distribution trend of the crushed body is good after the rock sample is damaged by the impact load.

According to the slope of the linear regression formula in Figure 8, the fractal dimension of the rock sample crushed body under different impact pressures can be obtained and the average particle size of the broken bodies can be calculated according to formula (11); the calculation result is shown in Table 3. According to Table 3 and Figure 7, the number of rock sample broken bodies and $D_f$ increases significantly with the continuous increase of impact air pressure and there is a clear positive correlation but the average particle size of the broken bodies continues to decrease. It can be seen that $D_f$ can quantitatively characterize the degree of rock fragmentation. The greater the $D_f$, the higher the degree of rock fragmentation.

5.2. Fractal and Law of Energy Consumption

5.2.1. Fractal Law. In order to study the relationship between the fractal dimension $D_f$ of metamorphic tuff and the strain rate $\varepsilon$, Figure 9 is drawn. It can be seen that the fractal dimension is positively correlated with the strain rate. When the average strain rate increases from 34.70 s$^{-1}$ to 56.18 s$^{-1}$, the fractal dimension of the rock fragment increases from 1.82 to 2.24, indicating that the rock is broken within this strain rate range. The degree changes significantly with the strain rate, but the $D_f$ value gradually decreases with increasing strain rate and eventually stabilizes. The degree
of rock fragmentation increases as the strain rate increases, and the corresponding $D_f$ value also increases.

5.2.2. Law of Energy Consumption. If the kinetic energy required for fragment splashing and the energy required for the contact between the specimen and the end face of elastic bar are ignored, the incident energy for the contact between the specimen and the end face of rock is shown in Figure 10. The energy carried by the stress wave is shown in formula (12)–(14) and the crushing dissipation $W_s$ and energy density $E_v$ [46, 47] of the rock specimen can be obtained by combining formula (15). The relationship is shown in formula (18), and the calculation results of dissipation energy and energy density of typical rock samples under different impact pressures are shown in Table 4.

$$E_v = \frac{W_s}{V}. \quad (18)$$

According to the energy dissipation results of typical rock samples at different strain rates, the relationship between incident energy $W_i$, reflected energy $W_r$, transmission energy $W_t$, dissipation energy $W_s$, and the strain rate $\varepsilon$ is shown in Figure 10. The energy carried by the stress wave increases with the increase of the strain rate [48]. When the strain rate increases from 17.56 s$^{-1}$ to 67.34 s$^{-1}$, the incident energy increases by 186.88 J and the dissipated energy increases with the strain rate. The increase is the smallest, with only 39.36 J. When the strain rate is 17.56 s$^{-1}$, the incident energy, reflected energy, transmission energy, and dissipation energy are increased by about 3 times compared with the strain rate of 67.34 s$^{-1}$, indicating that the strain rate has an effect on the incident, reflection, transmission, and dissipation energy. The impact is significant.

Figure 11 shows the variation of energy density $E_v$ with the strain rate. Combining Figure 7 with the broken shape of rock samples under different impact pressures, it can be seen that the energy density of metamorphic limestone is linearly correlated with the loading strain rate. With the increase of $E_v$, the degree of rock fragmentation increases. This is because metamorphic limestone, as a natural material, contains a large number of primary fissures. With an increasing strain rate, microscopic cracks in the rock intersect and penetrate, which leads to the destruction of the rock sample.

6. Conclusions

(1) In the dynamic impact test, with the increase of strain rate, the average block size of metamorphic tuff fracture bodies decreases significantly but the number of fracture bodies increases significantly, reflecting that the degree of rock fragmentation shows a strong correlation with the strain rate. When the loading strain rate is low (17.56 s$^{-1}$~34.70 s$^{-1}$), the rock specimen is damaged to a low degree, the

Table 4: Calculation results of energy values of typical rock samples under different strain rates.

| Specimen number | $\varepsilon$ (s$^{-1}$) | $W_i$ (J) | $W_r$ (J) | $W_t$ (J) | $W_s$ (J) | $E_v$ (J·cm$^{-3}$) |
|-----------------|--------------------------|-----------|-----------|-----------|-----------|---------------------|
| #1              | 17.56                    | 68.79     | 39.14     | 16.89     | 12.76     | 0.13                |
| #4              | 26.92                    | 97.50     | 58.47     | 18.42     | 20.61     | 0.21                |
| #7              | 34.70                    | 157.31    | 84.76     | 42.14     | 30.41     | 0.31                |
| #10             | 56.18                    | 209.45    | 103.48    | 58.79     | 47.18     | 0.48                |
| #13             | 67.34                    | 255.67    | 134.37    | 69.18     | 52.12     | 0.53                |

Figure 10: Relation curve between incident energy, reflection energy, transmission energy, dissipation energy, and strain rate.

Figure 11: The relationship between energy density and strain rate.
residual compressive capacity is high, and the morphology of the crushed body is a blocky cleavage structure with a laminar fracture structure, which belongs to cleavage damage. Under the condition of high strain rate (67.34 s⁻¹), the rock specimen is broken to a high degree, the residual compressive strength is small, and the morphology of the broken body is in the form of a laminar fracture structure, columnar cleavage structure, and conical body structure, which belongs to cleavage damage and shear damage.

(2) In the impact test, the strain rate of the specimen increases with the increase of impact air pressure. The initial slope of the stress-strain curve (dynamic modulus of elasticity), the peak stress (dynamic compressive strength), the corresponding strain, and the maximum strain amplitude are positively correlated with the strain rate.

(3) By sieving the fractured rock masses, the mass percentages of fractured rock masses at different dimensions are obtained. The fractal characteristics of the fractal dimension of rock specimens are significantly affected by the strain rate, and the Df of metamorphic tuffs were 1.74, 1.83, 2.25, and 2.31 at strain rates of 26.92 s⁻¹, 34.70 s⁻¹, 56.18 s⁻¹, and 67.34 s⁻¹, respectively; the loading strain rate is positively correlated with the fractal dimension, but the fractal dimension gradually decreases and stabilizes as the growth rate of the strain rate slows down.

(4) The incident energy, reflected energy, transmitted energy, and dissipated energy of metamorphic tuff specimens under impact loading increase continuously with an increasing strain rate, and the energy all increases about three times when increasing from 17.56 s⁻¹ to 67.34 s⁻¹. The cause of rock specimen damage is explained from the energy point of view. The energy density of specimens under impact loading increased linearly with an increasing strain rate. The energy density pattern of rock specimens under different strain rate conditions shows good consistency with the degree of rock fragmentation.

Data Availability

The data involved in the results generated or analyzed during this trial are all included in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors’ Contributions

Qingyun Qian is co-first author, Yonghui Huang is corresponding author, and Jianguo Wang is co-corresponding author.

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