Research Article

Analysis of Dynamic Damage Fractal and Energy Consumption Characteristics of Dolomite Marble

Ting Zuo ¹, Zehu Zhao,¹ Jianguo Wang ^{1,2}, Xianglong Li ^{1,2}, Zihao Tao ¹,
and Changhui Yang¹

¹Faculty of Land Resources Engineering, Kunming University of Science and Technology, Kunming, Yunnan 650093, China

²Yunnan Key Laboratory of Sino-German Blue Mining and Utilization of Special Underground Space, Kunming University of Science and Technology, Kunming, Yunnan 650093, China

Correspondence should be addressed to Jianguo Wang; wangj0831@163.com and Xianglong Li; lxl00014002@163.com

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To investigate the damage fractal and energy dissipation of dolomite marble under blasting load, Dahongshan Copper Mine was selected as the test object and one-dimensional SHPB impact tests with different strain rates were carried out. The dynamic compressive strength, damage morphology, fractal fragmentation, and energy dissipation of the rock were analyzed. The results showed that the absorbed energy per unit volume and the crushing energy per unit mass of dolomite marble are closely related to the dynamic compressive strength. The fractal dimension D of dolomite marble increases with increasing strain rate, and the smaller the average block size of the rock, the degree of crushing deepens. In addition, as the incident energy increases, the crushing energy of the rock also increases, and the energy dissipation intensifies. Finally, after comparative analysis, the reasonable strain rate range is $68.14\text{--}77.61\text{ s}^{-1}$, and the reasonable specific energy absorption value range is $0.65\text{--}0.98\text{ J/cm}^3$. The fractal pattern of rock deformation and damage can be reasonably explained from the perspective of energy dissipation.

1. Introduction

Blasting has been an indispensable technology in current mining methods [1–3]. Therefore, it is vital to study the impact of blasting stress waves on the surrounding rock mass as well as the process of rock damage and the mechanism of fragmentation. Dynamic mechanical characteristics and energy consumption regularities of rocks are involved in various engineering fields and natural disasters, such as roadway excavation, hydraulic engineering excavation, underground mine mining, earthquakes, and landslides. This geological engineering has enabled the vigorous development of rock dynamics and related disciplines, and has gradually attracted the attention of the field of rock and soil mechanics [4]. When using mechanical equipment to break the rock or blasting technology for excavation, the strain rate of rock is basically $10^1\text{--}10^3\text{ s}^{-1}$; therefore, the split Hopkinson pressure bar (SHPB) test is used to study the dynamic mechanical characteristics of rock [5, 6].

So far, there have been many valuable research results on the dynamic mechanical characteristics and energy dissipation regularities of rocks [7]. For example, Ding et al. [8] combined fractal theory, dynamic caustics, and high-speed photography to analyze the influence of static stress. The results showed that the static stress accelerates the propagation speed of explosion cracks in the direction of larger static stress, and the propagation length is longer. Besides, based on the theory of fractal rock mechanics and fracture mechanics, Deng et al. [9] proposed a new model of energy consumption. The test results showed that the fragments produced by rock fragmentation under impact load have fractal characteristics. The larger the fractal dimension, the higher the degree of rock fragmentation. In addition, Ding et al. [10] investigated the fractal damage in the breakage zone, the fracture zone, and the crush zone. The results showed that the filling medium acts as a buffer, attenuates the blast energy transfer, and inhibits the formation and development of the fracture zone. Furthermore, in order to

explore the broken fractal characteristics of the surrounding rock of underground mine tunnels under the action of blasting load, Wang et al. [11] selected the pomegranate biotite schist as the test object and carried out a one-dimensional SHPB impact test. Analyze from the angles of shape and energy consumption density of crushing. Comparative analysis obtains a reasonable range of strain rate and a reasonable range of crushing energy density.

In the use of fractal theory combined with other aspects, Sun et al. [12] used fractal theory to calculate the correlation between stress and acoustic emission data synchronization. The results showed that the fractal characteristics of stress and acoustic emission coupling characteristics become more obvious with the increase of the correlation dimension. Liu et al. [13] evaluated the acoustic emission signal of coal fracture under uniaxial compression, combined with fractal theory to analyze the frequency spectrum, energy, and fractal characteristics of acoustic emission waveforms under different stress levels. Yang et al. [14] proposed a new method for predicting the risk of rock burst based on the analysis of the fractal dimension of the spatial distribution. It is found that the fractal dimension of the acoustic emission spatial distribution of the coal sample is significantly reduced, which verifies that the acoustic emission monitoring is carried out. Kou et al. [15] analyzed the fractal dimension of the three-dimensional failure fragments under the condition of hydraulic-mechanical coupling load. The test results showed that the peak strength of the precracked rock sample under the condition of fixed confining pressure and triaxial compression increases with the increase of internal fluid pressure. In addition, as the internal fluid pressure increases, the fracture surface roughness of the microscale crack initiation area decreases. Based on the theory of fractal theory, Zhang et al. [16] studied the influence of reservoir temperature, flow rate, and fracture morphology on the thermal convection. The results showed that with the increase of rock temperature, the outlet temperature and overall heat transfer coefficient (OHTC) increase.

At present, the dynamic mechanical characteristics of various rocks have been studied, but there are few studies on the relationship between the fractal characteristics of rock fragmentation and dissipated energy after impacted. Since the failure of the specimen is mainly a process of energy accumulation and release [17], the study of the energy dissipation characteristics during the specimen failure process can explain the failure mechanism of the specimen in a macroscopic view. In addition, the fractal dimension can be used to quantitatively express the failure form of the rock in order to reflect the degree of fracture of the specimen [18]. This paper takes the dolomite marble of the surrounding rock of Dahongshan Copper Mine of Yuxi Mining Co., Ltd. as the research object. The uniaxial impact test is carried out on the dolomite marble with the split Hopkinson pressure bar. Through the test results, the dynamic mechanical characteristics, damage degree, and energy dissipation regularity of the dolomite marble under different strain rates are analyzed. Based on the analysis, the present work can provide reference significance for analyzing the damage of

dolomite marble under blasting load during roadway driving.

2. Test Preparation and Procedure

2.1. Test Device and Principle. This experiment was carried out on a $\Phi 50$ mm split Hopkinson pressure bar in the Laboratory of Rock Mechanics, Kunming University of Science and Technology. As shown in Figure 1, the test system is composed of nitrogen pressure device, bullet, incident bar, transmission bar, data acquisition system, and energy absorption device. The bullet length is 0.6 m, the incident bar and transmission bar are both 2 m, the elastic modulus of the compression bar is 210 GPa, the material is alloy steel with a density of 7.85 g/cm³, and the longitudinal wave velocity is 5190 m/s. The bullet is powered by nitrogen pressurization, and a laser velocimeter is used to measure the velocity of the bar under impact. In order to eliminate the end effect as well as the tip effect of the roadway rock specimen, a layer of petroleum jelly was smeared on both ends of the rock specimen to ensure the two end surfaces of the specimen.

The basic principle of the SHPB test is based on the theory of stress wave propagation in an elastic compression bar [19]. The three-wave method is usually used to process the test data, and the strain rate $\dot{\epsilon}_s$, strain ϵ , and stress σ_s of the specimen can be expressed by equation (1) [20]:

$$\begin{aligned}\dot{\epsilon}_s &= \frac{C}{L_s} [\epsilon_i(t) - \epsilon_r(t) - \epsilon_t(t)], \\ \epsilon &= \frac{C}{L_s} \int_0^{t_0} [\epsilon_i(t) - \epsilon_r(t) - \epsilon_t(t)] dt, \\ \sigma_s &= \frac{EA}{2A_s} [\epsilon_i(t) - \epsilon_r(t) - \epsilon_t(t)],\end{aligned}\quad (1)$$

where A_s , A is the cross-sectional area of test specimen and the compression bar (m²); C is the elastic longitudinal wave velocity of the compression bar (m/s); E is the modulus of elasticity of the compression bar (GPa); L_s is the length of test specimen (m); ϵ_i , ϵ_t and ϵ_r are the strains of the incident, transmitted, and reflected waves at a certain moment t , respectively; and t is the propagation time of the stress wave in the bar (s).

The incident energy W_I , the reflected energy W_R , and the transmitted energy W_T of the compression bar are calculated during the whole crushing process of the rock as follows [21]:

$$\begin{cases} W_I(t) = AEC \int_0^t \epsilon_I^2(t) dt, \\ W_R(t) = AEC \int_0^t \epsilon_R^2(t) dt, \\ W_T(t) = AEC \int_0^t \epsilon_T^2(t) dt. \end{cases}\quad (2)$$

Neglecting the energy loss of stress waves during propagation process, the absorbed energy of rock is shown in equation (3),

FIGURE 1: SHPB impact test system.

$$W_s = W_I - (W_R + W_T). \quad (3)$$

According to the characterization method of the absorption energy per unit volume of the specimen in rock dynamics analysis, the specific energy absorption value ω_{cp} is introduced to characterize the absorption energy per unit volume of dolomite marble, and the influence of the volume factor on test results is further reduced. As shown in equation (4),

$$\omega_{cp} = \frac{W_s}{V}, \quad (4)$$

where W_s is the absorbed energy of specimen (J) and V is the volume of specimen (cm^3).

Meanwhile, in order to study the energy dissipation regularity of dolomite marble, ω_d is defined as the energy dissipation per unit mass of rock absorbed by crushing, as shown in equation (5).

$$\omega_d = \frac{W_s}{M_s}, \quad (5)$$

where ω_d is the crushing energy consumption per unit mass of specimen (J/g); W_s is the absorbed energy of specimen (J); and M_s is the mass of specimen (g).

2.2. Test Preparation. The specimens were taken from Yuxi Mining's Dahongshan Copper Mine. The marble was taken from a large block in the same area, in order to ensure the integrity and uniformity of rock specimens. According to the requirements of rock mechanics test, the nonparallelism of the two ends of specimen during processing should be less than 0.02 mm. The central axis of the specimen needs to be perpendicular to the two end surfaces, and its axial deviation

should be less than $\pm 0.25^\circ$ [22]. In order to eliminate the end effect and inertia effect of rock, the specimens were machined into cylinders with a size of $50 \text{ mm} \times 50 \text{ mm}$. The basic physical parameters of the specimens measured before the test are shown in Table 1, and D-1#~D-15# are dolomite marble specimens, as shown in Figure 2.

Before test, the specimens were prepunched to determine the optimal impact pressure. Five impact pressures of 0.40 MPa, 0.45 MPa, 0.50 MPa, 0.55 MPa, and 0.6 MPa were determined based on the damage pattern of the test specimen after the test. Conduct 3 sets of parallel tests for each impact air pressure, respectively, to eliminate test errors.

3. Test Results and Analysis

3.1. Analysis of Breakage Patterns. The damage pattern of dolomite marble was obtained by using separate tests under different impact air pressures as shown in Figure 3. At strain rates of 44.31 to 54.90 s^{-1} , the rock breaks in a splitting pattern, which represents tensile damage [23]. At strain rates of 60.72 to 86.05 s^{-1} , the fragmentation degree of the specimen increases with increasing strain rate, and the fragmentation size gradually decreases with the increase of the strain rate. To analyze this phenomenon, the stress wave propagates first to the specimen surface and then to the entire specimen, making the effective stress distribution uniform [24, 25]. At the same time, internal microdefects are activated and a small amount of cracks appear. As the stress continues to increase, the specimen continues to develop cracks in initial crack defect state, and cracks appear at the direction parallel to the compressive stress and gradually run through the ends of specimen, finally forming the axial splitting tensile damage. In the case of relatively complex stresses, the number of microcracks in the specimen

TABLE 1: Average value of physical parameters of test specimen.

Specimen	Length (mm)	Diameter (mm)	Aspect ratio	Quality (g)	Density ($\text{kg}\cdot\text{m}^{-3}$)	Modulus of elasticity (GPa)	Poisson's ratio	Compressive strength (MPa)
Dolomite marble	49.53	48.50	1.02	270.23	2953.19	78.71	0.32	70.95

FIGURE 2: Dolomite marble.

FIGURE 3: Failure modes of dolomite marble under different impact velocities.

increases and the interaction forces between the apparent cracks grow. At the meanwhile, a certain amount of strain energy is accumulated in the specimen during the impact process. After the incident stress wave completely penetrates the specimen, the strain energy stored in the specimen starts to release and continuously promote crack penetration, thus forming the damage pattern above.

3.2. Dynamic Strength Characteristic Analysis. The characteristic parameters of rock fragmentation are shown in Table 2. The peak strain is the strain value corresponding to the peak stress in the stress-strain curve.

The relationship curves between the dynamic compressive strength of rock with the specific energy absorption value, the energy consumption per unit mass of fracture, and the strain rate are shown in Figures 4 and 5. From Figure 4, it can be seen that the dynamic compressive strength of dolomite marble presents a significant strain rate effect [26]. For example, when the strain rate increases from about 44.31 s^{-1} to 86.05 s^{-1} , the dynamic compressive strength of rock increases from 163.38 MPa to 212.6 MPa, and it has a power function relationship with the strain rate. Figure 5 shows that as the dynamic compressive strength of dolomite marble increases, the energy absorbed per unit volume and the energy consumption per unit mass of the rock gradually increase accordingly. After linear fitting results, it can be

obtained that the dynamic compressive strength of the dolomite marble specimen shows significant linear relationships with the energy absorbed per unit volume and the energy consumption per unit mass. As shown in equation (6), the general formula of the regression curves is as follows:

$$\begin{cases} y_1 = A_1 + B_1 \cdot \exp(C_1 \cdot x), \\ y_2 = A_2 + B_2 \cdot \exp(C_2 \cdot x), \end{cases} \quad (6)$$

where y_1 is the absorbed energy per unit volume of the rock specimen, J/cm^3 ; A_1 , B_1 , C_1 , A_2 , B_2 , and C_2 are fitting coefficients; y_2 is the crushing energy consumption per unit mass of the rock specimen, J/g ; and x is the dynamic compressive strength of the rock specimen, MPa.

The dynamic compressive strength of rock changes significantly under the action of different strain rates, which is called the strain rate effect. This is the mechanical response characteristics caused by the change of one-dimensional stress state of brittle materials such as rocks. As the strain rate increases, the internal cracks of the rock develop; thus, a lot of external energy is needed for the propagation and penetration of these cracks. However, as the time of the impact loading process is extremely short, the energy accumulation is insufficient. Thus, the external energy can only be offset by increasing its own stress, and at the same time, the absorption energy per unit volume and the energy consumption per unit mass of the rock specimen are

TABLE 2: Rock fragmentation characteristic parameters under different strain rates.

Serial number	Impact pressure/MPa	Impact velocity/(m·s ⁻¹)	Strain rate/(s ⁻¹)	Dynamic compressive strength/MPa	Peak strain	Incident energy/J	Absorbed energy/J	Specific energy absorption/(J·cm ⁻³)	Absorbed energy per unit mass(J·g ⁻¹)
D-2#	0.40	10.27	44.31	163.38	0.0084	153.08	51.28	0.56	0.19
D-4#	0.43	10.73	48.94	165.63	0.0075	168.68	54.11	0.59	0.20
D-5#	0.45	11.68	54.90	175.77	0.0089	190.36	58.77	0.65	0.21
D-7#	0.50	12.85	60.72	190.03	0.0096	235.74	68.41	0.75	0.25
D-9#	0.58	13.15	68.14	194.47	0.0090	246.88	70.22	0.77	0.25
D-10#	0.55	13.66	77.61	201.39	0.0102	279.48	76.36	0.84	0.28
D-12#	0.60	15.65	86.05	212.68	0.0113	349.95	88.96	0.98	0.32

FIGURE 4: Relationship between the dynamic compressive strength and strain rate of dolomite marble.

FIGURE 5: Relationship between the dynamic compressive strength of dolomite marble with ω_d and ω_{cp} .

increased. Therefore, for actual working conditions such as roadway blasting and mechanical dynamic loading, the dynamic mechanical strength of the surrounding rock should be fully considered when the roadway is excavated or supported.

3.3. Fractal Characteristics of Rocks

3.3.1. Fragment Screening and Calculation of Fractal Dimension. In order to quantitatively describe the degree of fragmentation of the specimen, it can be expressed intuitively by the fragmentation distribution of the fragments after the rock specimen is broken, which can reflect the regularity of the failure degree of the rock specimen with the increasing strain rate. Use a standard sieve of 0–25 mm size to screen the impacted rock specimens, weigh the mass of the remaining fragments on the sieve (Table 3), and then convert it to the percentage of rock fragments of different sieve sizes. The fragmentation distribution curve of dolomite marble is shown in Figure 6.

As can be seen from Figure 6, the percentage of the dolomite marble fragments with the size larger than 25 mm after impact damage under conventional uniaxial impact loading is above 35.19% in all cases. As the strain rate increases from 44.31 s⁻¹ to 86.05 s⁻¹, the proportion of the fragments larger than 25 mm decreases from 66.71% to 35.19%, with relatively flat changes for the distribution of fragments equal to or smaller than 20 mm in size.

In addition to the particle size distribution, the fractal dimension is also an important indicator of the fractal characteristics of rock, which increases with the degree of fragmentation of the specimen [27].

$$Y = \left(\frac{r}{r_m} \right)^b, \quad (7)$$

where b is the corresponding regression coefficient, and on the basis of the mass-frequency relationship, the crushing bulk distribution equation of rock specimen can be obtained as follows:

$$Y = \frac{M_r}{M_t}, \quad (8)$$

$$= \left(\frac{r}{r_m} \right)^{3-D},$$

where M_r is the mass of rock fragments with a particle size less than r ; M_t is the total mass of rock fragments; and r_m is the maximum particle size. The following equation can be obtained by taking logarithm on both sides of equation (8) at the same time:

TABLE 3: Impact test sieve sizes and corresponding weighing masses.

Strain rate (s ⁻¹)	Sieving diameter (mm)										Total (g)
	0	0.3	0.5	1	2.5	5	10	15	20	25	
44.31	0.22	0.35	1.54	0.83	1.23	5.34	10.33	28.71	40.89	179.81	269.25
48.94	0.42	1.01	1.21	2.51	2.48	9.13	8.69	31.76	43.91	168.04	269.16
54.90	0.72	1.76	1.72	3.89	3.52	8.04	20.21	40.97	40.2	142.76	263.79
60.72	2.48	3.65	3.31	10.93	3.26	14.32	33.52	50.28	27.97	116.82	266.54
68.14	1.59	5.34	10.2	4.57	13.47	20.43	47.55	14.28	28.87	119.44	265.77
77.61	7.72	3.76	2.72	17.89	8.24	38.04	38.47	15.43	17.89	112.76	262.92
86.05	5.45	4.37	9.85	22.42	19.9	29.45	27.45	33.42	22.36	94.85	269.52

FIGURE 6: Fragmentation distribution of dolomite marble under different strain rates.

$$\ln Y = \ln \left[\frac{M_r}{M_t} \right], \quad (9)$$

$$= (3 - D) \ln \left(\frac{r}{r_m} \right).$$

Therefore, the slope of the line fitted through the coordinate system of $\ln [M_r/M_t] - \ln r$ is the fractal dimension D .

The $\ln [M_r/M_t] - \ln x$ curves for the distribution of dolomite marble fragments are shown in Figure 7.

As can be seen from Figure 7, the percentage of cumulative mass under the sieve for crushed bulk of dolomite barite is linearly correlated with the sieve hole size in a double logarithmic coordinate system. And the slope of its particle size characteristic curve decreases with increasing strain rate, indicating a gradual increase in mass at the fines end of the crushed dolomite barite and a deeper degree of crushing. The average fragmentation size and fractal dimension D of the dolomite marble fragments are shown in Table 4. The correlation coefficients R^2 are all at high levels from the data listed in the table, indicating that the distribution of rock fragmentation mass under impact loading is consistent with the fractal pattern.

FIGURE 7: Grain size characteristic curve of dolomite marble.

3.3.2. Relationship between Fractal Dimension with Strain Rate and Average Fragmentation. It can be seen from Figure 7 that the linear fitting degree of the double logarithm function image is as high as, indicating that the self-similarity of the fragmentation distribution after rock fragmentation is high, or the fractal characteristics are significant. The reason is that the aggregation of small internal cracks leads to the macroscopic destruction of rock, which is in turn formed by multiplication of smaller cracks, and this self-similarity eventually leads to a self-similarity in the distribution of size. Thus, a quantitative description of rock fragmentation can be expressed in terms of fractal dimension. The fractal dimension D is therefore related to the strain rate and the average fragment size, respectively (see Figures 8 and 9). The average fragment size is expressed as a block size with a cumulative percentage under a screen of 50%. The formula is shown in equation (10).

$$d_s = \frac{\sum r_i d_i}{\sum r_i}, \quad (10)$$

where d_s is the average size of the crushed rock mass at different screen diameters; r_i is the screen diameter; and d_i is the percentage of rock mass.

The following analysis yields the law of block size distribution and the law of change in the degree of fragmentation of rocks under different dynamic loads. It can be seen from Figures 8 and 9 that the fractal dimension has a linear

TABLE 4: Fragmentation statistics of dolomite marble under impact loading.

Specimen no.	D-2#	D-4#	D-5#	D-7#	D-9#	D-10#	D-12#
Average crushing size/mm	24.30	23.62	22.30	19.82	18.81	17.52	16.27
Fractal dimension	1.88	2.02	2.12	2.35	2.40	2.54	2.57
Correlation coefficient R^2	0.85	0.87	0.88	0.75	0.75	0.81	0.77

FIGURE 8: Relationship between the fractal dimension and the strain rate.

FIGURE 9: Relationship between the fractal dimension and the average fragmentation size.

relationship with strain rate and average fragmentation size, and the correlation between the two is strong. In the experiment, the strain rate of dolomite marble increases from 48.94 s^{-1} to 86.05 s^{-1} , the fractal dimension D increases from 2.02 to 2.54, and the average fragmentation size decreases from 23.62 mm to 16.27 mm. It shows that the fragmentation

distribution of dolomite marble has self-similarity characteristic, and the fractal characteristics are significant.

3.4. Regularity of Energy Dissipation. According to the regularity of thermodynamics, rock failure is actually a process of energy absorption, transformation, and release [28–31]. This is because the energy dissipation characteristics of the rock during damage are closely related to its internal damage level. As a direct result of the external energy acting on the rock causing internal damage to the rock, each stage of the cracking process requires external energy to replenish, multiply, sprout, expand, and penetrate, and the whole process is an energy dissipation process. Therefore, using the concept of energy dissipation can reflect the whole process of rock deformation and damage more reasonably. At the same time, the law of energy dissipation also plays an important role in rock mining [32–35] and fracture simulation [36, 37].

3.4.1. Specific Energy Absorption Value, Absorbed Energy, and Incident Energy. The specific energy absorption value is an effective index to determine the energy absorbed by rock under impact load, which indicates the intensity of energy absorbed per unit volume in impact compression test. Figure 10 shows the relationship between the specific energy absorption values and the absorbed energy with incident energy for the dolomite marble specimens. It can be seen from this figure that the specific energy absorption values and absorbed energy of the rock specimens increase with the increase of incident energy and have strong linear relationships, with the regression coefficient of the fitted curves larger than 0.9.

3.4.2. Crushing Size and Energy Consumption. According to the screening results of rock fragmentation, the relationship between average fragmentation and specific energy absorption value and the relationship between fractal dimension and specific energy absorption value can be obtained. The average fragment size of rock specimens under different impact loads is 16.27–24.30, and the fractal dimension is 1.88–2.57. As shown in Figure 11, the mass fractal dimension of dolomite marble specimens increases with increasing specific energy absorption value and shows a linear relationship, while the average fragmentation size decreases with the increasing specific energy absorption value and shows an exponential function.

The greater the specific energy absorption value, i.e., the energy consumption density, the greater the degree of rock fragmentation. This is because the more the energy consumed per unit volume of the rock specimen during the impact compression test, the more energy is used to deform and break the rock and the faster the microcracking breed development, resulting in more fracture surfaces and smaller

FIGURE 10: Relationship between specific energy absorption values with absorbed energy and incident energy.

FIGURE 11: Relationship between average fragment size and specific energy absorption value.

scale fragments. The average fragment size can therefore be used to quantify the degree of rock fragmentation.

3.4.3. Degree of Fragmentation and Energy Dissipation in Relation to Strain Rate. In order to investigate the variation of specific energy absorption value and fragmentation degree of dolomite marble at different strain rates, the relationship between specific energy absorption value, average fragmentation size, incident energy, and strain rate at different strain rates is given in Figure 12. The analysis shows that the specific energy absorption value of the rock specimen increases with increasing strain rate which is in linear correlation, with a fitted curve data correlation coefficient of 0.967. The mean crushing bulk increases with increasing

FIGURE 12: Curves of specific energy absorption, average fragmentation, and incident energy at different strain rates.

strain rate which is also linearly correlated, with a fitted curve data correlation coefficient of 0.968. The incident energy increases with increasing strain rate in a roughly linear relationship, with a fitted curve data correlation coefficient of 0.964. As the strain rate increases and new cracks created in the rock specimen, more energy is absorbed by the specimen. The higher the specific energy absorption value, the higher the incident energy, but the average fragmentation size is reduced. Therefore, increasing the strain rate can significantly increase the degree of rock fragmentation.

Rock failure can be seen as a process of continuous energy transformation, where the underlying cause of deformation and damage is the dissipation of energy. Therefore, it is necessary to use energy dissipation to characterize the fracture degree of rock. The variation of specific energy absorption value, average fragmentation size, and incident energy with strain rate is shown in Figure 12. As can be seen from this figure, when the strain rate is low, the rock is less damaged, with more large blocks and fewer small blocks. As the strain rate increases, the fragmentation of rock deepens, with the amount of large masses decreasing and the amount of small masses gradually increasing. The specific energy absorption value increases with increasing strain rate, which indicates that the more the energy absorbed by the rock, the smaller the rock fragmentation and the deeper the fragmentation.

4. Discussion

In summary, an increase in strain rate allows the effective crushing bulk of the rock to gradually migrate toward the fine grain end, enhancing the crushing effect [38, 39]. However, the increased crushing effect means that the crushing energy consumption density (specific energy absorption value) increases. Therefore, a reasonable range of strain rate and crushing energy consumption density is of great practical importance to enhance rock crushing and reduce energy consumption. The slope of the particle size characteristic curve in Figure 7 is characterized as the distribution of rock fragmentation size, also known as the bulk distribution factor

FIGURE 13: The relationship diagram for determining the reasonable strain rate range.

FIGURE 14: The relationship diagram for determining the reasonable range of crushing energy consumption density.

Q. Figure 13 shows the bulk distribution factor Q and fractal dimension D as a function of strain rate, and Figure 14 shows the bulk distribution factor Q and fractal dimension D as a function of crushing energy dissipation density.

From the fragment size distribution coefficient curve in Figure 13, it can be seen that the slope of the curve changes faster and the decline rate increases when $\dot{\epsilon}$ approaches 48.94 s^{-1} . Therefore, in order to achieve a better crushing effect the $\dot{\epsilon}$ interval can be initially chosen to be 48.94 to 77.61 s^{-1} , and from the fractal dimension curve the $\dot{\epsilon}$ interval is 68.14 – 86.05 s^{-1} . Similarly, the two curves in Figure 14 give the crushing energy density ranges of 0.65 – 0.84 J/cm^3 and 0.75 – 0.98 J/cm^3 , respectively.

According to the relationship between strain rate and crushing energy density in Table 2, the reasonable strain rate range to achieve rock crushing can be treated as the

intersection of the above sets, which should be 68.14 – 77.61 s^{-1} , and the reasonable crushing energy density range should be 0.65 – 0.98 J/cm^3 (the dashed line range in Figures 13 and 14).

5. Conclusions

In this paper, a representative dolomite marble was selected to carry out SHPB rock dynamic mechanical tests, and a series of test results were obtained, including rock fragmentation characteristics, strength index, and energy parameters under different strain rates. The final research investigated the relationship between the kinetic parameters and the fractal dimension, and provides a reference basis for further research on the dynamic mechanical properties of high ground stress rocks in triaxial impact tests. The following conclusions were mainly obtained:

- (1) There is a significant strain rate effect on the dynamic compressive strength of dolomite marble. The dynamic compressive strength increases with increasing strain rate and satisfies a multiplicative power relationship. The absorbed energy per unit volume and the crushing energy per unit mass of rock both increase linearly with increasing dynamic compressive strength.
- (2) The fractal dimension D can quantify the crushing characteristics and energy dissipation of rock. The distribution of fractal size of dolomite marble under impact loading satisfies the fractal regularity, and the fractal dimension D increases with increasing strain rate. The fractal dimension D of dolomite marble at strain rates ranging from 44.31 to 86.05 s^{-1} is 1.88 – 2.57 , and the average fragmentation size is 16.27 – 24.30 mm .
- (3) The whole deformation and damage process of the dolomite marble can be reasonably explained by the concept of energy dissipation. The greater the specific energy absorption value of a rock under impact loading, the smaller the average fragmentation size of the rock and the greater the fractal dimension, indicating a larger intense fragmentation of the rock.
- (4) The reasonable strain rate range for the dolomite marble to both improve the crushing effectiveness and reduce the crushing energy consumption is 68.14 – 77.61 s^{-1} , and the reasonable range of crushing energy consumption density is 0.65 – 0.98 J/cm^3 .

Data Availability

The data used to support the findings of this study are included in the article.

Disclosure

Zehu Zhao is the co-first author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Conceptualization, methodology, validation, data curation, visualization, and writing original draft preparation were performed by Z. T. and X. L.; experimental guidance and data analysis were performed by J. W.; theoretical analysis was carried out by Z. Z.; formal analysis writing, reviewing, and editing were conceived by all authors. All authors have read and agreed to the published version of the manuscript.

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