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Research Article

Influence of Incremental Impact on the Damage of Coal-Rock under Unidirectional Constraint

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Taking the briquette sample as research object, the influence of the incremental impulse (momentum) on the damage of coal-rock under different uniaxial axial pressure was studied by using the self-developed pendulum impact dynamic loading test device, cooperating with the ultrasonic detection device. Meanwhile, the influence of constant impulse on the damage degree of coal-rock was compared. The results show that the damage degree of coal-rock increases with the increase of the impulse, and the damage fitting curve is upward concave, indicating that the coal sample tends to accelerating failure. Moreover, with the increase of axial pressure, the variation gradient of the damage degree of coal-rock tends to moderate and the cumulative damage degree decreases under the same impulse, and the impact resistance of coal-rock increases. When the impulse is constant, the damage degree of coal-rock increases with the number of impact, and the damage curve is upward convex, indicating that coal-rock has a tendency to slow down the damage. The cumulative damage degree of coal-rock decreases with the increase of axial pressure, and the number of impact needed to destroy coal-rock is increased. In addition, the damage model of coal-rock was proposed, and the criterion of coal-rock damage was obtained, which shows that the damage degree of coal-rock increases with the increase of impact load and decreases with the increase of static axial load.

1. Introduction

Most rocks in nature lie in the complicated environment where there is a combination of confining pressure and dynamic loads, and some are under unidirectional constraints (one-dimensional static loads). Mining coal pillars are subject to the gravity load of the overlying strata as well as the dynamic effects of periodic weighting. Viaduct piers suffers dynamic disturbance when a high-speed train is going by on them. All these engineering problems can be simplified to study the effect of dynamic impact on rock (coal-rock) under unidirectional constraint. The researches on damage of rock under impact loading have been quite mature so far. For example, Tang and Xu [1] measured the whole dynamic stress-strain curve of rock by means of the pendulum impact pressure bar technique in 1987. Li et al. [2] conducted an experimental study of rock mechanical characteristics under coupled static and dynamic loads and found that rock breaks with tensile failure mode under coupled static and dynamic loads. Li et al. [3] conducted the Hopkinson pressure bar shock failure test and static loading failure test and obtained the total absorbed energy, total dissipated energy, and damage variables of rock failure under varied impact loads and the change laws of the total absorbed energy of rock under static loading. Zhao et al. [4] carried out a systematic experimental investigation into the evolution law of the internal microstructure and the new surface fissures of briquette coal under different impact loads and analyzed the mechanism of impact loads on the evolution of the internal microstructure of briquette coal. Rock dynamics is an important research subject in mining and geotechnical engineering. Dynamic impact, on the one hand, can break rock (coal) efficiently, increase gas migration channels, improve coal seam permeability, etc.; on the other hand, it can induce mine disasters such as rock bursts, coal and gas outbursts, and water inrush from coal and rock mass.

At present, there are few studies on the damage of rock caused by dynamic impact under unidirectional constraint. Especially, the research on the coupling relationship between unidirectional static load constraint, impact load, and damage evolution of coal-rock internal structure is still insufficient. However, it is of great theoretical significance and practical value to study the impact load on coal-rock damage under static load constraint. Therefore, regarding coal-rock as the object, the damage evolution law of coal-rock under unidirectional constraint was studied after coal-rock was subjected to the impact of incremental impulse, and the effects of constrained static load and impact load on coal-rock damage were analyzed. Furthermore, the difference of damage evolution of coal-rock under cyclic impact of constant impulse and incremental impulse was compared and analyzed. The unidirectional constrained dynamic impact model is shown in Figure 1.

According to Figure 1, there are two types of dynamic impact models of unidirectional constraint: (1) the direction of constrained static load P_s is the same as that of impact load P_d, and (2) constrained static load P_s is perpendicular to impact load P_d. These two impact models represent two different scientific problems, and the constitutive relationship and damage mechanism are quite different under the two impact models. Therefore, the two unidirectional constrained dynamic impact models must be distinguished and studied separately. In this study, we chose the second unidirectional constrained dynamic impact model, as shown in Figure 1(b).

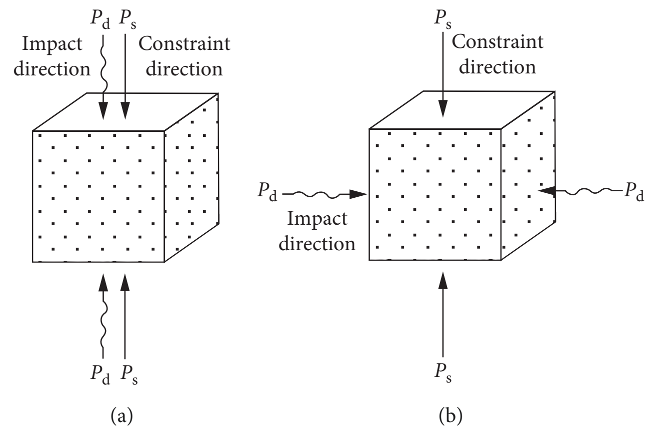

Figure 1: Unidirectional constrained dynamic impact model.

2. Statistical Description of Coal-Rock Damage Degree

The macroscopic failures of rock-like materials are induced by their microscopic damage. The damage degree of rock-like materials can reflect the level of rock failure when rock material is subjected to load. Under certain loading, the internal defects of rocks will gradually evolve into micro-cracks and further form macroscopic failures, which will lead to the change of elastic modulus, ultrasonic wave velocity, and other parameters of rocks. The microscopic damage characteristics of rock-like materials can be described by acoustic, optical, and electromagnetic signals, which can reflect the evolution of the internal damage of rock-like materials [5]. Based on the microscopic damage characteristics of rock-like materials, there are several research methods about the characteristics as follows: statistics of rock damage degree based on ultrasonic detection technology [6]; rock damage based on nuclear magnetic resonance technology [7, 8]; location research of rock damage based on acoustic emission [9, 10]; rock temperature field evolution based on infrared imaging technology [11–13]; simulation of rock damage under impact loads based on numerical software like LS-DYNA [14, 15]; and rock damage based on digital speckle technology and the constitutive model of rock damage under impact loads [16, 17].

Since the existing technology is difficult to make direct observation and statistics of rock damage, it is necessary to define the damage degree to describe it. The methods [18, 19] of defining the damage degree now mainly include damage scalar defined on pore area, damage tensors defined on pore configuration, and damage variables defined on the variation of elastic modulus. It is particularly hard to carry out direct description and measurement of pore area or pore configuration. In addition, the damage degree of rock can also be defined by the change of ultrasonic wave velocity. To study the influence of dynamic impact on coal-rock under unidirectional constraint, the initial wave velocity of the coal-rock under initial constraint is recorded as V_0, and V_n is the wave velocity of the coal-rock under the same constraint after n times of impact load. And then the damage degree can be expressed as [20]

$$D_n = 1 - \left(\frac{V_n}{V_0}\right)^2. \tag{1}$$

Rock-like materials will be damaged to varying degrees after being subjected to impact load. During the generation of the damage, there will be different acoustic characteristics and ultrasonic transmission parameters. Therefore, the quantity change factor of the internal structure of rock-like material after each impact can be calculated by establishing the relationship between the ultrasonic velocity and the damage degree of rock-like material, and then the damage degree of rock materials can be calculated by indirect statistics.

3. Test Device and Program

3.1. Test Device. Figure 2 shows a pendulum impact loading test device with unidirectional restraint. Composed of a frame, a pendulum, a dial, and a constraint loading mechanism, the device employs a loading assistor to apply different one-dimensional static load on coal-rock and can exert different impact loads on coal-rock by adjusting the height of pendulum. As shown in Figure 2, the pendulum, cylindrical, connects the bearing by the rod. When calculating the

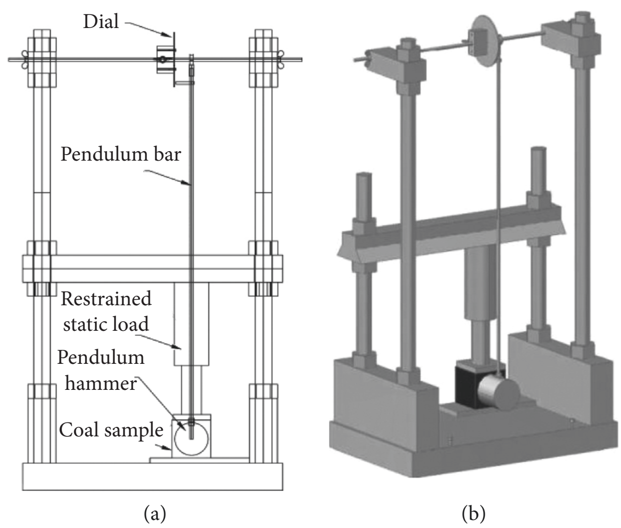

Figure 2: Pendulum impact loading test device with unidirectional restraint.

momentum of the pendulum on the coal sample, the equivalent mass [21] of the pendulum and the rod needs to be taken into consideration (the rod has a greater impact on the equivalent mass, while other parts have a smaller one on it). According to actual measurement, the effective length of the rod L is 0.73 m; the mass of it m_2 is 0.457 kg; the mass of the pendulum m_1 is 1.303 kg, and the diameter of it d is 0.06 m.

The moment of inertia of the rod:

$$I_L = \frac{1}{3} m_2 L^2 = 0.0812\,\mathrm{kg\cdot m^2}. \tag{2}$$

Equivalent mass:

$$m = m_1 + \frac{I_L}{L_2} = 1.455\,\mathrm{kg}. \tag{3}$$

Assuming that there is perfect elastic collision between the pendulum and the coal sample, and the impact time of the pendulum falling at different heights on the coal sample is the same. It is of much representative significance to use the impulse to express impacting energy, because the existing testing means are impossible to accurately measure the impact time of the pendulum on the coal sample. Based on the impulse and energy theorem, with dissipated energy ignored, it can be considered that the gravitational potential energy of the pendulum is completely converted into the kinetic energy of the coal sample. Then, the impulse per unit area is as follows:

$$I = \frac{m\sqrt{2gh}}{0.25\pi d^2}. \tag{4}$$

That is,

$$I = 1139.696\sqrt{h}. \tag{5}$$

Ultrasonic testing employs a HC-U81 ultrasonic concrete tester, whose sampling period is 0.05 μs~2.0 μs, sound-interval measuring accuracy is 0.05 μs, and amplitude measuring range is 0–170 dB. The parameters of the testing system are as shown in Table 1. Vaseline is used as the couplant between the sensor and the coal sample.

Table 1: Ultrasonic system parameter setting.

Sampling period (μs)	Transmitting voltage (V)	Measuring point spacing (mm)	Test surface	Test mode
0.5	500	70	Surface	Opposite measurement

3.2. Coal Sample. Natural coal masses have developed joint fissures [22] and are intractable, while briquette coal shows remarkable consistency with raw coal in its mechanical properties. Besides, briquette coal is easy to process and has little discreteness. Therefore, many researchers generally adopt briquette coal whose mechanical properties are similar to those of raw coal for testing. This test took briquette as the research object. The raw coal samples were taken from Daanshan Coal Mine of Beijing Haohua Energy Co., Ltd. When preparing briquette samples, the raw coal was first crushed to screen coal powder with particle size less than 0.5 mm for reserve, and then the coal powder, cement, and water were mixed according to the ratio of 10 : 2.5 : 2. After that, the briquette sample can be made by using the square briquette preparation device to apply a molding pressure of 25 MPa. The size of briquette samples is 70 mm × 70 mm × 70 mm with the difference no more than 2 mm, as shown in Figure 3. The main mechanical parameters of coal sample are shown in Table 2.

According to the distribution of NMR (nuclear magnetic resonance) T_2 spectra of the coal samples, as shown in Figure 4, the pore size distribution of coal samples is obtained after reasonable conversion, and the area of the T_2 spectrum curve and the horizontal axis is positively correlated with the porosity of coal samples. The porosity of briquette samples is about 25%; the pore radius is between 0.01 and 100 μm; the pore radius is mainly concentrated in 1–10 μm, and the maximum peak value is about 1 μm. Moreover, the porosity of raw coal samples is around 5%, with the pore radius distributed within 0.001–10 μm and concentrated within 0.001–0.1 μm; the maximum peak value is about 0.01 μm.

The aforementioned three research results show that the differences between the briquette sample and the raw coal sample are mainly manifested in three aspects: the strength, the pore structure quantity, and the pore structure scale. However, in terms of the ultrasonic wave velocity, the porosity, and the pore distribution characteristics of two samples, the briquette sample is still remarkably similar to the raw coal sample.

3.3. Test Program. To investigate the influence of the size of unidirectional constraint static load and the incremental shock on the damage of coal-rock, a constrained pendulum impact dynamic loading test device may be used to apply initial static axial compression of different sizes to a coal sample, leaving it under the conditions of unidirectional constraints. The pendulum of the device served as the power source to give impact load to the coal sample. The height of the pendulum can be changed, so that the pendulum at

(a) (b) (c)

Figure 3: Test coal sample. (a) Briquette size; (b) briquette sample; (c) raw coal sample.

Table 2: The main mechanical parameters of coal sample.

Material	Density (kg·m^{-3})	Elastic modulus (MPa)	Uniaxial compressive strength (MPa)	Porosity (%)
Coal	1.312	8948	5.64	28

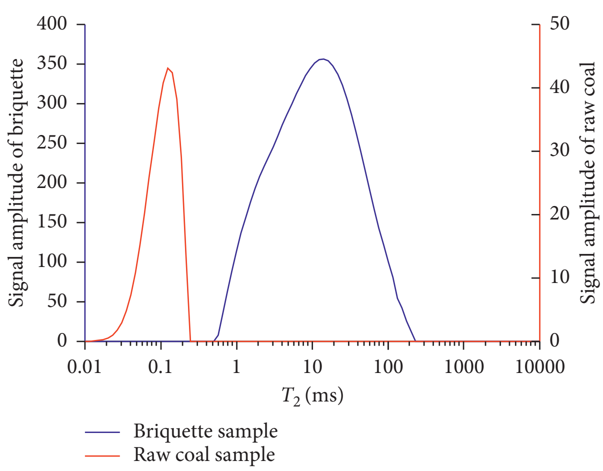

Figure 4: Nuclear magnetic resonance (NMR) test results of coal samples.

different heights exerts a different impulse on the coal sample. The impulse of various gradients can be used to carry out a dynamic impact test for the coal sample under one-dimensional static-load constraints. The test was divided into 7 groups in total. The first 5 groups use the orthogonal method, where the unidirectional static axial compressions of 0, 1.127, 3.38, 3.943, and 4.506 MPa were applied to each group of coal samples, respectively, according to the uniaxial compression strength σ_c of the coal sample (corresponding static axial compressions are 0, 20%, 60%, 70%, and 80% of the uniaxial compression strength σ_c), and then incremental cyclical impact load was applied to each group of coal samples under static axial constraints by the pendulum loading device, with the pendulum's height of its center of gravity at 0, 0.274, 0.548, 0.821, and 1.095 m, respectively. The pendulum at different heights will produce different impact loads, and incremental heights can provide incremental impulses. The incremental impulse means that the momentum of impact on the specimen increases gradually from small to large with the number of impact. The last two groups apply the unidirectional axial compression of 0, 3.38 MPa, respectively, to the coal samples, and the same cyclical impact load was applied to each group of the coal samples (pendulum height at 0.548 m) until the failure of the coal samples, as shown in Figure 5 and Table 3. The test load condition is shown in Table 3.

4. Relationship between Impact Loads and Coal-Rock Damage Degree

4.1. Relationship between Incremental Impulse Cyclical Impact and Coal-Rock Damage Degree

4.1.1. Relationship between Coal-Rock Damage Degree and Incremental Impulse. Internal microfractures of coal-rock expand and result in microcataclysm under external loading. The ultrasonic wave velocity measured by testing gradually decreases with the increasing of coal-rock damage. Converting wave velocity through formula (1) can obtain the damage degree D_n of the coal sample after suffering cyclical impact of incremental impulse under one-dimensional static axial compression. The fitting curve of the coal-rock damage degree D_n and the incremental impulse I can be obtained according to the experimental data, as shown in Figure 6. The paper gives the illustration based on the fitting curve of the incremental impulse cyclical impact under a 3.38 MPa static load constraint. According to statistics, the closer the fitting degree R^2 is to 1, the better the fitting effect is. The fitting degree R^2 in the fitting curve shown in Figure 6 is 0.9626, which can better describe the relationship between the coal-rock damage degree D_n and the incremental impulse I under unidirectional constraints. Figure 6 shows that the damage degree D_n gradually increases with the number of cyclical impact under the incremental impulse. This is principally because the damage degree has a cumulative effect, and the impact every time is an effective one. Therefore, the damage degree D_n accumulates with the number of impact. The shape of the fitting curve as shown in Figure 6 is upward concave on the whole, meaning that the coal-rock damage degree tends to accelerate the damage under the incremental impulse. The reason for this is that under external loading, coal-rock has its


(a)

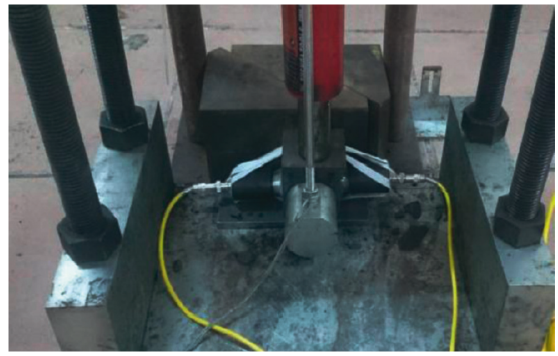
(b)

Figure 5: Test case. (a) Global test; (b) local pendulum impact.

Table 3: Test load condition.

Height, h (m)	Impulse per unit area, I (N·s·m^{-2})
0	0
0.274	596.3
0.548	846.75
0.821	1037.56
1.095	1192.6

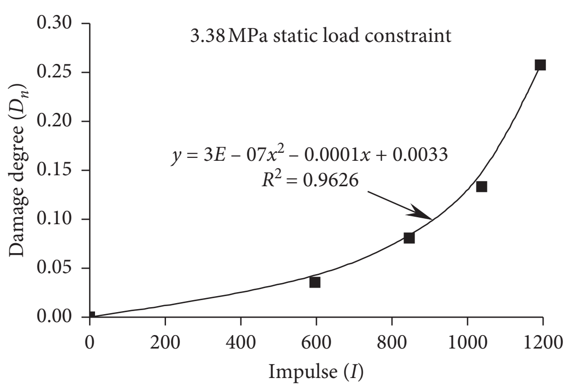

Figure 6: The relationship between damage degree and incremental impulse.

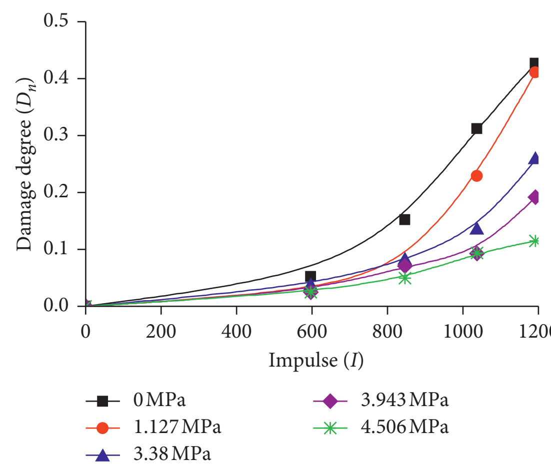

Figure 7: The relationship between damage degree and incremental impulse under different axial compression.

internal microfractures expanded to develop crack clusters, incur penetrating cracks, and finally form macrofailure. The damage degree of coal-rock changes in the failure process of coal-rock from microcosmic to macroscopic view. Additionally, the incremental impulse can make the damage degree of coal sample increase rapidly and accelerate the failure of coal sample.

4.1.2. Relationship between Coal-Rock Damage Degree and One-Dimensional Static Load. The curve of the coupling relationship between the coal-rock damage degree and the incremental impulse under different axial compression is shown in Figure 7. According to the complete stress-strain curve of coal-rock, when the static load is less than the uniaxial compression strength of coal-rock, the strength of coal-rock increases with the increase of one-dimensional static load. The one-dimensional static loads for the test here are 0, 1.127, 3.38, 3.943, and 4.506 MPa, respectively, all less than the uniaxial compression strength of coal-rock. The one-dimensional static loads of 0 and 1.127 MPa were considered as low axial compression constraints, and those of 3.38, 3.943, and 4.506 MPa were considered as high ones. According to Figure 7, the coal-rock shows similar damage degrees under different axial compression when it is subjected to the first impact of a 596 N·s·m^{-2} impulse. With the impulse increasing gradually, the damage degrees of the coal-rock under different axial compression gradually become more differentiated, and the change in the damage degree tends to decrease with increasing axial compression in general. Under low axial compression constraints, the failure trend of coal-rock increases rapidly after the coal-rock is subjected to cyclical incremental impulses. The cumulative damage degrees are more than 0.41, and there is evident macroscopic failure in the coal-rock. Under high axial compression constraints, after the coal-rock damage degree is subject to the same impulse, the failure trend is obviously moderate compared with that under low axial compression constraints. The cumulative damage degree is 0.25 at maximum, and there is no evident macroscopic failure in the coal-rock. Besides, under the constraint that the axial compression is 4.506 MPa, the damage degree of coal-rock is approximately linear with the increase of impulse, and the damage degree of coal-rock is just 0.11. From the comparison of the cumulative damage degrees of the coal-rock under different axial pressure, as shown in Figure 6, the cumulative damage degree of coal-rock decreases gradually with the increase of axial compression when every group of the coal-rock is subject to the same impulse. It indicates that when coal-rock is subject to the same incremental impulse, the size of static axial compression has a significant impact on the change of the damage degree of coal-rock. This is mainly due to the fact that the internal microfractures of coal-rock gradually close up under axial pressure, which leads to less microfractures in coal-rock and difficult propagation when the coal-rock is subject to incremental impulse impact. Furthermore, the greater the axial compression is, the better the closing effect of the internal microfractures. Therefore, with the increase of axial pressure, the increasing gradient of damage degree for coal-rock decreases, the cumulative damage degree also decreases relatively, and the impact resistance of coal and rock increases.

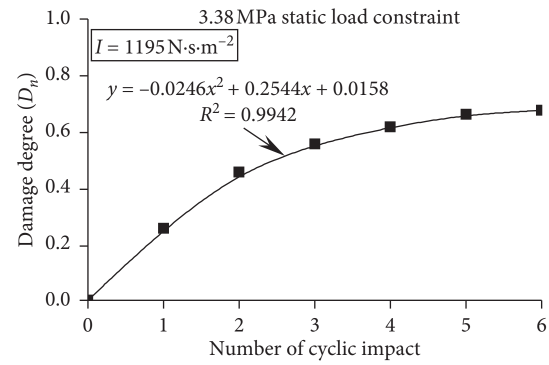

FIGURE 8: The relationship between damage degree and constant impulse.

4.2. Relationship between Cyclical Impact of Constant Impulse and Coal-Rock Damage Degree

4.2.1. Relationship between Damage Degree and the Number of Constant Cyclical Impact. Converting the ultrasonic wave velocity measured through formula (1) can obtain the damage degree *Dn* of the coal sample after suffering cyclical impact of constant impulse under one-dimensional static axial compression. The fitting curve of the damage degree *Dn* of the coal-rock and the number of impact can be obtained according to the experimental data, as shown in Figure 8. This paper gives the illustration based on the fitting curve of the constant impulse ($I = 1195\,\mathrm{N{\cdot}s{\cdot}m^{-2}}$) cyclical impact under 3.38 MPa static load constraint. The correlation coefficient R^2 of the fitting curve in Figure 8 is 0.9942 with a better fitting effect. Figure 8 shows that the damage degree D_n gradually increases with the number of impact under the incremental impulse. This is mainly due to the cumulative effect of the damage degree. Under constant cyclical impact, the internal microfractures of coal-rock will gradually expand until macrofailure takes places, and the growth rate of microcracks slows down gradually. However, the cumulative damage degree of the coal-rock will reach 0.674 after repeated cyclic impact, and the macroscopic damage is obvious. Meanwhile, the fitting curve is convex in general, meaning that the damage degree of coal-rock tends to slow down damage under constant impulse. This may be because the number of new microfractures in coal-rock decreases markedly after repeated impact, which makes it more difficult for microfractures to form new crack clusters and penetrating cracks, thus slowing down the coal-rock damage. However, due to the continuous expansion of microfractures, original crack clusters will continue to expand to be penetrating cracks under cyclical impact, while microfractures form new crack clusters again. This leads to the aggravation of the damage degree of coal-rock and is macroscopically manifested as the changes of the damage degree of coal-rock.

4.2.2. Relationship between Damage Degree and One-Dimensional Static Axial Compression. Figure 9 shows the comparison curves of the relationship between the damage degree of coal-rock and the incremental impulse under different axial compression. In terms of the cumulative damage degree and its increasing trend, when there is no axial compression constraint, the damage degree of coal-rock increases rapidly, and the damage eventually reaches 0.78. When the axial pressure is 3.38 MPa, the cumulative damage degree of coal-rock increases relatively slowly, and the ultimate cumulative damage is 0.67. The macroscopic damage of both is obvious. However, the damage degree under the axial compression constraint of 0 is much more obvious, indicating that the greater the axial compression, the smaller the cumulative damage degree. This is mainly due to the fact that when the axial compression is greater, the internal microfractures of the coal-rock close up gradually, which leads to less microfractures in coal-rock and difficult propagation, when the coal-rock is subject to incremental impulse impact load. Besides, the greater the axial compression, the better the closing effect of the microfractures. Therefore, the increasing gradient of damage degree for coal-rock decreases with the increase of axial pressure, and the impact resistance of coal-rock increases. In terms of the number of impact, the coal sample will be damaged when it is subjected to three times impact without axial compression constraints, and the coal sample will be damaged when it is subjected to six times impact under 3.38 MPa axial compression constraints. It indicates that the number of impacts needed to destroy coal-rock is increased with increasing axial compression. The reason is that the greater the axial compression, the fewer the internal microfractures of the coal-rock, the more difficult the damage process, and the more external loads it need. Therefore, in case of constant impulses, the greater the axial compression, the more the number of impact required for complete damage of coal-rock.

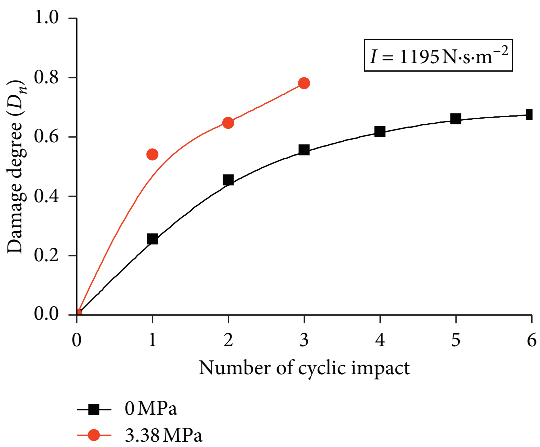

Figure 9: The relationship between damage degree and the number of cyclic impact under different axial compression.

4.3. Comparative Analysis of Coal-Rock Damage Degree by Incremental Impulses and Constant Impulse Cyclical Impact. According to Figures 7 and 9, a comprehensive comparative analysis can be conducted for the evolutionary relationship of the coal-rock damage degrees under incremental impulses and constant impulse cyclical impact. It can be known from the two figures that under incremental impulses and constant impulse impact, the number of the internal microfractures increases, leading to the increase of the damage degree. Because of the cumulative effect, the damage degree will gradually increase with the number of cyclical impact. With the increase in one-dimensional static axial compression, some microfractures in the coal-rock will close up, and others become difficult to expand. As the axial pressure increases, the change will be more remarkable, resulting in decrease in the damage degree. This indicates that increasing axial compression can effectively improve the impact resistance of coal-rock, and the higher the axial compression, the stronger the impact resistance. In case of incremental impulse impact, the propagation process of internal microfractures of coal-rock accelerates the damage. Then, the fitting curve of the damage degree is upward concave in general, showing a trend towards accelerating damage. In case of constant impulse impact, the fitting curve of the damage degree is upward convex in general, showing a trend towards decelerating damage. The reason may be that the internal microfractures of the coal-rock reduce markedly with repeated impact, which makes it more difficult for microfractures to form new crack clusters and penetrating cracks.

4.4. Microfracture Damage Model Analysis. The damage of coal-rock under external loading is essentially attributable to the propagation of their internal microfractures. The damage mechanism of coal and rock under external loads can be found by analyzing the propagation of microcracks. According to Griffith's strength theory, rock-like materials have many microfractures inside, which can be divided into vertical ones and horizontal ones. As shown in Figure 10, microfractures can be simplified as an ellipse, and its semimajor axis and semiminor axis are a and b, respectively.

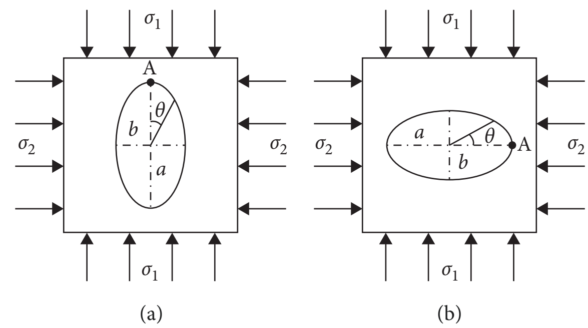

Figure 10: Microfracture damage model.

The axial length ratio of the ellipse can be expressed as $m = a/b$, where m is determined by material properties. It can be assumed that m is the material coefficient, σ_1 is the static load, and σ_2 is the equivalent impact load. The failure of coal-rock is essentially caused by tensile stress from microfractures, which leads to the propagation of microfractures and macroscopic damage. The absolute value of the tensile stress at point A of the microfracture tip is the maximum, and the damage degree of coal-rock increases with the increasing absolute value of the tensile stress.

4.4.1. Vertical Microfracture Damage Model. Based on the knowledge of elastic mechanics [23, 24], the formula for calculating the tangential stress of the vertical microfracture ellipse is as follows:

$$\sigma_t = \sigma_1 \frac{m^2 \sin^2\theta + 2m\sin^2\theta - \cos^2\theta}{\cos^2\theta + m^2\sin^2\theta} + \sigma_2 \frac{\cos^2\theta + 2m\cos^2\theta - m^2\sin^2\theta}{\cos^2\theta + m^2\sin^2\theta}, \tag{6}$$

where $\theta = 0$, the tangential stress of point A:

$$\sigma_t = (1 + 2m)\sigma_2 - \sigma_1. \tag{7}$$

As σ_1 is a static load and σ_2 is an equivalent impact load, and $\sigma_2 > \sigma_1$ can be assumed here. According to formula (7), $\sigma_t > 0$, so point A of vertical microfracture has no tensile stress. Thus, tip cracking will not appear in vertical microfractures.

4.4.2. Horizontal Microfracture Damage Model. Based on the knowledge of elastic mechanics [23, 24], the formula for calculating the tangential stress of the horizontal microfracture ellipse is

$$\sigma_t = (\sigma_1 + \sigma_2) - \frac{[(a-b)(\sigma_1+\sigma_2) + (a+b)(\sigma_1-\sigma_2)]}{a^2\sin^2\theta + m^2\cos^2\theta} \times \left(a\sin^2\theta - b\cos^2\theta\right), \tag{8}$$

where $\theta = 0$, the tangential stress of point A:

$$\sigma_t = (1 + 2m)\sigma_1 - \sigma_2. \tag{9}$$

Suppose $\sigma_2 > \sigma_1$ and based on formula (9), when $\sigma_2 > (1 + 2m)\ \sigma_1$, the tangential stress $\sigma_t < 0$. Point A of horizontal microfracture has tensile stress. Then, tip cracking will appear in vertical microfractures.

4.4.3. Comprehensive Microfracture Damage Model. Coal-rock has many vertical and horizontal microfractures inside. Microfracture tips will start cracking under external loading when certain conditions are met. Based on the microfracture damage model, the criterion for microfracture tip cracking can be obtained as follows:

$$\sigma_2 > (1 + 2m)\sigma_1, \tag{10}$$

where σ_1 and σ_2 are external loads acting on the subject and m is the material coefficient. According to formula (9), when the condition meets the criterion, the absolute value of the tensile stress σ_t at point A of the microfracture tip increases with the increasing impact load σ_2 and decreases with the static load σ_1. This is consistent with the law that the damage degree of coal-rock increases with the increasing impact load and decreases with the increasing static load.

5. Conclusions

The coal and rock masses in many projects are subjected to the dynamic impact under unidirectional constraints. Therefore, in this paper, coal-rock was taken as the research object, and the damage evolution law of coal-rock subject to incremental dynamic impact under unidirectional constraints was studied by applying different one-dimensional static loads and incremental impact loads. The main conclusions are drawn as follows:

(1) Under the incremental impulse impact, the damage degree of coal-rock increases with the increase of the impulse, and the damage fitting curve is generally upward concave in shape, indicating that the coal-rock damage degree shows a trend towards accelerating damage.

(2) In case of constant impulse impact, the damage degree of coal-rock increases with the number of cyclic impact, and the fitting curve is generally upward convex in shape, demonstrating that the coal-rock damage degree shows a trend towards decelerating damage under the constant impulse.

(3) When the coal-rock is subject to incremental impulses or constant impulses, the damage degree increases gradually with the number of cyclic impact, and the cumulative damage degree decreases with the increasing axial compression. This indicates that the high static axial pressure can effectively increase the impact resistance of the coal-rock.

(4) The microfracture damage model of coal-rock is established. The criterion of microfracture initiation is obtained. It is theoretically indicated that the coal-rock damage degree increases with the increasing impact load and decreases with the increasing static axial pressure.

Data Availability

The data used to support the findings of our study are included within the article, and they are available from the corresponding author upon request if necessary.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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