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STUDY ON THE DYNAMIC MECHANICAL PROPERTIES AND CONSTITUTIVE MODEL OF MAGNETITE SPECIMENS UNDER IMPACT LOADING

Blasting operations during open-pit mining can cause cumulative degradation of slope stability, increasing the likelihood of slope failures. This study investigates the dynamic behaviour and crack-propagation characteristics of rock masses in steep open-pit slopes under impact loading. Magnetite specimens from an open-pit mine in Hunan Province were tested using a 50.00 mm Split Hopkinson Pressure Bar (SHPB) system under different impact air pressures. A block discrete element SHPB numerical model was established, and a strain-rate-dependent dynamic damage constitutive model was developed based on the viscoelastic Zhu-Wang-Tang framework. Results indicate that magnetite exhibits a pronounced strain-rate effect. The fractal dimension of fragmented blocks increases with impact air pressure, and fragmentation becomes more severe at higher strain rates, accompanied by a greater proportion of fine and powdery particles. Numerical simulations show that tensile failure dominates the cracking process, and both the total crack number and length increase with impact load, consistent with laboratory fracture patterns. The proposed constitutive model agrees well with experimental dynamic stress-strain curves, with R^2 values of at least 0.90, confirming its accuracy. The findings provide insights for evaluating the stability of steep slopes in magnetite open-pit mines and for improving disaster prevention.

Keywords: Magnetite; damage constitutive; SHPB; numerical simulation

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1. Introduction

With the continuous increase in the mining depth of metal open-pit mines, the proportion of high and steep slopes has risen significantly, making slope stability an increasingly critical issue. Under the combined influence of primary geological structures and external environmental factors, jointed features of slopes become more pronounced, posing greater challenges to the safe and efficient extraction of mineral resources. The presence of dominant joint sets or penetrating structural planes provides the fundamental conditions for landslides in jointed high and steep slopes, while the mechanical properties of infilling materials within joints or structural planes are much lower than those of intact rock, highlighting the difficulty of stabilizing joint-controlled slopes. Moreover, during open-pit mining, large-scale blasting with multiple blast holes, heavy explosive charges, and high vibration intensities causes cumulative degradation of the mechanical properties of jointed rock masses and slope stability. Macroscopically, this is manifested as the cumulative damage effect of blasting vibrations on slope rock masses, further increasing the likelihood of catastrophic failures in jointed high and steep slopes. Therefore, understanding the mechanical response of rock under impact loading has become a fundamental prerequisite for ensuring slope stability [1]. Thus, clarifying the damage characteristics and internal crack propagation behaviour of rocks under dynamic loading is essential for scientifically evaluating slope stability and effectively implementing disaster prevention and mitigation measures.

The Split Hopkinson Pressure Bar (SHPB), recognised by the International Society for Rock Mechanics (ISRM) as a standardised testing method, is widely used to determine and analyse the dynamic mechanical parameters of rock materials [2-5]. Xie et al. [6] carried out experiments on magnetite concrete specimens under different strain rates, showing that magnetite concrete is a rate-sensitive material. Si et al. [7] investigated the fragmentation characteristics and dynamic mechanical response of magnetite under different impact loads and cyclic impacts. The results revealed that higher strain rates lead to higher fractal dimensions and finer fragmentation. SEM microstructural analysis indicated that intergranular fracture dominated under low-load cyclic impacts, while with increasing impact load, the fracture mode gradually transformed into transgranular cracking. Niu et al. [8], aiming to explore energy evolution and failure modes during blasting, performed multi-level impact tests on magnetite specimens using the SHPB system. The results showed that dynamic peak compressive strength and energy dissipation density increased exponentially with strain rate, while fragment size decreased exponentially, indicating a significant strain rate effect. Liu et al. [9] tested the dynamic mechanical properties and energy dissipation characteristics of magnetite under different strain rates using the SHPB apparatus, and further simulated the failure process with ANSYS/LS-DYNA. The simulation revealed that failure was initiated by cross-shaped reflected tensile stresses at the incident end. Sun et al. [10] combined SHPB tests to study the strength characteristics, particle size parameters, and energy evolution of magnetite. Their results demonstrated that the enhancement of the elastic energy storage limit is the key to improving dynamic compressive strength; meanwhile, increasing fracture energy promoted nonlinear crack propagation, leading to higher fractal dimensions, smaller characteristic particle sizes, and elevated failure risk. Mishra et al. [11] investigated the dynamic stress-strain response of various rocks through SHPB tests at different strain rates. By comparing dynamic and static peak compressive strengths, they determined the dynamic increase factors (DIFs) of these rocks and proposed relevant empirical equations.

In addition, the dynamic damage constitutive modelling of rocks and the numerical simulation of rock behaviour using Split Hopkinson Pressure Bar (SHPB) systems have also attracted

extensive attention from researchers. Zhao et al. [12] investigated the dynamic mechanical properties of underground soft rock using the SHPB system. By means of dimensional analysis, they simplified a modified overstress constitutive model. Furthermore, incorporating continuum damage theory and statistical strength theory, they developed a damage-based overstress constitutive formulation applicable to the full stress-strain process. Yan et al. [13] conducted impact tests on multi-defect rocks with different geometries using the SHPB device. The results indicated that dynamic strength was strongly influenced by defect geometry and strain rate, while energy dissipation density exhibited a positive correlation and rate dependence. A dynamic damage constitutive model considering the coupling effects of micro- and macro-defects was proposed, which successfully fitted the dynamic stress-strain curves of defective rocks. Qu et al. [14] examined the dynamic mechanical behaviour of weathered granite at high strain rates through SHPB tests. Based on energy theory and statistical damage theory, they established a dynamic statistical damage constitutive model for weathered granite, which was validated by comparison between theoretical results and experimental curves. Wang et al. [15] carried out dynamic compression tests on granite using an improved SHPB system. A statistical damage constitutive model based on the Weibull distribution was established, and the influencing factors of the model parameters were analysed. The proposed model was capable of accurately describing the effects of treatment temperature and strain rate on the stress-strain response of granite. Hou et al. [16] performed constant strain-rate loading tests on granite specimens under different impact velocities using the SHPB system. A new constitutive model based on the nonlinear viscoelastic ZWT model was developed to describe the dynamic mechanical behaviour of granite, and the corresponding constitutive parameters were determined. Chen et al. [17] explored the influence of immersion time on pillar rock samples and constructed a statistical damage model based on acoustic emission ring counts, providing theoretical support for evaluating water-rich pillars and preventing rock bursts in deep goaf areas. Zhu et al. [18] employed LS-DYNA to numerically simulate the SHPB testing process and investigated the influence of particle breakage on the dynamic mechanical properties of coal-rock cemented bodies. Lv et al. [19] investigated the mechanical behaviour and failure modes of fibre-reinforced high-strength concrete (FRHSC) under impact loading using LS-DYNA. Li et al. [20] conducted SHPB dynamic impact simulations on cemented backfill using LS-DYNA and quantitatively described its damage degree and failure process under dynamic loading. Li et al. [21] carried out numerical simulations of SHPB passive confining pressure tests on coal-rock using LS-DYNA to investigate the influencing factors of the dynamic mechanical behaviour of coal-rock materials. Zhan et al. [22] applied LS-DYNA to examine the dynamic characteristics of grouted mudstone aggregates under varying grout content ratios and moisture conditions. Dong et al. [23] established an impact loading numerical model of jointed rock masses with non-penetrative joints using PFC^{2D} and analysed their deformation characteristics, failure modes, and stress wave propagation. Tao [24], based on PFC^{3D}, conducted dynamic impact loading tests on coal samples with different bedding inclinations to investigate their meso-scale mechanical responses. Zhang et al. [25] adopted PFC^{3D} to perform cyclic impact tests at different impact velocities on pegmatite gabbro and analysed its damage characteristics and failure mechanisms. Wu et al. [26] combined FLAC^{3D} numerical simulations to study stress wave attenuation in broken sandstone with varying block sizes. Shen et al. [27] used UDEC coupled with a Grey Wolf Optimizer-BP neural network technique to simulate stress wave transmission in SHPB tests and to develop a data-driven approach for efficiently modifying Barton-Bandis joint constitutive model parameters in coal-rock masses. Simulating

crack initiation and propagation is essential for revealing the failure mechanisms of brittle rock materials [28]. However, FLAC and LS-DYNA are unable to capture explicit crack locations and cannot adequately reproduce the initiation, extension, and coalescence of fractures at both macro- and meso-scales [28].

In contrast, UDEC and PFC are capable of effectively modelling crack initiation and propagation during rock failure [29].

Nevertheless, PFC involves numerous microscopic contact parameters, some of which have limited influence on macroscopic responses, and its parameter calibration process often results in excessively high tensile strength estimates [30-33]. UDEC, on the other hand, partially overcomes the limitations of the bonded-particle model in PFC [34]; it requires only five contact parameters [35] and enables the tracking and extraction of crack locations [36]. Therefore, UDEC provides higher practical applicability in simulating crack propagation and evolution.

This study was conducted at the Miaochong Iron Mine, as shown in Fig. 1, located on the boundary between Qidong County and Hengyang City, Hengyang City. The Miaochong mining area is situated in a low mountainous region. Within the 36-43 W mining units, the highest elevation is located in the western part (west of Line 42) at 720.40 m, while the lowest elevation lies near the Tudi Temple in the southeastern part at 430.00 m, with a relative height difference of 100.00-300.00 m. The terrain is relatively steep, with slopes generally ranging from 30° to 40°, and vegetation is well developed.

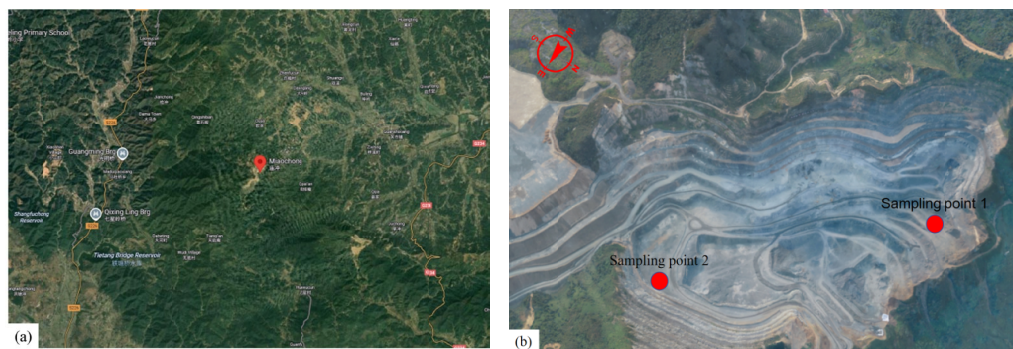


Fig. 1. Location and general overview of the mine in Hunan Province, China
(a: Geographical location of the Miaochong Iron Mine; b: General view of the open-pit mine and sampling points)

In this study, SHPB impact compression tests under different impact air pressures were conducted to analyse the dynamic fragmentation characteristics and stress-strain responses of magnetite specimens. Combined with sieve analysis, the fractal characteristics of the fractured rock fragments were comprehensively investigated. Numerical simulations of the SHPB tests were performed using UDEC 7.0 to examine the initiation, propagation, evolution, and spatial distribution of cracks within the specimens under impact loading. Furthermore, a dynamic damage constitutive model for magnetite considering strain-rate effects was developed. The findings provide a valuable reference for blasting excavation in similar mines and for the safety protection of steep slopes.

2. Geology and mining status

The exposed strata in the Miaochong Iron Mine include the Quaternary, Cambrian, Sinian, and the Banxi Group. The mine is located on the southwestern flank of the Guandimiao short-axis dome, where the regional structural line trends northwest-southeast. The geological structures in the mining area are complex, with intense folding and well-developed faults. The ore-bearing horizon belongs to the Upper Subgroup of the Banxi Group and, according to lithological characteristics, can be divided into three sections: the upper ore-bearing horizon, the main ore-bearing horizon, and the lower ore-bearing horizon. The mine area is dominated by hard, fractured rock layers with low water abundance. The first mined orebody lies above the local erosion base level, and there are no large surface water bodies, indicating relatively simple hydrogeological conditions.

The maximum mining elevation is 752.00 m, while the bottom elevation of the open pit is 452.00 m, with a maximum vertical height of 300.00 m. The upper portion of the open pit measures 850.00 m $\times$ 750.00 m, while the lower portion is 850.00 m $\times$ 30.00 m. The final slope angle ranges from 28°-31° in the overburden and strongly weathered layers, and 48°-49° in the ore-bearing rock. The bench slope angle is 40° in the overburden and strongly weathered layers, and up to 65° in the ore rock. The eastern slope has already reached a height of more than 230.00 m, making it a typical jointed, high and steep slope. The structural planes of the rock mass intersect obliquely with the bench slope surface as shown in Fig. 2, significantly increasing the risk of slope failure. The orebody mainly consists of hematite and magnetite, with well-developed fractures. Quartz veins, calcite veins, and epidote veins are interspersed within the rock mass, further exacerbating discontinuity and mechanical heterogeneity.



Fig. 2. Geotechnical conditions of the eastern and western slopes of the mine
 (a: West slope; b: East slope; c: Development of joints and fractures in the west slope;
 d: Development of joints and fractures in the east slope)

3. Methods

3.1. Specimen preparation

According to the Engineering Rock Mass Testing Method Standard (GBT 50266-2013) [37] and the relevant ISRM standards [38], the dimensions of the magnetite specimens for dynamic tests were 50.00 mm × 50.00 mm (diameter × height), while those for static tests were 50.00 mm × 100.00 mm and 50.00 mm × 25.00 mm (diameter × height). The non-parallelism between the specimen ends and the axial direction was controlled within 0.02 mm. The end faces were kept perpendicular to the axis with a maximum deviation of less than 0.25°. Representative machined magnetite specimens are shown in Fig. 3. To determine the basic mechanical properties of the magnetite, uniaxial compression and Brazilian splitting tests were conducted using a TAW-2000 testing system. The obtained fundamental mechanical parameters of the magnetite specimens are listed in TABLE 1.

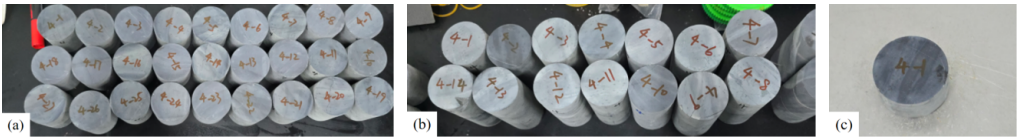


Fig. 3. Photograph of magnetite specimens
(a: $\Phi 50.00$ mm $\times$ $H50.00$ mm specimen; b: $\Phi 50.00$ mm $\times$ $H100.00$ mm specimen;
c: $\Phi 50.00$ mm $\times$ $H25.00$ mm specimen)

TABLE 1

Basic physical and mechanical parameters

Uniaxial compressive strength σ_c (MPa)	Static elastic modulus E_c (GPa)	Poisson's ratio μ	Density ρ ($\text{kg}\cdot\text{m}^{-3}$)	Tensile strength σ_t (MPa)
123.90	14.10	0.24	3287.00	13.31

3.2. Experimental apparatus and principle

A Split Hopkinson Pressure Bar (SHPB) system with a diameter of 50.00 mm was employed, which consists of a dynamic strain gauge, incident bar, transmission bar, absorption bar, buffer device, projectile, power device, and data processing system. The basic parameters of the SHPB test apparatus are listed in TABLE 2, and the schematic diagram of the device structure is shown in Fig. 4.

During the test, the magnetite specimen was placed between the incident bar and the transmission bar, ensuring coaxial alignment of the specimen and the bars. To reduce the influence of friction, a thin layer of Vaseline was applied to the contact surfaces between the specimen and the bars. Strain gauges were symmetrically attached to both sides of the bars, 1000.00 mm away from the bar-specimen interfaces, to record the incident, reflected, and transmitted signals. In each impact test, the projectile was launched from the same position at the bottom of the firing chamber. Impact tests were conducted under air pressures of 0.30 MPa, 0.40 MPa, 0.50 MPa, and 0.60 MPa, with five specimens tested for each pressure level, and anomalous data were excluded.

TABLE 2

Basic parameters of SHPB test device

Bar material	Elastic modulus of the bars (GPa)	Longitudinal wave velocity of the bars ($\text{m}\cdot\text{s}^{-1}$)	Length of the incident bar and transmission bar (mm)	Diameter of the incident bar and transmission bar (mm)	Length of the projectile (mm)	Diameter of the projectile (mm)
Ni18	190.00	4900.00	2000.00	50.00	400.00	50.00

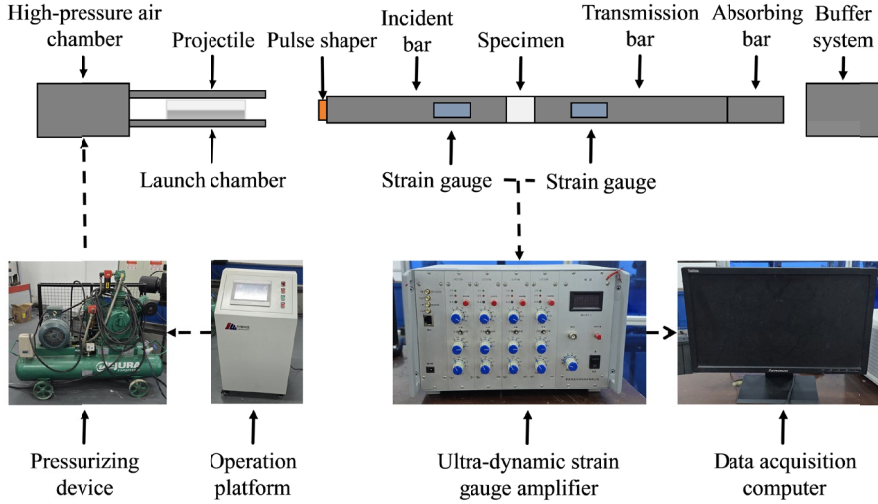


Fig. 4. Schematic diagram of the SHPB test system

Based on the waveforms of the incident wave $\sigma_I(t)$, reflected wave $\sigma_R(t)$, and transmitted wave $\sigma_T(t)$ recorded by the data acquisition system, the incident, reflected, and transmitted stresses were obtained. Using the three-wave method, the relationships between the average stress σ , strain ε , and strain rate $\dot{\varepsilon}$ of the specimen and time were calculated as follows:

$$\begin{aligned}
 \sigma(t) &= \frac{A_e}{2A_s} [\sigma_I(t) - \sigma_R(t) + \sigma_T(t)] \\
 \varepsilon(t) &= \frac{1}{\rho_e C_e L_s} \int_0^t [\sigma_I(t) + \sigma_R(t) - \sigma_T(t)] dt \\
 \dot{\varepsilon}(t) &= \frac{1}{\rho_e C_e L_s} [\sigma_I(t) + \sigma_R(t) - \sigma_T(t)]
 \end{aligned} \tag{1}$$

Where $\sigma(t)$ is the average stress at a given moment t , MPa; A_e is the cross-sectional area of the bars, m^2 ; A_s is the cross-sectional area of the magnetite specimen, m^2 ; $\sigma_I(t)$ is the incident stress at time t , MPa; $\sigma_R(t)$ is the reflected stress at time t , MPa; $\sigma_T(t)$ is the transmitted stress at time t , MPa; $\varepsilon(t)$ is the strain at a given moment t ; ρ_e is the density of the bars, $\text{kg}\cdot\text{m}^{-3}$; C_e is the longitudinal wave velocity of the bars, $\text{m}\cdot\text{s}^{-1}$; L_s is the length of the magnetite specimen, m ; $\dot{\varepsilon}(t)$ is the strain rate at a given moment t , s^{-1} .

3.3. Stress equilibrium verification

A typical impact waveform from the dynamic loading test on magnetite specimens is shown in Fig. 5. The superposition of σ_I and σ_R coincides well with σ_T , indicating that the specimen remained under stress equilibrium during impact loading.

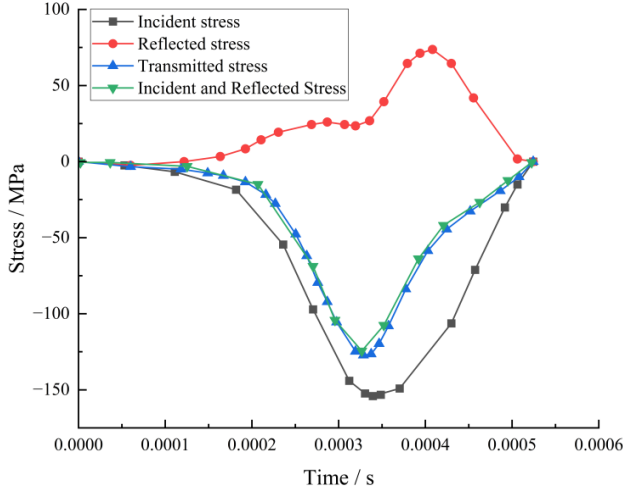


Fig. 5. Dynamic stress equilibrium curve

4. Results

When the magnetite specimen failed, the stress peak was taken as the dynamic compressive strength, and the strain rate corresponding to the stress peak was considered the average strain rate in the test [39]. Although five specimens were tested under each impact air pressure, some tests with anomalous signals or invalid results were excluded, and three valid datasets were finally retained for each loading condition for statistical analysis. To further evaluate the repeatability and dispersion of the experimental results, the mean value and standard deviation (SD) were calculated for each loading condition. As shown in TABLE 3, the SD values of the average strain rate and dynamic peak stress are relatively limited compared with their corresponding mean values, indicating acceptable repeatability among specimens tested under the same impact air pressure. The dynamic elastic modulus and dynamic peak strain show slightly greater dispersion, which may be attributed to the inherent heterogeneity of magnetite specimens and the stochastic initiation and propagation of microcracks during high-rate impact loading. Nevertheless, the main dynamic parameters exhibit consistent variation trends with increasing impact air pressure and strain rate, suggesting that the experimental data are reliable and can reasonably reflect the strain-rate-dependent dynamic mechanical response of magnetite specimens. The dynamic mechanical parameters of magnetite specimens under different impact air pressures are presented in TABLE 3.

TABLE 3

Statistical table of test data

Impact air pressure (MPa)	Average strain rate $\dot{\epsilon}$ (s ⁻¹)	Evaluation parameters		Dynamic peak stress σ_d (MPa)	Evaluation parameters		Dynamic elastic modulus E_d (GPa)	Evaluation parameters		Dynamic peak strain ϵ	Evaluation parameters		Fractal dimension F
		Average (s ⁻¹)	SD		Average (MPa)	SD		Average (GPa)	SD		Average	SD	
0.30	26.74			79.19			18.82			0.0052			Specimen not broken Specimen not broken Specimen not broken
	26.08	27.67	2.21	56.51	65.21	12.23	20.38	17.82	3.17	0.0047	0.0054	0.0009	
	30.20			59.94			14.27			0.0064			
0.40	50.71			103.08			21.55			0.0072			1.65 1.66 1.58
	50.34	52.02	2.60	93.72	94.37	8.40	17.36	18.50	2.67	0.0062	0.0077	0.0019	
	55.02			86.31			16.60			0.0098			
0.50	94.01			123.54			30.10			0.0058			1.80 1.86 1.88
	104.74	99.70	5.39	124.11	122.09	3.01	19.70	22.13	7.07	0.0102	0.0098	0.0038	
	100.34			118.63			16.60			0.0133			
0.60	151.38			154.41			27.40			0.0072			1.92 1.99 2.03
	175.00	161.41	12.21	137.32	156.21	19.85	20.29	28.71	9.15	0.0136	0.0128	0.0052	
	157.84			176.89			38.45			0.0175			

4.1. Dynamic stress-strain curves

Fig. 6 presents the typical stress-strain curves of magnetite specimens under different impact air pressures. It can be seen that, under various impact loading conditions, the stress-strain curves of the magnetite specimens exhibit a similar trend, which can be divided into four stages: compaction, elastic deformation, yielding, and failure. The first stage is the compaction stage, during which the internal pores of the magnetite specimen are compressed under impact loading, leading to the instantaneous closure of microcracks and voids. In this stage, the curve shows a slight downward concavity, and the duration is relatively short. The second stage is the elastic deformation stage, where the dynamic stress-strain curve is approximately linear. The third stage is the yielding stage, in which the slope of the curve decreases significantly and the specimen begins to undergo irreversible damage. At this point, cracks initiate and propagate, eventually connecting with each other. The fourth stage is the failure stage, during which the load-bearing capacity of the magnetite specimen decreases, deformation continues to increase, microcracks rapidly expand, coalesce, and ultimately lead to instability and failure, accompanied by the release of accumulated energy.

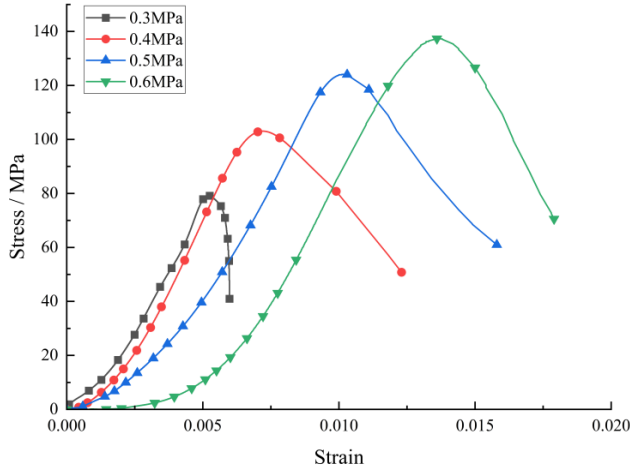


Fig. 6. Stress-strain curves of magnetite specimens under different impact air pressures

4.2. Dynamic peak stress and dynamic increase factor

Fig. 7 illustrates the relationship between the dynamic peak stress of magnetite specimens and strain rate. It can be observed that the dynamic peak stress increases with strain rate, following a power-exponential growth relationship, indicating that magnetite specimens exhibit a pronounced strain rate effect under impact loading. By fitting the scatter data, the following relationship can be obtained:

$$\sigma_d = 13.82 \dot{\varepsilon}^{0.48} \quad (2)$$

where σ_d is the dynamic peak stress of the magnetite specimen, MPa; and $\dot{\varepsilon}$ is the strain rate, s^{-1} . The fitting correlation coefficient (R^2) is 0.99, and the MAE is 2.81 MPa. The MAE represents the mean absolute deviation between the fitted values and the experimental data. A lower MAE

indicates a smaller fitting error. In this study, the MAE of 2.81 MPa is relatively small compared with the measured dynamic peak stress values, suggesting that the fitted relationship can reasonably describe the variation of dynamic peak stress with strain rate.

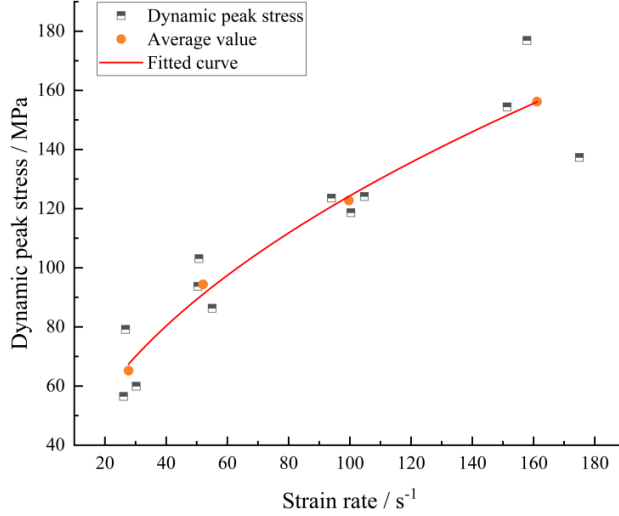


Fig. 7. Relationship between strain rate and dynamic peak stress of magnetite specimens

The dynamic increase factor (*DIF*) reflects the strengthening effect of rocks under different loading rates. It is defined as the ratio of the dynamic compressive strength to the static compressive strength, and is used to quantify the extent of strength enhancement of the material under impact loading [40]. TABLE 4 presents the dynamic increase factors of magnetite specimens under different impact air pressures.

$$DIF = \sigma_d / \sigma_c \quad (3)$$

where *DIF* is the dynamic increase factor; σ_d is the dynamic compressive strength of the specimen, MPa, as listed in TABLE 3; and σ_c is the static uniaxial compressive strength, MPa, as given in TABLE 1.

Fig. 8 shows the variation of the dynamic increase factor of magnetite specimens with strain rate. It can be seen that the dynamic increase factor exhibits a continuous upward trend as the strain rate increases. Further fitting yields:

$$DIF = 0.11\dot{\epsilon}^{0.47} \quad (4)$$

where *DIF* is the dynamic increase factor; $\dot{\epsilon}$ is the strain rate, s⁻¹. The correlation coefficient R^2 is 0.99, and the MAE is 0.039. The MAE represents the mean absolute deviation between the fitted *DIF* values and the experimental *DIF* values. Since *DIF* is a dimensionless parameter, the MAE is also dimensionless. The relatively low MAE value indicates that the fitting error is small, suggesting that the fitted relationship can reasonably characterise the increase in *DIF* with strain rate.

TABLE 4

Dynamic increase factor of magnetite specimens under different impact air pressures

Impact air pressure (MPa)	Dynamic increase factor	Average value
0.30	0.64	0.53
	0.46	
	0.48	
0.40	0.83	0.76
	0.76	
	0.70	
0.50	1.00	0.99
	1.00	
	0.96	
0.60	1.25	1.26
	1.11	
	1.43	

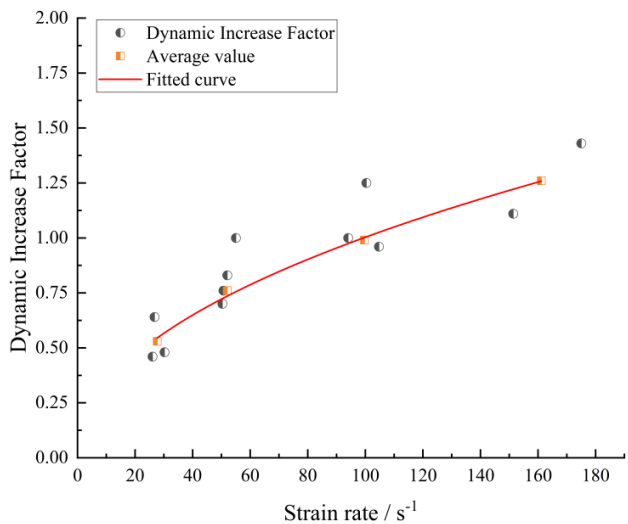


Fig. 8. Relationship between strain rate and dynamic strength enhancement factor of magnetite

The mechanical response of magnetite specimens under dynamic loading is closely related to the strain rate, essentially reflecting the sensitivity of their microstructure to strain rate. At lower strain rates, only a portion of the internal microcracks in the magnetite specimens are activated and propagate. In this case, failure occurs through limited energy accumulation and release, resulting in relatively low dynamic peak stress. As the strain rate increases, the loading time decreases, and the internal fractures cannot undergo instantaneous and sufficient propagation. The crack growth paths are constrained, making it difficult for the specimen to release energy through plastic deformation or gradual crack propagation. Consequently, the instantaneous

load-bearing capacity is enhanced, enabling the specimen to withstand external impact loading. Therefore, the dynamic peak stress of the specimens gradually increases with increasing strain rate. This conclusion is consistent with the findings reported in reference [9]. In contrast, under static loading, the stress is applied over a longer duration, allowing microcrack development, energy accumulation, and release to occur more gradually. In this case, the macroscopic strength of the specimen is primarily governed by inherent attributes such as mineral composition and structural characteristics, and thus maintains a relatively stable strength level.

4.3. Dynamic elastic modulus

The dynamic elastic modulus is an index used to evaluate the ease with which rocks undergo elastic deformation under dynamic loading [41]. Its calculation formula is as follows:

$$E_d = \frac{\sigma_a - \sigma_b}{\varepsilon_a - \varepsilon_b} \quad (5)$$

where E_d is the dynamic elastic modulus of the specimen, GPa; σ_a and σ_b are the stresses corresponding to 40% and 60% of the peak stress, respectively, MPa; and ε_a and ε_b are the strains corresponding to σ_a and σ_b , respectively.

Fig. 9 illustrates the relationship between the dynamic elastic modulus of the specimens and the strain rate under different impact air pressures. It can be observed that the dynamic elastic modulus increases with increasing strain rate. Further fitting yields:

$$E_d = 14.67 + 0.084\dot{\varepsilon} \quad (6)$$

where E_d is the dynamic elastic modulus of the specimen, GPa; $\dot{\varepsilon}$ is the strain rate of the specimen, s^{-1} . The correlation coefficient R^2 is 0.97, and the MAE is 0.69 GPa. The MAE represents

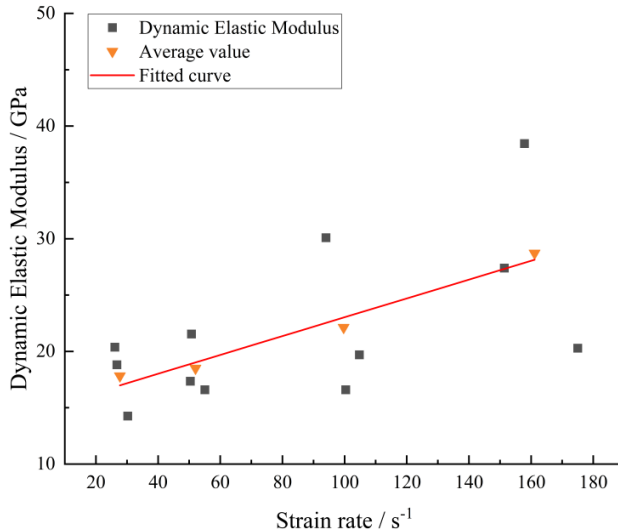


Fig. 9. Relationship between dynamic elastic modulus of magnetite specimens and strain rate

the mean absolute deviation between the fitted dynamic elastic modulus values and the experimental values. Compared with the measured dynamic elastic modulus, the MAE of 0.69 GPa is relatively low, indicating that the fitting error is acceptable. Therefore, the fitted relationship can reasonably describe the increasing trend of dynamic elastic modulus with strain rate.

4.4. Dynamic peak strain

Dynamic peak strain is an important indicator for evaluating the deformation behaviour of rocks under ultimate dynamic loading. Fig. 10 shows the relationship between dynamic peak strain and strain rate. It can be observed that the dynamic peak strain of magnetite specimens increases with increasing strain rate. At lower strain rates, specimens fail after relatively small strains, exhibiting pronounced brittle characteristics; at higher strain rates, larger strains are required for failure, indicating stronger ductile behaviour. The magnetite specimens thus gradually transition from distinct brittleness to ductility, reflecting a trend of enhanced ductility and reduced brittleness. The relationship between the two satisfies the following functional expression:

$$\varepsilon_f = 0.00113 \dot{\varepsilon}^{0.47498} \quad (7)$$

where ε_f is the peak strain of the specimen; $\dot{\varepsilon}$ is the strain rate of the specimen, s^{-1} . The correlation coefficient R^2 is 0.99, and the MAE is 0.0002. The MAE represents the mean absolute deviation between the fitted peak strain values and the experimental values. Since peak strain is a dimensionless parameter, the MAE is also dimensionless. The relatively low MAE value indicates that the fitting error is small, suggesting that the fitted relationship can reasonably describe the increase in dynamic peak strain with strain rate.

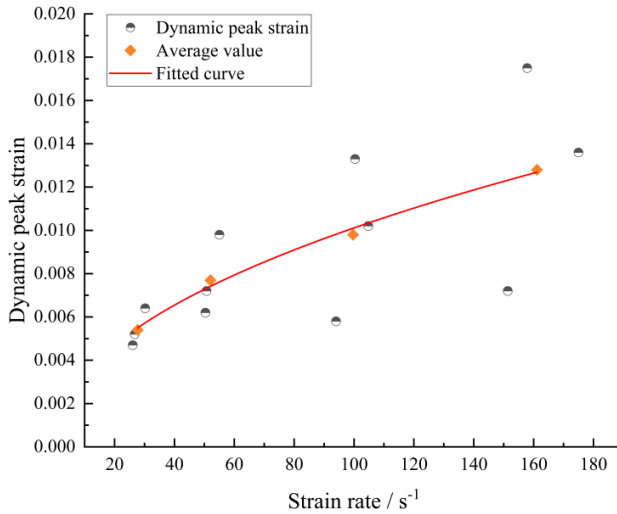


Fig. 10. Relationship between dynamic peak strain and strain rate of magnetite specimens

4.5. Fractal characteristics of fragmented rock blocks

Standard sieves of 0.315 mm, 0.63 mm, 1.25 mm, 2.50 mm, 5.00 mm, 10.00 mm, 16.00 mm, 20.00 mm, and 31.50 mm were used to screen the specimens after impact tests. A precision electronic balance was employed to weigh the fragments in each size fraction, which were then converted into cumulative mass passing values. The fragment size distributions of magnetite specimens under different impact air pressures are shown in TABLE 5. The failure morphology of the broken specimens was mainly characterised by long columnar, blocky, conical, fine-particle, and powder-like fragments. The following fragmentation characteristics were observed: under low impact air pressure (0.30 MPa), no fragmentation occurred; with increasing impact air pressure, the proportion of large-size fragments decreased significantly, while that of small-size fragments increased markedly, indicating a gradual intensification of fragmentation. This demonstrates that with the increase in impact air pressure, the development of internal cracks in magnetite specimens became more pronounced, with both the number and length of cracks increasing substantially, ultimately resulting in smaller fragment sizes after failure.

The fracture characteristics and fragment size distribution of magnetite specimens can intuitively reflect the extent of rock failure; however, such qualitative descriptions are insufficient for precise quantitative analysis. Therefore, based on fractal theory, the fragmentation effects of magnetite specimens under different impact air pressures were quantitatively analysed [40]. The fractal dimension can be determined from the mass-frequency relationship obtained through sieving tests [42]. The fragment size distribution equation of magnetite specimens under impact loading is expressed as:

$$M(x)/M_T = (X/X_m)^{3-F} \quad (8)$$

where M_T is the total mass of fragments, g; $M(x)$ is the cumulative mass passing through a sieve of size x , g; X is the particle size of the fragments, mm; X_m is the maximum particle size of the fragments, mm; and F is the fractal dimension of the fragments.

Taking the logarithm of both sides of the above equation yields:

$$\ln[M(x)/M_T] = (3 - F) \ln(X/X_m) \quad (9)$$

In the double-logarithmic coordinate system of $\ln[M(x)/M_T]$ versus $\ln(X/X_m)$, the data are fitted, and the slope $K = 3 - F$ is obtained, from which the fractal dimension is calculated as:

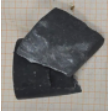
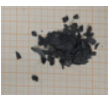
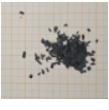
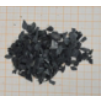
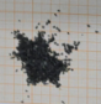
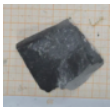
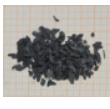
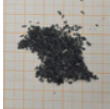
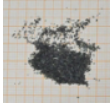
$$F = 3 - K \quad (10)$$

The logarithmic curves of fragment size distribution of magnetite specimens under different impact air pressures are shown in Fig. 11. It can be observed that, with the increase of strain rate, the slopes of the fitted straight lines of the specimens show an increasing trend. Based on Eq. (10), the fractal dimensions of fragmentation were calculated, as listed in TABLE 3. From Fig. 12, it can be concluded that:

$$F = 0.83\dot{\epsilon}^{0.17} \quad (11)$$

where F is the fractal dimension; $\dot{\epsilon}$ is the strain rate of the specimen, s^{-1} . It can be seen that the fractal dimension of the magnetite specimens increases with increasing strain rate. The correlation

TABLE 5
Fragment morphology of magnetite specimens after impact loading under different impact air pressures

Impact air pressure (MPa)	≥31.50 mm	20.00 mm-31.50 mm	16.00 mm-20.00 mm	10.00 mm-16.00 mm	5.00 mm-10.00 mm	2.50 mm-5.00 mm	1.25 mm-2.50 mm	0.63 mm-1.25 mm	0.315 mm-0.63 mm
0.40									
0.50									
0.60									

coefficient R^2 is 0.98, and the MAE is 0.017. The MAE represents the mean absolute deviation between the fitted fractal dimension values and the experimental values. Since fractal dimension is a dimensionless parameter, the MAE is also dimensionless. The relatively low MAE value indicates that the fitting error is small, suggesting that the fitted relationship can reasonably describe the increasing trend of fractal dimension with strain rate.

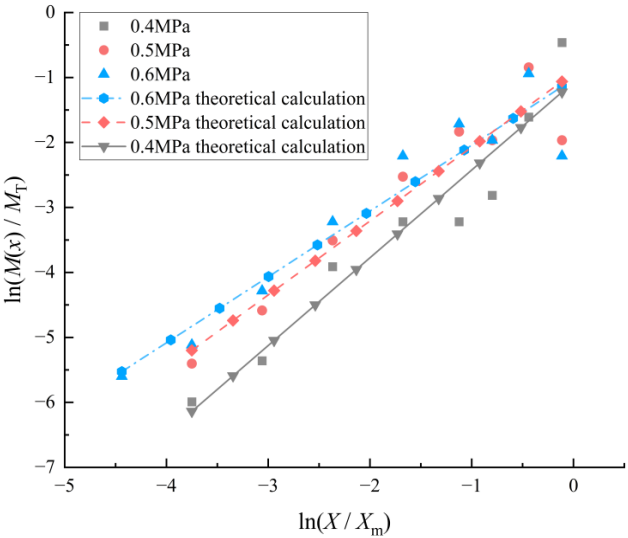


Fig. 11. Comparison of logarithmic curves of fragmented size distribution under different impact air pressures

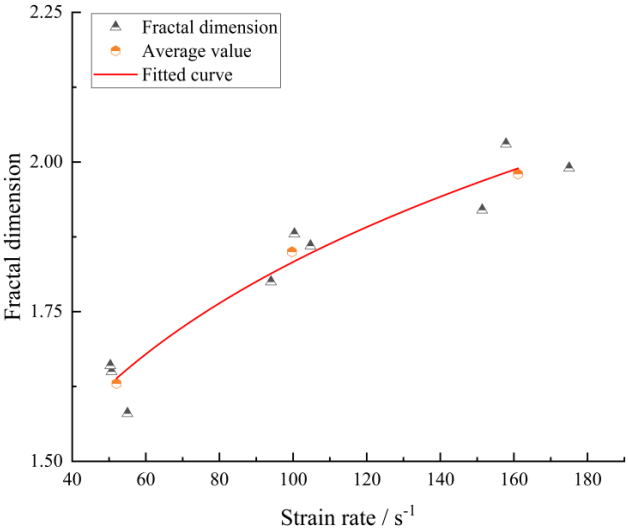


Fig. 12. The curve of fractal dimension changing with strain rate

4.6. SHPB block discrete element numerical simulation

A two-dimensional SHPB test model was established using UDEC 7.0. The incident bar and transmission bar were modelled with a diameter of 50.00 mm and a length of 2000.00 mm, while the specimen had a diameter of 50.00 mm and a length of 50.00 mm. In the simulation, the rock specimen was discretised using Voronoi blocks. To ensure computational performance and accurately capture fracturing and fragmentation characteristics, the block size was set to 1.00 mm. The mesh size of the incident and transmission bars was set to 10.00 mm, and the mesh of the specimen was refined to 0.90 mm. The constructed model and mesh division diagram are shown in Fig. 13.

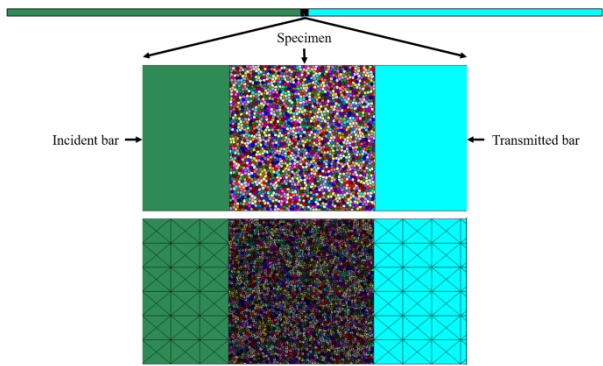


Fig. 13. Discrete element model and mesh division diagram of the SHPB test

Based on laboratory tests and geological data from the mine, the mesoscopic parameters were iteratively adjusted using a trial-and-error approach to ensure that the numerical results closely matched the macroscopic experimental outcomes. The final mechanical parameters determined are as follows [24]: the constitutive model of the rock blocks was defined as the Mohr-Coulomb model, with detailed parameters listed in TABLE 6. The bars in the SHPB system were required to possess high yield strength and elastic modulus to allow stress waves to be generated and propagated without attenuation, while exhibiting minimal deformation and avoiding large-strain failure [24]. Therefore, the incident and transmission bars were assigned an elastic constitutive model, with specific parameters provided in TABLE 7. The contact model within the specimen was defined as the Coulomb-slip model, and its detailed parameters are presented in TABLE 8 to ensure computational accuracy. The interfaces between the specimen and the two bars were also modelled using the Coulomb-slip contact model, with the corresponding parameters summarised in TABLE 9.

TABLE 6

Constitutive parameters of the rock blocks

Density ($\text{kg}\cdot\text{m}^{-3}$)	Internal friction angle ($^{\circ}$)	Cohesion (MPa)	Tensile strength (MPa)	Poisson's ratio	Young's modulus (GPa)
3287.00	40.00	30.00	13.31	0.24	14.10

TABLE 7

Constitutive model of bars

Density ($\text{kg}\cdot\text{m}^{-3}$)	Bulk modulus (GPa)	Shear modulus (GPa)
7800.00	160.00	75.00

TABLE 8

Internal contact parameters of the specimen

Shear stiffness (GPa)	Normal stiffness (GPa)	Internal friction angle ($^{\circ}$)	Cohesion (MPa)	Tensile strength (MPa)
25000.00	50000.00	40.00	30.00	15.00

TABLE 9

End-face contact parameters of the specimen

Shear stiffness (GPa)	Normal stiffness (GPa)	Internal friction angle ($^{\circ}$)	Cohesion (MPa)	Tensile strength (MPa)
25000.00	50000.00	3.00	0.00	0.00

A half-sine stress wave was applied at the end of the incident bar [43], with a stress duration of 250.00 μs and peak stress values of 140.00 MPa, 180.00 MPa, and 220.00 MPa determined according to the laboratory tests. Viscous absorbing boundaries were imposed in both the x - and y -directions along the left and right boundaries of the model.

Fig. 14 shows the stress waveforms obtained from the SHPB numerical simulation. As illustrated, the incident wave exhibits a classical half-sine shape with a smooth and gradual rise. The presence of a long and gentle rising front, together with a relatively flat segment in the reflected wave, indicates that stress homogenization and constant strain-rate loading were successfully achieved during the simulation [44]. Fig. 15 presents the stress equilibrium curves from

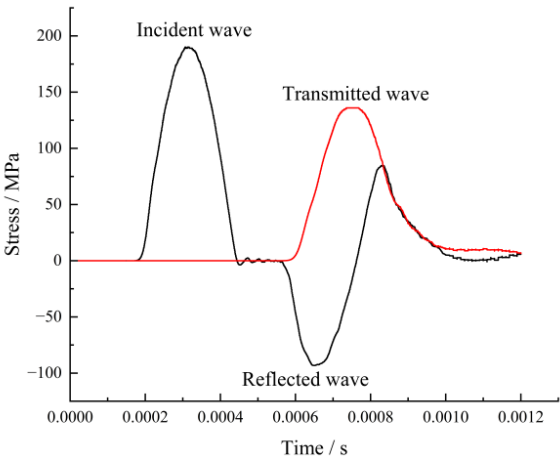


Fig. 14. Stress waveform diagram of the SHPB numerical simulation

the SHPB numerical simulation. It can be observed that the superposition of the incident stress and reflected stress nearly coincides with the transmitted stress, demonstrating that the specimen remains under stress equilibrium during impact loading.

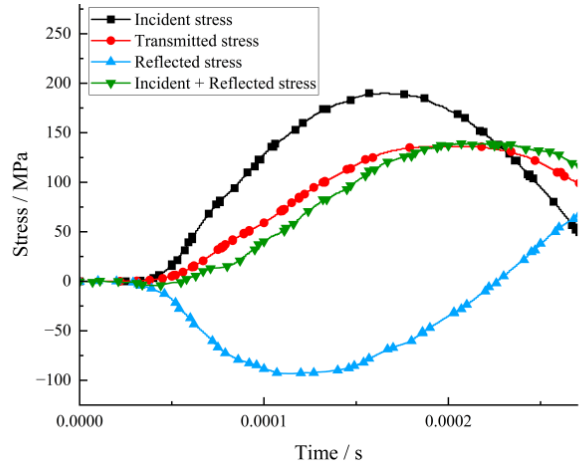


Fig. 15. Stress equilibrium curve of the SHPB numerical simulation

Four stress monitoring points were arranged along the axial direction of the specimen, as shown in Fig. 16. By analysing the stress-time histories at these monitoring points, the uniformity of the stress distribution within the specimen can be evaluated. The stress-time curves of the four monitoring elements are presented in Fig. 17. Before the specimen reaches its peak stress, the stress-time curves of the four monitoring points are nearly identical. Even after the specimen reaches peak stress, the curves still exhibit good consistency [22]. Therefore, the stress experienced by each element of the specimen is uniformly distributed, with no stress concentration observed. This confirms that the specimen satisfies the stress-uniformity assumption throughout the entire simulation process.

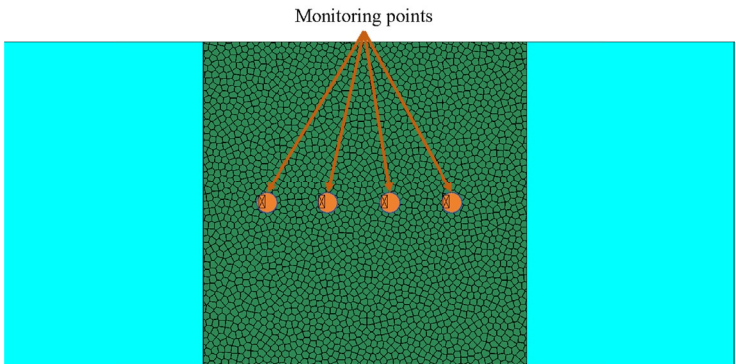


Fig. 16. Schematic diagram of monitoring point locations

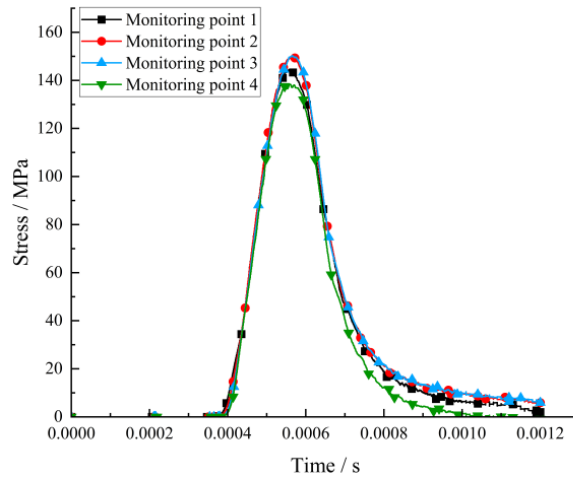


Fig. 17. Stress-time curves at different monitoring points

As shown in Fig. 18, the stress-strain curves obtained from the numerical simulation exhibit good agreement with the laboratory test results. The mean absolute errors of the stress-strain curves under impact air pressures of 0.40 MPa, 0.50 MPa, and 0.60 MPa are 7.10, 8.10, and 10.65, respectively, all within 10% [18]. This indicates that the block-based discrete element numerical modelling approach can reliably reproduce the SHPB laboratory test results.

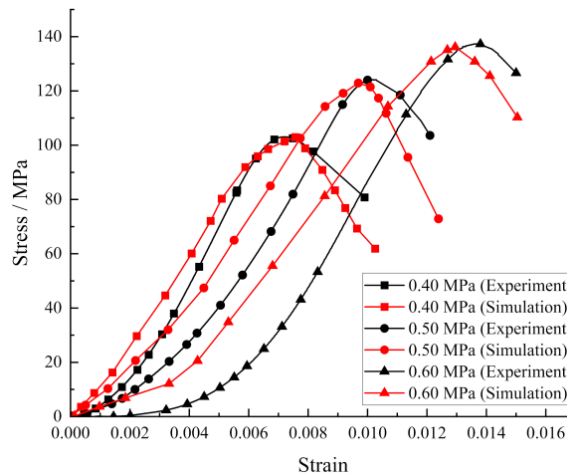


Fig. 18. Comparison of numerical simulation and experimental stress-strain curves

A fracture-statistics program was developed using the built-in FISH language in UDEC to analyse the total number and total length of tensile- and shear-failure contacts during the simulation [28], thereby revealing the influence of impact loading on crack development in the

specimen. Fig. 19 presents a comparison of crack evolution and fragmentation patterns in the simulated specimens. It can be observed that under different loading stress levels, tensile failure dominates the overall failure mode. The number of shear cracks initially increases, then gradually reaches a peak, and subsequently decreases. In contrast, the number of tensile cracks increases rapidly at first, then the growth rate slows down, and eventually stabilises. As the impact stress increases, both the total number and total length of internal cracks show a clear upward trend, indicating more extensive crack development within the specimen. The displacement in the Y-direction at failure also increases, and the proportion of small-sized fragments becomes larger, reflecting a higher degree of fragmentation. Overall, the failure characteristics observed in the numerical simulation show strong consistency with those observed in the laboratory SHPB tests.

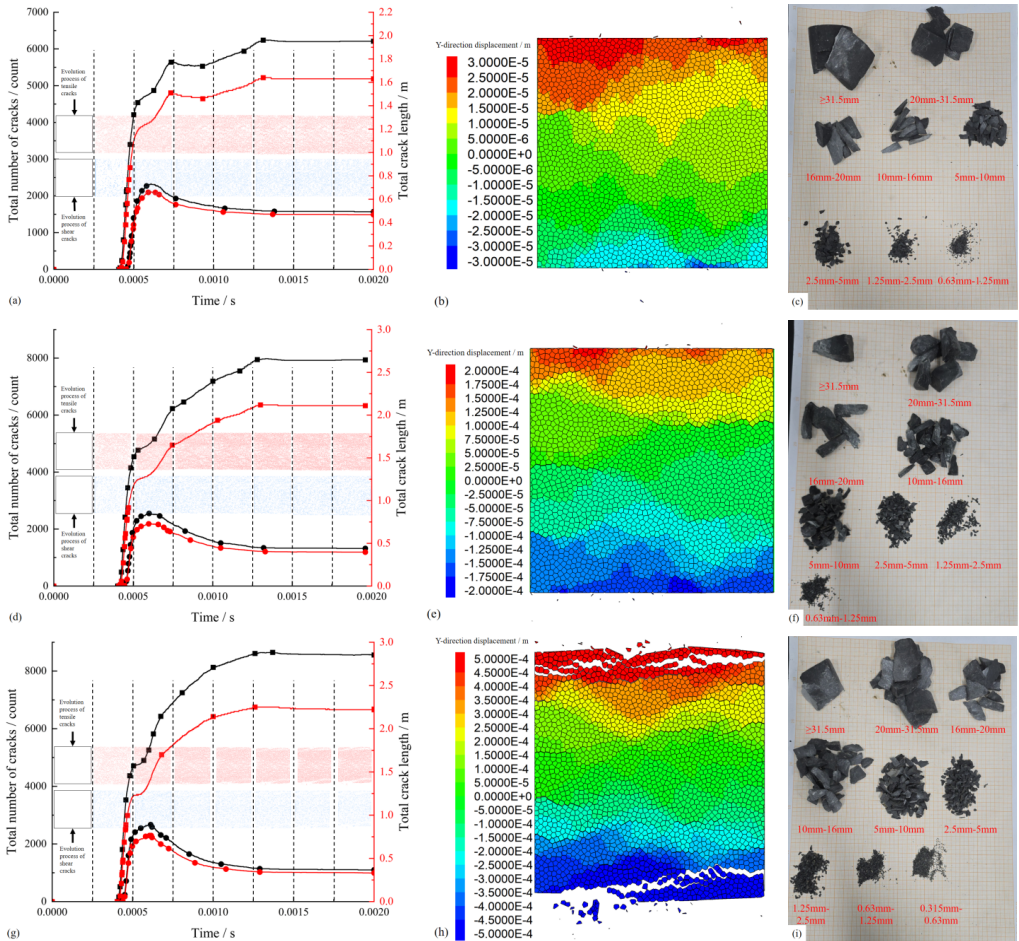


Fig. 19. Comparison of crack development and fragmentation of the specimen
(a): Crack number and crack length at 0.40 MPa; b: Y-direction displacement at 0.40 MPa; c: Fragmentation pattern at 0.40 MPa; d: Crack number and crack length at 0.50 MPa; e: Y-direction displacement at 0.50 MPa; f: Fragmentation pattern at 0.50 MPa; g: Crack number and crack length at 0.60 MPa; h: Y-direction displacement at 0.60 MPa; i: Fragmentation pattern at 0.60 MPa)

It should be noted that the UDEC model established in this study is a two-dimensional simplification of the SHPB impact loading process. The main purpose of using the 2D UDEC model is to track crack initiation, propagation, coalescence, and spatial distribution within the specimen section, and to provide a mechanistic explanation for the fracture patterns observed in the laboratory SHPB tests. Therefore, the numerical results are mainly used to reveal the relative evolution of cracks and the dominant failure mechanism under different impact air pressures. However, the actual dynamic fracture process of magnetite specimens under SHPB impact loading is inherently three-dimensional. Out-of-plane crack propagation, three-dimensional fracture surfaces, radial fragmentation, block rotation, and the complex stress state caused by end friction and lateral inertia cannot be fully captured by the present 2D model. Therefore, the UDEC simulation results should not be interpreted as a complete three-dimensional reproduction of specimen failure. Instead, they should be regarded as a qualitative and semi-quantitative explanation of the crack evolution mechanism. Future studies may combine CT scanning and 3DEC simulations to further investigate the three-dimensional fracture morphology and dynamic fragmentation behaviour of magnetite under impact loading.

5. Results and discussion

5.1. Model development

The Zhu-Wang-Tang (ZWT) constitutive equation can effectively describe the strain-rate dependence of materials. The basic components of the model are shown in Fig. 20 [45-47], and its mathematical expression is given in Eq. (12). In addition, the model can simulate the mechanical response of rock materials by introducing a damage factor that accounts for the inherent characteristics of the rock.

$$\sigma = E_0 \varepsilon + \alpha \varepsilon^2 + \beta \varepsilon^3 + E_1 \int_0^t \dot{\varepsilon}(\tau) \exp\left(-\frac{t-\tau}{\theta_1}\right) d\tau + E_2 \int_0^t \dot{\varepsilon}(\tau) \exp\left(-\frac{t-\tau}{\theta_2}\right) d\tau \quad (12)$$

where E_0 , α , and β are elastic parameters related to material properties, MPa; E_1 and E_2 are the elastic constants of the low-frequency and high-frequency Maxwell elements, respectively;

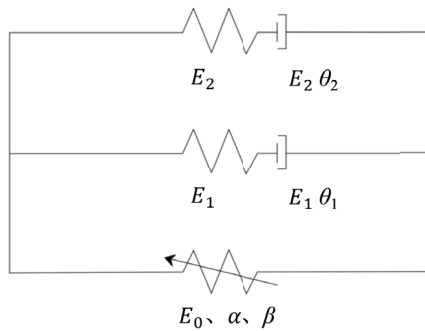


Fig. 20. ZWT model

θ_1 and θ_2 are the corresponding relaxation times of the low- and high-frequency Maxwell elements, s; ε is the strain of the specimen; t is the time, s; τ is the normalized time, s; and $\dot{\varepsilon}(\tau)$ is the instantaneous strain rate at time τ , s^{-1} .

Under the impact loading condition with a time scale of 10^{-6} - 10^{-4} s [48], the low-frequency Maxwell element with a relaxation time of 10^{-2} -1 s cannot undergo sufficient relaxation. At this point, the low-frequency Maxwell element degenerates into a simple spring with an elastic constant E_1 , and Eq. (12) is reduced to:

$$\sigma = E_a \varepsilon + \alpha \varepsilon^2 + \beta \varepsilon^3 + E_2 \int_0^t \dot{\varepsilon}(\tau) \exp\left(-\frac{t-\tau}{\theta_2}\right) d\tau \quad (13)$$

where $E_a = E_0 + E_1$.

By introducing a damage variable D :

$$\sigma = (1-D) \left[E_a \varepsilon + \alpha \varepsilon^2 + \beta \varepsilon^3 + E_2 \int_0^t \dot{\varepsilon}(\tau) \exp\left(-\frac{t-\tau}{\theta_2}\right) d\tau \right] \quad (14)$$

Assuming that the distribution of the mechanical properties of the elementary bodies of magnetite specimens is statistical, the failure probability density under loading follows the Weibull statistical distribution function [49]. Since the damage variable is a parameter describing the degree of damage in the ore, it can be expressed as:

$$D = 1 - \exp\left[-\left(\frac{\varepsilon}{\varepsilon_f}\right)^n\right] \quad (15)$$

where ε_f denotes the peak strain, which has the corresponding relationship given in Eq. (7); and n is the damage parameter of the material.

Substituting Eq. (14) and Eq. (15) into Eq. (13) yields:

$$\sigma = \exp\left[-\left(\frac{\varepsilon}{\varepsilon_f}\right)^n\right] \left[E_a \varepsilon + \alpha \varepsilon^2 + \beta \varepsilon^3 + E_2 \int_0^t \dot{\varepsilon}(\tau) \exp\left(-\frac{t-\tau}{\theta_2}\right) d\tau \right] \quad (16)$$

Under constant strain-rate loading conditions, Eq. (16) can be further simplified to:

$$\sigma = \exp\left[-\left(\frac{\varepsilon}{\varepsilon_f}\right)^n\right] \left\{ E_a \varepsilon + \alpha \varepsilon^2 + \beta \varepsilon^3 + E_2 \theta_2 \dot{\varepsilon} \left[1 - \exp\left(-\frac{\varepsilon}{\dot{\varepsilon} \theta_2}\right) \right] \right\} \quad (17)$$

5.2. Model validation

First, the strain rate $\dot{\varepsilon}$ can be directly obtained from the experimental data, and then the relationship between dynamic peak strain and strain rate in Eq. (7) can be used to determine ε_f . Second, by subtracting two stress-strain curves at high strain rates, the approximate ranges of E_2

and θ_2 can be obtained [50]. The parameter E_a is approximately equal to the slope of the initial rising segment of the curve; the parameters α and β control the slope of the stress-strain curve during the yield stage; and the parameter n is optimized through fitting. The determined model parameters are listed in TABLE 10.

TABLE 10
Dynamic damage constitutive model parameters of magnetite specimens

Impact air pressure (MPa)	$\dot{\epsilon}$ (s ⁻¹)	n	E_a (MPa)	α (GPa)	β (GPa)	E_2 (GPa)	θ_2 (μ s)
0.30	26.74	3.50	10.00	6400.00	10000.00	20.00	5.00
0.40	50.71	2.00	57.00	4900.00	20000.00	1.20	4.00
0.50	104.74	2.20	100.00	2500.00	40000.00	1.30	3.40
0.60	175.00	2.60	100.00	200.00	140000.00	1.00	6.00

Fig. 21 shows the comparison between the experimentally measured stress-strain curves and those calculated by the dynamic damage constitutive model under different impact air pressures. Overall, the calculated curves show a similar trend to the experimental curves, indicating that the proposed model can reasonably describe the main dynamic stress-strain response characteristics of magnetite specimens under impact loading. According to the model fitting evaluation parameters, the coefficients of determination (R^2) under impact air pressures of 0.30 MPa, 0.40 MPa, 0.50 MPa, and 0.60 MPa are 0.90, 0.99, 0.96, and 0.92, respectively, all not lower than 0.90. The corresponding mean absolute errors (MAEs) are 6.47, 2.95, 4.40, and 5.97, respectively, indicating that the fitting errors remain within an acceptable range. These results suggest that the proposed constitutive model has a reasonable ability to reproduce the dynamic deformation behaviour of magnetite specimens under the tested impact loading conditions.

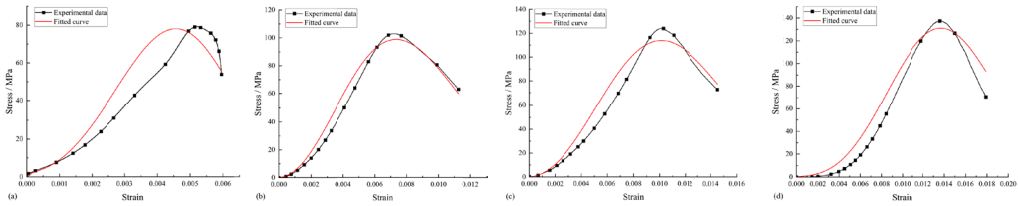


Fig. 21. Fitting comparison of stress-strain curves of magnetite specimens under different impact air pressures (a: 0.30 MPa; b: 0.40 MPa; c: 0.50 MPa; d: 0.60 MPa)

TABLE 11
Evaluation parameters of damage constitutive models

Impact air pressure (MPa)	Evaluation parameters	
	R^2	MAE
0.30	0.90	6.47
0.40	0.99	2.95
0.50	0.96	4.40
0.60	0.92	5.97

5.3. Engineering relevance of SHPB results to field blasting-induced slope response

It should be noted that the SHPB test is a high-strain-rate impact test conducted at the specimen scale, whereas the dynamic response of open-pit slope rock masses under field blasting is characterised by strong spatial variability. In the near-blast zone, the rock mass is subjected to the combined effects of detonation pressure, blasting gas, and strong stress waves, which may result in a high transient strain rate and severe local damage. In contrast, the far-field slope rock mass is mainly affected by blasting vibration, and both the vibration intensity and the induced strain rate decrease gradually with increasing propagation distance. Therefore, the SHPB results obtained in this study should not be directly regarded as the overall blasting vibration response of the entire slope. Instead, they are more suitable for interpreting the high-strain-rate dynamic damage behaviour of magnetite in the near-blast zone or strongly disturbed region.

From an engineering perspective, the connection between laboratory impact loading and field blasting disturbance can be established through field blasting vibration monitoring. The peak particle velocity, dominant frequency, propagation distance, and maximum charge per delay are the key parameters reflecting the intensity of blasting disturbance. In general, the blasting-induced strain rate in the field increases with increasing peak particle velocity and dominant frequency, and decreases as the distance from the blasting source increases. When reliable field monitoring data are available, the monitored peak particle velocity and dominant frequency can be used to estimate the order of magnitude of the blasting-induced strain rate in the slope rock mass. This estimated field strain-rate level can then be compared with the strain-rate range obtained from SHPB tests, thereby clarifying the applicable engineering range of the laboratory results.

The strain rates obtained in SHPB tests are generally higher than those induced by far-field blasting vibration in slopes. This difference reflects the scale effect and loading-mechanism difference between laboratory impact tests and field blasting. However, this does not mean that the SHPB results are disconnected from engineering practice. For rock masses close to the blasthole or located in the strongly disturbed zone, the loading process is closer to high-rate impact loading, and the dynamic mechanical parameters obtained from SHPB tests can provide a useful basis for evaluating local damage, strength enhancement, deformation response, and crack development under intense blasting disturbance. For the far-field slope response, the SHPB results should be combined with field vibration monitoring and slope-scale dynamic numerical simulations rather than being used independently.

Accordingly, the dynamic peak stress, dynamic elastic modulus, dynamic peak strain, strain-rate-dependent relationships, and dynamic damage constitutive model obtained in this study can be introduced into slope-scale blasting dynamic analysis as material parameters and constitutive inputs. Combined with the monitored peak particle velocity, dominant frequency, and blasting vibration attenuation law, these parameters can be used to analyse the dynamic stress level, strain-rate distribution, local damage range, and stability degradation trend of slope rock masses under different blasting conditions. Therefore, the results of this study provide a parameter basis for linking laboratory SHPB tests with field blasting disturbance responses and offer a reference for blasting damage evaluation, blasting parameter optimisation, and disaster prevention in magnetite open-pit slopes.

6. Conclusions

The purpose of this study is to explore the influence of impact load on rock mass in the process of open-pit mining. Based on SHPB dynamic tests under varying impact air pressures, fractal fragmentation analysis, and UDEC 7.0 block discrete-element numerical simulations, the dynamic response behaviour, crack-propagation characteristics, and applicable dynamic damage constitutive relationship of magnetite were systematically revealed:

- (1) SHPB tests under different impact air pressures indicate that magnetite exhibits a pronounced strain-rate effect. Specifically, the dynamic elastic modulus, peak strain, and dynamic compressive strength all increase significantly with increasing strain rate.
- (2) Sieve analysis combined with fractal theory shows that the fractal dimension of rock fragments increases with impact air pressure. The post-impact fragments are mainly prismatic, blocky, conical, fine granular, or powder-like. At higher strain rates, the proportion of small-sized fragments increases markedly, indicating more fully developed internal cracking, greater crack quantity and length, and consequently smaller fragment sizes after failure. The SHPB numerical model established using UDEC 7.0 demonstrates good agreement with laboratory test results and successfully reveals the internal crack-propagation patterns under impact loading.
- (3) By integrating experimental data with the Zhu-Wang-Tang (ZWT) viscoelastic constitutive model and introducing a Weibull statistical damage factor, a strain-rate-dependent dynamic damage constitutive model for magnetite was established. The fitted results show good agreement with experimental stress–strain curves, with all R^2 values exceeding 0.90, indicating that the model effectively captures the dynamic strength characteristics of magnetite under impact loading.
- (4) The findings of this study can provide meaningful guidance for scientifically evaluating the stability of high and steep slopes in magnetite open-pit mines and for the effective implementation of disaster prevention and control measures. However, the specimens used in this study were processed intact magnetite samples, and thus the natural heterogeneity of in-situ rock masses and the influence of structural planes were not considered. Moreover, the impact loading conditions were limited, and the mechanical behaviour under higher strain rates or more complex environments was not covered. It should also be acknowledged that the UDEC model used in this study is a two-dimensional simplification of the SHPB impact loading process. Although it can effectively reveal the relative crack evolution and dominant failure mechanism of magnetite specimens, it cannot fully reproduce the inherently three-dimensional fracture process under impact loading. Future studies may combine CT scanning and 3DEC simulations to further investigate the three-dimensional fracture morphology and dynamic fragmentation behaviour of magnetite.

Acknowledgment

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