Dynamic mechanical properties of structural anisotropic coal under low and medium strain rates

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Abstract

The static mechanical properties of coal rock show anisotropism, which makes the permeability have anisotropic characteristics partly. The dynamic impact mechanical characteristics of structural anisotropic coal under low and medium strain rates were studied by using self-made vertical Split Hopkinson Bar (SHPB) equipment. The peak stress, the strain rate, dynamic elastic modulus and failure characteristics of raw coal with three coring directions were analyzed under the influence of five impact loads and structural anisotropy. The peak stress increases linearly with impact load, and the maximum strain rate and the dynamic elastic modulus increase exponentially with impact load. The coal samples display anisotropic mechanical characteristics. The values of maximum strain rate, peak stress and dynamic elastic modulus are ranked with directions by the perpendicular to bedding direction (Z direction), the parallel to bedding direction (X direction), and the oblique 45° to bedding direction (Y direction). Dynamic mechanical properties of structural anisotropic coal provide a theoretical basis for gas seepage in far-blasting field.

1 Introduction

Gas drainage in coal mine could effectively prevent coal and gas outburst, but the low gas drainage efficiency of low-permeability coal takes a challenge for gas drainage [1]. For hard coal, the deep hole blasting is a conventional technology to generate cracks in coal seam, which is beneficial for the gas permeability and drainage efficiency [2]. The porous medium permeability is affected by the connection of pores and cracks [3–5]. The layout and optimization of blast holes have obtained significant attention and made acceptable achievements in the isotropy coal circumstances [6–8]. In fact, the coal seam has abundant bedding and cleat structures during long geological history, which partly leads to the anisotropy of coal body about the mechanical properties [9,10]. The internal structures of coal will be changed by dynamic load [11,12], and according to the failure characteristics of coal body under blasting, the damage scope can be roughly divided into four areas: enlarged cavity, crushing area, cracking area and vibration area. In the crushing area, most of the hard coal is crushed under the impact load. In the vibration area, the coal particle vibrates elastically, and the coal structure...
does not change after blasting. In the cracking area, radial and circumferential cracks appear in coal, forming macroscopic and microscopic cracks. The blasting will lead to invisible micro-cracks in the place far away from the deep hole blasting location, which is helpful to improve the permeability of coal body. Therefore, the dynamic mechanical failure properties of coal body under different impact loads are of great significance for determining the parameters of deep hole blasting.

The dynamic properties of coal body in the field test of deep hole blasting is difficult to be obtained, therefore, the indoor test methods of the dynamic mechanical properties were studied, such as Split Hopkinson Bar (SHPB), light gas gun test, pneumatic impact device, hammer penetrometer and plane oscilloscope generator. Among them, SHPB is a common device to test the strain rate in the range of \(10^1 \text{ to } 10^3 \text{ s}^{-1}\), in which the strain rate represents general mechanical impact, blasting and explosion dynamic loads, etc. [13–15]. Some researchers improved the device to test the dynamic mechanical properties of coal rock for high strain rate \((10^2 \text{ to } 10^4 \text{ s}^{-1})\) and medium strain rate \((10^1 \text{ to } 10^2 \text{ s}^{-1})\) [16–21]. However, the dynamic mechanical properties of coal rock under low strain rate \((0 \text{ to } 10 \text{ s}^{-1})\) are rarely studied. It is difficult for horizontal SHPB impact device to obtain stable low velocity and low strain rate at low impact pressure [22]. Therefore, the self-made vertical SHPB impact device, which combines the advantages of the drop hammer device and horizontal SHPB impact device, was adopted to obtain the dynamic mechanical characteristics of structural anisotropic coal.

Bedding and cleat in coal rock have great influence on its dynamic performance. Jeager [23] first proposed the concept of strength anisotropy of coal rock caused by single weak plane effect in 1960, and formed the single weak plane theory, which is the initial research achievement about the anisotropy of coal rock. At first, researchers tested the static mechanical properties of anisotropic coal rock, and pointed out that the compressive strength and tensile strength of coal rock have obvious anisotropic characteristics [24,25]. With the wide application of SHPB technology, researchers had tested the mechanical properties of anisotropic coal body under high strain rate by the SHPB impact device. J. R. Klepaczko et al. [26] analyzed the elastic and viscoelastic properties of coal at the different strain rates under impact load for the first time, determined that the elastic properties of coal show strain rate sensitivity under low and medium strain rates. Zhao et al. [27], Wang et al. [28] conducted an experimental study on dynamic fracture toughness of coal samples under impact load by using SHPB impact device, and discussed the effect of impact speed and bedding angle. Wu et al. [29] carried out the dynamic compression tests by using the SHPB impact device under different impact speeds for five different layered rocks with the bedding angles of 0˚, 22.5˚, 45˚, 67.5˚ and 90˚. The results showed that the dynamic compressive strength with the dip angle of 0˚ is the highest, and with the dip angle of 67.5˚ is the lowest. Xie et al. [21] developed a comparative experiment on dynamic mechanical failure characteristics of raw coal samples in different coring direction and sandstone samples with good homogeneity, which showed significant differences in the dynamic failure stress-strain curves. The characteristics of anisotropy are important factors that lead to the long plastic deformation stage and curve fluctuation of raw coal. These results showed that the dynamic mechanical properties of structural anisotropic coal rock are obviously different, which can be defined as anisotropic characteristics. However, only few lectures focus on the dynamics mechanical properties of structural anisotropic coal under low strain rate.

In order to reveal the dynamic mechanical properties of coal body in deep hole blasting under the different distances and directions, the coal samples in three coring directions (parallel to the bedding direction, oblique 45° to bedding direction and perpendicular to the bedding direction) were tested by the self-made vertical SHPB impact device under low strain rate and
Table 1. The measured value of consistent coefficient.

| Measured value | The average value |
|---------------|------------------|
| 1.17          | 1.24             | 1.22             | 1.21             |

five kinds of impact loads, which ensure the integrity of coal samples and provide the theoretical basis for the next permeability test.

2 The preparation of coal samples

The coal samples of Yangquan mine were studied in the laboratory, which provided the theoretical basis and service for the study of dynamic mechanical properties. No specific license is required for Yangquan mine, and no endangered or protected species are involved in the sampling process. The coal samples were taken from No.2 coal mine in Yangquan, Shanxi Province, China. They are all primary structural coal. The water content (1.27%), ash content (18.46%), and volatile matter (9.34%) of coal were determined. The coal metamorphic degree is anthracite. According to the ministry standard of coal industry of the people's Republic of China (MT49-1987), the drop hammer method is a common method to measure the consistent coefficient of coal, and the average consistent coefficient of coal samples is 1.21, as shown in Table 1. The bedding and cleat of coal body are obvious, which could be easily distinguished in the sampling process, as shown in Fig 1A and 1B. In this study, the coal samples were cored in parallel to the bedding direction ($\theta=0^\circ$, represented by symbol X), oblique 45° to bedding direction ($\theta=45^\circ$, represented by symbol Y), and perpendicular to the bedding direction ($\theta=90^\circ$, represented by symbol Z), as shown in Fig 1C and 1D.

![Image](https://doi.org/10.1371/journal.pone.0236802.g001)

Fig 1. Preparation of coal samples (a) Schematic diagram of bedding plane (b) Enlarged diagram of butt cleats and face cleats (c) Coal block after three coring directions (d) Schematic diagram of three coring directions (e) Some coal samples.
The diameter and height of coal samples are 50 mm. The 45 coal samples were tested for dynamic impact test (5 impact loads), and 3 coal samples were taken for each impact load. Some coal samples are shown in Fig 1E.

3 The basic mechanical property parameters of coal samples

The uniaxial compression strength (UCS), Brazilian disc test (BDT) and variable angle shear tests were carried out to determine the mechanical parameters of coal samples, such as the elastic modulus $E$, Poisson's ratio $\mu$, uniaxial compressive strength $\sigma_c$, uniaxial tensile strength $\sigma_t$, shear strength $\tau_f$ and internal friction angle $\phi$. In the uniaxial compression test, the axial and transverse strain of coal samples were measured by the resistance strain gauge and YE2539 static strain gauge. Brazilian disc test and variable angle shear test were completed with corresponding clamps, respectively.

The mechanical property parameters of coal samples are shown in Table 2. According to the different coring directions, it can be seen that the average compressive strength in the Z direction is maximum and in the Y direction is minimum.

4 Dynamic impact test of coal samples

4.1 Experimental system

The self-made vertical SHPB impact device was adopted, with a similar principle to the horizontal impact SHPB device. The driving device is the only difference, and the driving device of horizontal SHPB impact device is pneumatic loading, while the driving device of vertical SHPB impact device is gravity loading. For horizontal SHPB impact device, the higher the gas pressure is, the more stable the impact speed is. On the contrary, the smaller the gas pressure is, the more unstable the impact speed is. Therefore, there is a minimum gas pressure value for the bullet to exit the chamber. The vertical SHPB impact device without high-pressure gas is easy to operate at low speed, and its safety is better than that of horizontal SHPB impact device. Comparing with the drop hammer device, the self-made vertical SHPB impact device has the following advantages in: 1) investigating the stress-strain relationship under low speed and low strain rate 2) avoiding the difficulty of directly measuring the stress or strain of the samples under the impact load. 3) calculating indirectly the dynamic mechanical constitutive relationship of the samples. However, the dynamic constitutive relation of the samples cannot be obtained by the drop hammer device.

The self-made vertical SHPB device [30] is mainly composed of the bullet (30 mm in length), incident bar (1000 mm), transmission bar (1000 mm), absorbing bar (700 mm), damper, Jack, clamp holder (in Fig 2D), supporting device (in Fig 2C) and strain gauge, as shown in Fig 2. The incident bar, transmission bar, and absorbing bar are all elastic bars, and the diameter of the bullet and the three elastic bars are 50 mm.

There is a scale on the side wall of the accelerating conduit 2, which could adjust the impact load. First of all, the generator 1 lifts the bullet 4 through the wire rope 3. After that, when the bullet 4 is released freely at a certain height, it will impact the incident bar. Finally, the strain gauge 13 will immediately generate a pulse signal and transmit it to the dynamic strain gauge.
In order to avoid the inaccurate test results caused by the shaking of the elastic bars during the impact process, the confining pressure applied on the three elastic bars is adjusted to ensure that all bars are in a fixed state before and after the impact. The support device 7 is used to regulate whether the sample is in line with the central axis of the elastic bars during the test. In order to reduce the friction effect, the vaseline was applied to lubricate the interface between the elastic bars and the coal sample.

4.2 Experiment principle

The density of the elastic bars used in the test is 7850 kg/m$^3$, the elastic modulus of the elastic bars is 210 GPa, and the speed of wave propagation in the elastic bars is 5.19 km/s.

The impact velocity $v$ of the bullet is obtained as

$$v = \sqrt{2gH}$$  \hspace{1cm} (1)

Where $g$ is the acceleration of gravity, 9.8 m/s$^2$; $H$ is the free-falling height of the bullet’s center of gravity, m.

The impulse of the bullet is obtained as

$$I = Ft = mv - mv_0$$  \hspace{1cm} (2)

Where $F$ is the resultant force of all external forces including gravity, N; $t$ is the impact time, s;
\[ m \text{ is the mass of the bullet, } kg; \quad v \text{ and } v_0 \text{ are the end velocity and initial velocity of the bullet, m/s.} \]

According to Eq (1), the impulse value can be obtained under the \( H \), as shown in Table 3. According to the impact load, the coal samples are divided into five groups, and coal samples in three coring directions are taken as a group. Dynamic impact test was carried out from small impulse to large impulse.

According to the simplified "three-wave equation", the stress, strain, and strain rate can be obtained as follows:

\[
\sigma(t) = E \frac{A_0}{A} \varepsilon(t) \quad (3)
\]

\[
\dot{\varepsilon}(t) = -\frac{2C}{L_0} \varepsilon(t) \quad (4)
\]

\[
\varepsilon(t) = -\frac{2C}{L_0} \int_0^t \dot{\varepsilon}(t) dt \quad (5)
\]

In the Eq (3)~Eq (5), \( \dot{\varepsilon}(t) \), \( \varepsilon(t) \) and \( \sigma(t) \) are loading strain rate, strain and loading stress of coal samples respectively; \( \varepsilon_r(t) \) and \( \varepsilon_t(t) \) are reflected wave strain and transmitted wave strain in the compression bar respectively; \( E \), \( C \) and \( A \) are elastic modulus, wave velocity and cross-sectional area of the compression bar respectively; \( A_0 \) and \( L_0 \) are cross-sectional area and the length of the sample respectively.

5 Impact test results and discussions

5.1 Test signal characteristics and denoising

In the experiment, the shape of the input wave is changed by using the copper strip as shaping, and the friction effect of the end face is weakened by using the lubricant. Herein, the Fourier transform was used to denoise the test signal. The filtering effect in Fig 3 is taken as an example to illustrate the denoising result of the calibration signal. The original signals and denoising
signals of the incident wave ($I$ wave), reflected wave ($R$ wave) and transmitted wave ($T$ wave) measured in calibration test (falling height is 4m) are shown in Fig 3A and 3B. It can be seen from Fig 3A that the original signal is affected by noise, which needs to be denoised. The incident bar generates a pulse reflection signal with a low peak value, which approximately meets the one-dimensional stress assumption. As shown in Fig 3B that the peak value of the filtered signal is almost unchanged, and the noise has been filtered out. The denoised waveform is beneficial for data processing and analysis.

Under the impact test, the deformation and failure process of coal body is generally manifested as pore shrinkage, coal body compaction, particle contact area enlargement, fracture group formation, and partial interregional adhesion reduction, etc.

5.2 The strain rate

According to Eq (4), the strain rate curves under impact load can be calculated, as shown in Table 4, Figs 4 and 5. The maximum strain rate ($\dot{\varepsilon}_{\text{max}}$) increases exponentially with impact

| $\dot{\varepsilon}_{\text{max}}$/s$^{-1}$ | $\dot{\varepsilon}_{\text{max}}$/s$^{-1}$ | $\dot{\varepsilon}_{\text{max}}$/s$^{-1}$ | $\dot{\varepsilon}_{\text{max}}$/s$^{-1}$ | $\dot{\varepsilon}_{\text{max}}$/s$^{-1}$ | $\dot{\varepsilon}_{\text{max}}$/s$^{-1}$ | $\dot{\varepsilon}_{\text{max}}$/s$^{-1}$ |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| $\theta=90^\circ$ | $\theta=0^\circ$ | $\theta=45^\circ$ | $\theta=90^\circ$ | $\theta=0^\circ$ | $\theta=45^\circ$ | $\theta=90^\circ$ |
| $\dot{\varepsilon}_{\text{max}}$/s$^{-1}$ | $\dot{\varepsilon}_{\text{max}}$/s$^{-1}$ | $\dot{\varepsilon}_{\text{max}}$/s$^{-1}$ | $\dot{\varepsilon}_{\text{max}}$/s$^{-1}$ | $\dot{\varepsilon}_{\text{max}}$/s$^{-1}$ | $\dot{\varepsilon}_{\text{max}}$/s$^{-1}$ | $\dot{\varepsilon}_{\text{max}}$/s$^{-1}$ |
| 10.21 | Z1-$\alpha$ | 10.087 | 9.545 | X1-$\alpha$ | 8.017 | 8.682 | Y1-$\alpha$ | 7.561 | 7.561 |
| | Z1-$\beta$ | 9.534 | X1-$\beta$ | 8.454 | | | Y1-$\beta$ | 8.044 | 7.078 |
| | Z1-$\gamma$ | 9.015 | X1-$\gamma$ | 9.576 | | | Y1-$\gamma$ | 8.044 | 7.078 |
| 12.94 | Z2-$\alpha$ | 16.213 | 16.474 | X2-$\alpha$ | 15.112 | | Y2-$\alpha$ | 14.339 | 14.569 |
| | Z2-$\beta$ | 17.054 | X2-$\beta$ | 15.065 | | | Y2-$\beta$ | 14.812 | 14.569 |
| | Z2-$\gamma$ | 16.156 | X2-$\gamma$ | 15.948 | | | Y2-$\gamma$ | 14.812 | 14.569 |
| 15.16 | Z3-$\alpha$ | 25.316 | 24.568 | X3-$\alpha$ | 24.015 | 23.389 | Y3-$\alpha$ | 22.271 | 22.712 |
| | Z3-$\beta$ | 24.323 | X3-$\beta$ | 23.238 | | | Y3-$\beta$ | 22.047 | 22.047 |
| | Z3-$\gamma$ | 24.066 | X3-$\gamma$ | 22.914 | | | Y3-$\gamma$ | 23.817 | 23.817 |
| 17.1 | Z4-$\alpha$ | 34.043 | 34.551 | X4-$\alpha$ | 34.021 | 33.714 | Y4-$\alpha$ | 31.815 | 32.361 |
| | Z4-$\beta$ | 34.027 | X4-$\beta$ | 33.755 | | | Y4-$\beta$ | 32.726 | 32.726 |
| | Z4-$\gamma$ | 35.583 | X4-$\gamma$ | 33.366 | | | Y4-$\gamma$ | 33.542 | 33.542 |
| 18.86 | Z5-$\alpha$ | 47.335 | 46.421 | X5-$\alpha$ | 44.377 | 44.775 | Y5-$\alpha$ | 42.815 | 43.754 |
| | Z5-$\beta$ | 46.512 | X5-$\beta$ | 45.231 | | | Y5-$\beta$ | 43.942 | 43.942 |
| | Z5-$\gamma$ | 45.416 | X5-$\gamma$ | 44.717 | | | Y5-$\gamma$ | 44.505 | 44.505 |
load in the same coring directions, and the correlation coefficients are above 0.99. Moreover, under the same impact load, the maximum strain rate is the largest in the Z direction, middle in the X direction, and smallest in the Y direction. However, the overall differences are not significant.

5.3 The characteristics of the stress-strain curve

Under different impulses, the stress-strain curves of coal samples can be calculated according to Eq (3), Eq (5), as shown in Fig 6 and Table 4. The stress-strain curve can be roughly divided into linear elastic stage, plastic deformation stage and failure stage. The curve almost has no concave section and obvious initial compaction stage, but directly enters the linear elastic stage. The stress increases linearly with the strain approximately in the initial stage of strain. The reason is that the coal samples are relatively dense, the internal micro-cracks are not well developed. Under the impact load, the macroscopic and microscopic defects of the coal samples are too late to close, and the compaction stage is very short.

As shown in Fig 6, the stress rises rapidly with the strain rate. The curve basically has no plastic plateau, which indicates that the coal samples show obvious brittleness with the change
of strain rate. When the stress value rises to 80% of the ultimate strength, the upward trend of the curve slows down, showing a similar strengthening stage to that of rock [31,32]. The degree of slowing down is related to the number of cracks, indicating that the primary cracks start to close, and the strain growth rate is accelerated. This phenomenon will appear in coal rock with internal cracks [33].

Fig 6 shows that the peak stress is obviously different in three coring directions. Under the same impulse, the peak stress of coal samples in the Z direction is the maximum, and the $s_{\text{max}}$ value is 15.506 MPa. The peak stress is the minimum in the Y direction, and the $s_{\text{max}}$ value is 12.072 MPa. The average values of the peak stress are shown in Table 5.

Fig 7 shows the relationship between the impulse and average peak stress in three coring directions. The peak stress increases linearly with the impact load, and the correlation coefficients are all above 0.98. Obviously, the impact load and structural anisotropy have significant influence on the peak stress of coal body.

### 5.4 Dynamic Intensity Growth Factor (DIF)

In order to compare the growth of dynamic strength of coal body with that of static strength under different impact loads, the ratio of dynamic strength to static strength is defined as Dynamic Intensity Growth Factor (DIF), that is:

$$DIF = \frac{\sigma_d}{\sigma_c}$$  \hspace{1cm} (6)

Where, $\sigma_d$ and $\sigma_c$ are dynamic and static compressive strength of coal samples respectively. The DIF can be calculated via Eq (6) and data of Table 5, as shown in Table 6. The relationship between DIF and impulse is fitted, as shown in Fig 8.

Fig 8 shows that the DIF of coal samples increases linearly with the impact load in three coring directions. The dynamic compressive strength does not exceed the static compressive
strength, which due to the fact that the coal samples are not broken, and only some microcracks and internal damage are produced in the coal body [34].

Fig 6. Stress–strain curves of coal samples under different impulses.

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5.5 Dynamic elastic modulus

The dynamic stress-strain curve of coal rock is the arc, and secant modulus is used instead of elastic modulus to reflect the average stiffness of coal rock.

\[
E_{50} = \frac{\sigma_{50}}{\varepsilon_{50}}
\]

Where, \(\sigma_{50}\) is the stress value when the dynamic compressive strength peaks at 50%, \(\varepsilon_{50}\) is the corresponding axial strain. The dynamic elastic modulus is obtained by processing the

![Fig 7. The relationship between the impulse and average peak stress.](https://doi.org/10.1371/journal.pone.0236802.g007)
measured stress-strain curve, as shown in Table 7. The relationship between the average dynamic elastic modulus and impulse in three coring directions is shown in Fig 9.

As can be seen from Fig 9, the dynamic elastic modulus increases exponentially with the impact load, and the correlation coefficients are all greater than 0.98.

### 6 Failure characteristics of coal samples

Fig 10 shows the different failure mode characteristics of coal samples under different impulses. The failure degree of coal samples increases with the impulse, the transformation

| Impulse /kg·m⁻¹ | θ=90° | DIF | θ=0° | DIF | θ=45° | DIF |
|-----------------|--------|-----|------|-----|--------|-----|
| 10.21           | Z1-α   | 0.279 | X1-α | 0.376 | Y1-α   | 0.347 |
|                 | Z1-β   |      | X1-β |      | Y1-β   |      |
|                 | Z1-γ   |      | X1-γ |      | Y1-γ   |      |
| 12.94           | Z2-α   | 0.363 | X2-α | 0.508 | Y2-α   | 0.514 |
|                 | Z2-β   |      | X2-β |      | Y2-β   |      |
|                 | Z2-γ   |      | X2-γ |      | Y2-γ   |      |
| 15.16           | Z3-α   | 0.452 | X3-α | 0.657 | Y3-α   | 0.617 |
|                 | Z3-β   |      | X3-β |      | Y3-β   |      |
|                 | Z3-γ   |      | X3-γ |      | Y3-γ   |      |
| 17.1            | Z4-α   | 0.535 | X4-α | 0.812 | Y4-α   | 0.780 |
|                 | Z4-β   |      | X4-β |      | Y4-β   |      |
|                 | Z4-γ   |      | X4-γ |      | Y4-γ   |      |
| 18.86           | Z5-α   | 0.611 | X5-α | 0.937 | Y5-α   | 0.919 |
|                 | Z5-β   |      | X5-β |      | Y5-β   |      |
|                 | Z5-γ   |      | X5-γ |      | Y5-γ   |      |

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Fig 8. Variation of the DIF with the impulse.

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Table 7. The dynamic elastic modulus under different impulses.

| $I$ /kg m$^{-1}$ | $\theta$=90° | $E_{50}$/GPa | $E_{50}$/GPa | $\theta$=0° | $E_{50}$/GPa | $E_{50}$/GPa | $\theta$=45° | $E_{50}$/GPa | $E_{50}$/GPa |
|-----------------|--------------|-------------|-------------|--------------|-------------|-------------|--------------|-------------|-------------|
| 10.21           | Z1-\(\alpha\)| 4.761       | 4.119       | X1-\(\alpha\)| 3.008       | 2.998       | Y1-\(\alpha\)| 3.096       | 2.719       |
|                 | Z1-\(\beta\)| 3.647       | X1-\(\beta\)| 2.817       | Y1-\(\beta\)| 2.104       |              |              |              |
|                 | Z1-\(\gamma\)| 3.950       | X1-\(\gamma\)| 3.169       | Y1-\(\gamma\)| 2.958       |              |              |              |
| 12.94           | Z2-\(\alpha\)| 5.465       | 4.855       | X2-\(\alpha\)| 3.969       | 3.955       | Y2-\(\alpha\)| 4.172       | 3.794       |
|                 | Z2-\(\beta\)| 4.612       | X2-\(\beta\)| 4.001       | Y2-\(\beta\)| 3.561       |              |              |              |
|                 | Z2-\(\gamma\)| 4.487       | X2-\(\gamma\)| 3.894       | Y2-\(\gamma\)| 3.649       |              |              |              |
| 15.16           | Z3-\(\alpha\)| 5.471       | 5.192       | X3-\(\alpha\)| 4.926       | 4.489       | Y3-\(\alpha\)| 4.057       | 4.321       |
|                 | Z3-\(\beta\)| 5.403       | X3-\(\beta\)| 4.247       | Y3-\(\beta\)| 3.537       |              |              |              |
|                 | Z3-\(\gamma\)| 4.701       | X3-\(\gamma\)| 4.295       | Y3-\(\gamma\)| 4.549       |              |              |              |
| 17.1            | Z4-\(\alpha\)| 5.445       | 5.334       | X4-\(\alpha\)| 4.969       | 4.809       | Y4-\(\alpha\)| 3.548       | 4.598       |
|                 | Z4-\(\beta\)| 5.344       | X4-\(\beta\)| 4.995       | Y4-\(\beta\)| 4.441       |              |              |              |
|                 | Z4-\(\gamma\)| 5.825       | X4-\(\gamma\)| 4.463       | Y4-\(\gamma\)| 5.804       |              |              |              |
| 18.86           | Z5-\(\alpha\)| 6.426       | 5.646       | X5-\(\alpha\)| 4.909       | 5.009       | Y5-\(\alpha\)| 3.967       | 4.804       |
|                 | Z5-\(\beta\)| 5.013       | X5-\(\beta\)| 4.958       | Y5-\(\beta\)| 4.733       |              |              |              |
|                 | Z5-\(\gamma\)| 5.499       | X5-\(\gamma\)| 5.159       | Y5-\(\gamma\)| 5.521       |              |              |              |

from axial splitting failure state to radial crushing failure state shows the strain rate effect. There are many cracks in the coal samples. The nature of cracks indirectly determines the failure modes of the coal samples, which are caused by the generation and expansion of the internal cracks [34,35]. Under the lower impact load, the stress wave passes through the crack, which makes the original crack extend and expand. More energy is needed to generate a new crack. When the impact load is small, the energy generated is not enough to produce a new crack, and the development of the new crack is not obvious. Therefore, the stress concentration will appear at the crack tip to make it crack first under stress wave, then the crack will
Fig 10. Failure mode of coal samples under different impulses.

(1) Impulse = 10.21 kg·m/s

(2) Impulse = 12.94 kg·m/s

(3) Impulse = 15.16 kg·m/s

(4) Impulse = 17.1 kg·m/s

(5) Impulse = 18.86 kg·m/s

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expand along the tip, and finally the coal samples will be split axially. When the coal samples are subjected to high impact load, due to the existence of shear pressure, the coal samples will show brittleness. Some new cracks will be generated under the effect of stress wave, which will extend and penetrate, and the internal cracks in the coal samples will continue to increase. Therefore, the surface of the coal samples will show cracks, a small number of broken and other phenomena.

7 Conclusion

The dynamic stress-strain, dynamic elastic modulus and dynamic intensity growth factor properties of raw coal samples with three coring directions were studied by using the self-made vertical SHPB device under low strain rate and five kinds of impact loads. The conclusions are as follows:

1. The self-made vertical SHPB device is suitable for the loading of coal samples at low speed and low strain rate.

2. Under same coring direction, the strain rate increases exponentially with the impact load. The strain rate is weakly affected by the structural anisotropic coal.

3. The dynamic stress-strain characteristics of coal samples show great differences in directions. Under the same impact load, the average peak stress of coal samples is maximum in the perpendicular to the bedding direction, minimum in the oblique 45° to bedding direction, displaying the anisotropic characteristics of coal structure.

4. The dynamic elastic modulus and the dynamic intensity growth factor of the coal samples increase with the impact load, and the correlation coefficients are greater than 0.98, showing the correlation and sensitivity to the impact load.

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References

1. Shen BH, Liu JZ, Zhang H. The technical measures of gas control in China coal mines. Journal of China Coal Society. 2007; 32(7): 673–679.

2. Xing ZF, Yan YL, Li HJ. Mechanism and results of prevention of rockburst by controlled pressure relief deep holes. Journal of China Coal Society. 1996; 16(2):1–9.

3. Xie ZC, Zhang DM, Song ZL, et al. Optimization of drilling layouts based on controlled pre-splitting blasting through strata for gas drainage in coal roadway strips. Energies; 2017; 10: 1228.
4. Jiao HZ, Wang SF, Yang YX, et al. Water recovery improvement by shearing of gravity-thickened tailings for cemented paste backfill. Journal of Cleaner Production, 2020, 245, 118882.

5. Ding XH, Zhou W, Lu X, et al. Distribution characteristics of fragments size and optimization of blasting parameters under blasting impact load in open-pit mine. IEEE Access. 2019; 7:137501–137516.

6. Lin HF, Huang M, Li SG, et al. Numerical simulation of influence of Langmuir adsorption constant on gas drainage radius of drilling in coal seam, International Journal of Mining Science and Technology. 2016; 26(3): 377–382.

7. Yin GZ, Wang DK, Zhang DM, et al. Solid-gas coupling dynamic model and numerical simulation of coal containing gas. Chinese Journal of Geotechnical Engineering. 2008; 10(4): 1430–1435.

8. Yin GZ, Wang DK. A coupled elastoplastic damage model for gas-saturated coal. Chinese Journal of Rock Mechanics and Engineering. 2009; 28(5): 994–999.

9. Roslin Alexandra, Pokrajac Dubravka, Zhou YF. Cleat structure analysis and permeability simulation of coal samples based on micro-computed tomography (micro-CT) and scan electron microscopy (SEM) technology. Fuel. 2019; 254: 115579.

10. Wang H, Yue GW, Yue JW, et al. Permeability of coal associated with cleat and bedding structure: measurement and modeling. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 2019; 1–13

11. Xie GX, Yin ZQ, Hu ZX, et al. Disaster-causing mechanical mechanism of coal mining dilatancy of gassy seam in deep mine. Journal of China Coal Society. 2015; 40(1): 24–29.

12. Huang CG, Zhang YB, He JF, et al. Permeability improvements of an outburst-prone coal seam by means of presplitting and blasting with multiple deep boreholes. Energy Science & Engineering. 2019; 7: 2223–2236.

13. Xia KW, Yao W. Dynamic rock tests using split Hopkinson(Kolsky) bar system-A review. Journal of Rock Mechanics and Geotechnical Engineering. 2015; 7(1): 27–59.

14. Cai M, Kaiser PK, Suorineni F, et al. A study on the dynamic behavior of the Meuse/Haute-Marne argillite. Physics and Chemistry of the Earth Parts A/B/C. 2007; 32(8): 907–916.

15. Lu FY, Chen R, Lin YL, et al. Hopkinson rod experimental technology. Beijing: Science Press. 2013; 1–2

16. Oh SW, Min GJ, Park SW, et al. Anisotropic influence of fracture toughness on loading rate dependency for granitic rocks. Engineering Fracture Mechanics. 2019; 221: 106677.

17. Yao W, Xia KW. Dynamic notched semi-circle bend (NSCB) method for measuring fracture properties of rocks: Fundamentals and applications. Journal of Rock Mechanics and Geotechnical Engineering. 2019; 11(5): 1066–1093.

18. Wang SM, Liu YS, Du K, et al. Dynamic Failure Properties of sandstone under radial gradient stress and cyclical impact loading. Frontiers in Earth Science. 2019; 7: 251.

19. Jiao HZ, Wu YC, Chen XM, et al. Flexural toughness of basalt fibre-reinforced shotcrete and industrial-scale testing. Advances in Materials Science and Engineering. 2019; 1–8.

20. Xie BJ, Ai DH, Yang Y. An automatic pixel-level crack identification method for coals experiencing SHPB impact tests. Journal of Geophysics and Engineering. 2019; 16: 297–308.

21. Xie BJ, Wang XY, Lv PY. Dynamic properties of bedding coal and rock and the SHPB testing for its impact damage. Journal of vibration and shock. 2017; 36(21): 117–124.

22. Shang B, Wang TT. Development of a vertical split Hopkinson pressure bar. Chinese Journal of high pressure physics. 2018; 32(04): 70–74.

23. Jeager JC. Shear failure of anisotropic rocks. Geol. Mang. 1960.

24. Alexeev AD, Revva VN, Alyshev NA, et al. True triaxial loading apparatus and its application to coal outburst prediction. International Journal of Coal Geology. 2004; 58(4): 245–250.

25. Okubo S, Fukui K, Qing X. Uniaxial compression and tension tests of anthracite and loading rate dependence of peak strength. International Journal of Coal Geology. 2006; 68(3-4): 196–204.

26. Klepaczko JR, Hsu TR, Bassim MN. Elastic and pseudo viscous properties of coal under quasi-static and impact loading. Canadian Geotechnical. 1984; 21(2): 203–212.

27. Zhao YX, Gong SA, Hao XJ, et al. Effects of loading rate and bedding on the dynamic fracture toughness of coal: Laboratory experiments. Engineering Fracture Mechanics. 2017; 375–391.

28. Wang YB, Yang RS. Study of the dynamic fracture characteristics of coal with a bedding structure based on the NSCB impact test. Engineering Fracture Mechanics. 2017; 184: 319–338.

29. Wu RJ, Li HB, Li XF, et al. Broken energy dissipation and fragmentation characteristics of layered rock under impact loading. Journal of China Coal Society. 2019; 1–9.
30. Li MM, Liang WM, Yue GW, et al. Experiment and modeling of permeability under different impact loads in a structural anisotropic coal body. ACS Omega, 2020; 5(17): 9957–9968. https://doi.org/10.1021/acsomega.0c00269 PMID: 32391483

31. Zhang HD, Zhu ZW, Ning JG. Mechanical behavior of frozen soil under uniaxial dynamic loading. Chinese Journal of solid mechanics. 2005; 38(1): 21–39.

32. Ma QY. Experimental analysis of dynamic mechanical properties for artificially frozen clay by the split Hopkinson pressure bar. Journal of Applied Mechanics and Technical Physics. 2010; 51(3): 448–452.

33. Xie LX, Zhao GM, Meng XR. Research on excess stress constitutive model of rock under impact load. Chinese Journal of Rock Mechanics and Engineering. 2013; 32(S1): 2772–2781.

34. Li XB, Lok TS, Zhao J. Dynamic characteristics of granite subjected to intermediate loading rate. Rock Mechanics and Rock Engineering. 2005; 38(1): 21–39.

35. Gomez JT, Shukla A, Shannab A. Static and dynamic behavior of concrete and granite in tension with damage. Theoretical and Applied Fracture Mechanics. 2001; 36(1): 37–49.