Experimental Study on the Dynamic Response and Pore Structure Evolution of Coal under High-Pressure Air Blasting

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ABSTRACT: High-pressure air blasting (HPAB) is one of the main feasible technologies to improve the extraction efficiency of unconventional gases. At present, there are few visual studies on the evolution characteristics of pore structure in coal under HPAB, resulting in an unclear understanding of the mesoscopic damage evolution mechanism of coal under HPAB. To study the dynamic response and mesoporous structure evolution characteristics of coal under HPAB, simulated coal specimens were used in HPAB experiments. The pore structure characteristics of coal at different locations away from the blasthole after HPAB were analyzed by using computed tomography scanning and 3D reconstruction technology. The maximum sphere algorithm was used to study the law of pore connectivity and reveal the mesoscopic damage evolution mechanism of coal under HPAB. The results indicate that the stress wave and attenuation and the crack propagation direction are greatly affected by the confining pressure. Compared without confining stress, the radial strain attenuation index decreases by 11.97% and the lateral strain attenuation index increases by 15.36% under confining pressure. Without confining pressure, the crack direction is disordered. On the contrary, the crack expands along the $\sigma_1$ and $\sigma_2$ directions with confining pressure, while the expansion along other directions is inhibited. The stress wave has a great influence on the pore structure in the nearby zone. Compared with before HPAB, at 25 mm distance from the blasthole, the number of pores increased by 24.80%, the number of throats increased by 12.96 times, the maximum equivalent radius of throats increased by 52.15%, and the maximum channel length of the throat increased by 56.06%. With the increase of the distance, the stress wave has little influence on the pore structure in the middle and far zones. The porosity of representative elementary volume and the distance from the blasthole decay in a power function trend. The maximum disturbance distance under HPAB can reach nearly 110 times of the blasthole radius. The study results provide a theoretical basis for enhancing the coal seam permeability and gas drainage of low-permeability coal seam by HPAB.

1. INTRODUCTION

Unconventional natural gases (coalbed methane, shale gas, tight sandstone gas, etc.) are highly efficient and clean energies with abundant storage and a wide distribution. Their efficient exploitation is of great significance to optimizing the energy supply structure, promoting a low-carbon economy, and sustainable development of a green environment.1−7 However, the pumping of unconventional natural gases is affected by complex conditions such as high stress and low permeability, which limit their efficient pumping.8 Therefore, hydration fracturing technology and anhydrous fracturing technology are usually used to improve the permeability. As a relatively mature fracturing technology, hydrated fracturing technology is widely used in the extraction of oil, conventional gases, and unconventional gases.8−9 However, hydrous fracturing technology also has certain limitations,7−9 such as (1) the consumption of a large number of water resources, (2) the gas channel being occupied by water, which reduces the fluidity of the gas, and (3) the groundwater being polluted by water-based liquids. Therefore, anhydrous fracturing technology is considered a potential method to improve the efficiency of unconventional gas extraction.

In recent years, with the increasingly prominent environmental problems, the concept of green development has been deeply rooted in people’s minds. As a new hydrous physical fracturing technology with simple operation, high efficiency, and safety, high-pressure gas blasting technology [high-pressure air blasting (HPAB), liquid CO$_2$ phase change fracturing, etc.] can make up for the deficiencies of hydrated fracturing technology, and its application in the anti-reflection field of unconventional natural gases has gradually attracted...
attention. Some scholars used high-pressure gas blasting technology in the field of gas drainage and for permeability enhancement of low-permeability coal seams. Lv et al. and Li et al. carried out the HPAB test in the Dingji coal mine in Huainan. The results of the study found that the permeability of coal seams and gas drainage have been significantly improved after HPAB. When the high-pressure air is 60 MPa, the anti-reflection radius of the coal seam is less than 2 m. Cao et al. and Hu et al. researched the application effects of liquid CO$_2$ phase change fracturing (LCPCF) in low-permeability coal mines in Lu’an and Yangquan. It was found that the LCPCF can effectively improve the permeability of coal seams and reduce the probability of gas disasters. However, the high-pressure gas blasting technology as a measure to increase the permeability of low-permeability coal seams is still in the development stage, and the related theoretical research is not perfect. Domestic and foreign scholars have carried out a large number of studies on the anti-reflection field of high-pressure gas in unconventional gas low-permeability reservoirs using theoretical analysis, physical experiment, and numerical simulations. It was found that the amount of high-pressure gas, impact mode, and in situ stress have a great influence on the crack initiation mode and crack propagation law of coal. Some scholars detected the macroscopic mechanical properties and microstructure changes of coal and rock mass before and after high-pressure gas blasting by uniaxial/triaxial loading, acoustic emission detection, scanning electron microscopy (SEM), and mercury intrusion porosimetry (MIP) to reveal the cracking mechanism under a high-pressure gas impact. It is found that the compressive strength, wave velocity, and elastic modulus of rock mass decrease after a high-pressure gas impact, the stress−strain curve shows many sudden drops, and the increase of semi-closed and connected holes leads to the increase of permeability and degree of damage degree. Some scholars studied the effect of stress wave on the pore/fracture structure of coal. Wang et al. and Li et al. simulated stress wave impact on coal samples by the SHPB system. Combined with MIP and low-temperature liquid nitrogen (LTLN) analysis, it was found that stress wave can improve the microstructure of coal. Liao et al. and Xia et al. combined the mechanical test, SEM, and MIP to explore the effect of stress wave generated by liquid CO$_2$ phase change fracturing (LCPCF) on the pore/fracture structure of coal and found that the stress wave and high-energy CO$_2$ gas can cause irreversible damage to the coal microstructure. Liu et al. used SEM and LTLN to study the changes in the pore/fracture structure of coal induced by ultrasonic waves and found that the number and connectivity of coal fractures increased after ultrasonic treatment. At present, the researchers mainly carry out research on the macromechanical properties and two-dimensional microstructure of coal and rock mass. The three-dimensional pore structure of coal and rock mass at different positions of distance fractures after high-pressure gas fracturing is less characterized, which cannot accurately describe the spatial distribution and evolution law, and there is a lack of systematic research on the influence of micropore connectivity on the crack propagation law and damage fracture mechanism. The initiation, connection, and expansion mechanisms of the pore structure network of coal and rock mass under high-pressure gas blasting is not clear yet.

In this paper, the stress propagation and damage evolution of simulated coal specimens under HPAB are studied by using a self-developed HPAB system. After the shock from HPAB, the specimens at different positions from the blasthole are scanned into computed tomography (CT) slices by high-precision industrial CT. The processed CT slices are constructed into a 3D visualization model by 3D reconstruction software. The variation laws of parameters such as the porosity, pore length, and pore size distribution are analyzed through a 3D visualization model. The pore network model (PNM) is used to accurately identify the pore fracture topological space, which is used to reveal the evolution characteristics and disturbance law of pore structures in different areas of simulated coal samples under HPAB.

### Table 1. Basic Physical and Mechanical Parameters of Hard Coal

| Parameter                         | Value |
|-----------------------------------|-------|
| Uniaxial compressive strength (MPa) | 12−18 |
| Uniaxial tensile strength (MPa)   | 0.8−2 |
| Density (g/cm$^3$)                | 1.4−1.7 |
| Poisson’s ratio                    | 0.2−0.3 |
| Acoustic (m/s)                     | 1800−2000 |
| Elastic modulus (GPa)              | 2.3−3.2 |

### Table 2. Simulated Coal Mix Proportion (kg/m$^3$)

| Material          | Proportion (kg/m$^3$) |
|-------------------|-----------------------|
| Cement            | 100                   |
| Sand              | 280                   |
| Gypsum            | 14                    |
| Water             | 43                    |
| Perlite           | 2                     |
| Mica              | 2                     |
| Foaming agent     | 0.35                  |

2. METHODOLOGY

2.1. Simulation Test of Stress Field and Failure Morphology in Coal under HPAB. 2.1.1. Experimental Materials and Mix Proportion. Coal is a porous medium with strong heterogeneity and anisotropy. In view of the particularity and complexity of the physical and mechanical property parameters of coal, there are many inconvenient factors in the direct study of HPAB tests on coal (such as specimen processing and sensor embedding). It is necessary to eliminate the influence of joints, bedding, and anisotropy to study the pore structure evolution of coal under HPAB. Therefore, according to the similarity theory, the artificially simulated coal specimens are selected for the HPAB test.

There are certain differences in the basic mechanical parameters of the same coal due to the influence of formation pressure, temperature, and other factors. Therefore, the range of basic physical and mechanical parameters of hard coal in the Zhaogu mine obtained through field investigation and laboratory tests are shown in Table 1. Based on the range of physical and mechanical parameters of raw coal, aggregates, cementitious materials, and additives are used to make similar coal. Among them, the aggregate is fine sand with diameters of less than 6 mm; the cementitious materials include the Portland cement with a density of 3.0−3.15 g/cm$^3$ and the gypsum with a fineness of 400 mesh, the adhesive materials include the foaming agent with a density of 2.16 g/cm$^3$ and the mica with a particle size of 10−15 mesh, and the perlite with a diameter of 2−3 mm. After many debugging, the mix proportion of simulated coal was determined. The material mix ratio and basic physical and mechanical properties of simulated coal specimens are shown in Tables 2 and 3, respectively.

According to the methods above, two specimens with the size of 500 × 300 × 300 mm were prepared. During the
parallel specimen preparation, a blasthole with a depth of 200 mm and a diameter of 12 mm needed to be reserved 150 mm from one end of the specimen. Additionally, strain bricks with a size of $20 \times 20 \times 20$ mm needed to be embedded, respectively, at the intersections of 50, 110, 210, and 320 mm from the blasthole and 120 mm from the bottom of the specimen.

2.1.2. HPAB Test. To reveal the law of stress wave propagation and crack propagation in coal, a self-developed HPAB system was used. In the HPAB test, the air pressure was set over 15 MPa, two-direction loading, and the in-site stress $\sigma_1 = \sigma_2 = 0$ MPa and $\sigma_1 = \sigma_2 = 4$ MPa are applied to the specimens, respectively. The HPAB system is shown in Figure 1. The surface around the specimen is coated with a layer of the coupling agent with a thickness of 4–6 mm to avoid the error caused by boundary effects. The layout of measuring points and the schematic diagram of the stress field are shown in Figure 2.

|          | uniaxial compressive strength (MPa) | uniaxial tensile strength (MPa) | density (g/cm³) | Poisson’s ratio | acoustic (m/s) | elastic modulus (GPa) |
|----------|-------------------------------------|--------------------------------|----------------|----------------|---------------|-----------------------|
|          | 12.82                               | 1.06                           | 1.638          | 0.26           | 2152          | 2.52                  |

2.2. Characterization Test of the Specimen Pore Structure under HPAB. 2.2.1. Sampling Location of the Specimens and Experimental Equipment. The acquisition of specimens at different distances is the key technology to studying the characterization of microscopic pore structure under HPAB. Therefore, specimens of $30 \times 20 \times 20$ mm size were obtained by a cutting machine with strong anti-interference ability. The sampling location of the specimens is shown in Figure 3. The Phoenix vltomex s industrial CT was used for CT scanning of specimens at different positions. The specific parameters of the test conditions are as follows: the minimum spatial resolution is 5 $\mu$m, the voltage is 150 kV, the current is 110 $\mu$A, the number of slices is 1000, and the pixel is $2024 \times 2024$. The scanning process is shown in Figure 4. In the process of CT scanning, X-ray sources and electronic devices have interference effects on the sample scanning results, such as noise and stains, so it is impossible to conduct vector operation on the scanned image directly. Therefore, the image processing software should be used to remove the interference information of the scanned image.

2.2.2. 3D Reconstruction and Establishment of a PNM. AVIZO visualization software was used for the 3D reconstruction of the processed CT slices. Because the selection of specimen is too large, it exceeds the computing capacity of the computer and affects the efficiency of data analysis. Therefore, representative elementary volume (REV) was selected as the research objects for comparative analysis. After repeated debugging, a cuboid with dimensions of length $\times$ width $\times$ height = $4 \times 4 \times 3$ mm was selected as REV to

![Figure 1. HPAB system.](image)

![Figure 2. Layout of measuring points and the schematic diagram of the stress field.](image)

![Figure 3. Sampling location of the specimens.](image)

![Table 3. Average Values of Mechanical Parameters of Simulated Coal](image)
establish a 3D reconstruction model. To further reveal the geometric spatial structure characteristics of the pores inside the specimen subjected to HPAB, based on the 3D reconstruction model the maximum sphere search algorithm was adopted to establish the PNM.\textsuperscript{29,30} CT slices preprocessing and 3D visualization process are shown in Figure 5.

3. RESULTS AND DISCUSSION

3.1. Simulation Test Results and Analysis of Stress Field and Failure Morphology in Coal under HPAB.

3.1.1. Strain Wave Propagation in the Specimen under HPAB. The HPAB tests are carried out on two specimens. The relationship between the strain peak and the distance is obtained by the statistics of the peak values of radial strain and lateral strain at different measuring points. The results of strain peaks at each measuring point are shown in Table 4. The relationship curve between strain peak and distance at each measuring point is shown in Figure 6.

The conclusions drawn from Table 4 and Figure 6 are as follows: in the near region, the strain wave generated by HPAB attenuates rapidly, and the strain wave attenuates slowly with the increase of propagation distance. The strain wave attenuates in a power function trend and conforms to the formula $y = ax^b$. Without confining pressure, the attenuation indexes of radial strain and lateral strain are $-1.5194$ and $-1.5809$, respectively. Compared without confining stress, the radial strain attenuation index decreases by $11.97\%$ and the lateral strain attenuation index increases by $15.36\%$ under confining pressure.

Table 4. Results of Strain Peaks at Each Measuring Point

| confining stress $\sigma_1 = \sigma_2$ | strain direction | strain peaks at different measuring points/με | attenuation coefficient/α |
| --- | --- | --- | --- |
| 0 MPa | radial | −4984.41 | −1418.76 | −650.27 | −343.01 | −1.5194 |
| | lateral | 1622.10 | 500.75 | 117.62 | | −1.5809 |
| 4 MPa | radial | −5675.12 | −1875.06 | −918.54 | −523.02 | −1.3375 |
| | lateral | 1418.75 | 325.41 | 80.89 | | −1.8238 |
The main reason for this phenomenon is that under the action of confining stress, the compactness of the original micropores in the specimen is increased and the energy dissipation of stress wave in the process of propagation is reduced. When the stress wave decays to the confining stress, the stress wave will be offset by the confining pressure, which reduces the attenuation path of the stress wave. Tensile action in the lateral direction under HPAB needs to overcome the confining stress, the compactness of the original micropores in the specimen is increased and the energy dissipation of stress wave in the process of propagation is decreased rapidly.

3.1.2. Failure Morphology of the Specimen under HPAB.
Failure morphology of the specimen with/without confining pressure under HPAB is shown in Figure 7.

The failure morphologies of HPAB on the specimen are mainly divided into dynamic loading stages under the action of stress wave and the quasi-static loading stages of high-pressure air penetration. The crack propagation near the blasthole is mainly caused by stress waves. The stress waves decay rapidly with the increase of distance, and the crack propagation in the middle and far regions is mainly caused by stress waves and high-pressure air infiltration and disturbance. As can be seen in Figure 7, under the current test conditions, there is no fracture zone around the blasthole with or without confining pressure. The specimen without confining pressure has two main cracks, and the cracks’ directions are random. The main reason for this phenomenon is that macrocracks are formed by the initiation, connection, and propagation of randomly distributed micropores under HPAB. In the process of forming macrocracks, the development and propagation direction of micropores are random, so the macrocrack propagation direction of specimens without confining pressure is random. There are four main cracks on the surface of the specimen with confining pressure, and the crack expands along the $\sigma_1$ and $\sigma_2$ directions. Under the action of stress wave and bidirectional pressure, the randomly distributed microcracks mainly nucleate and connect along $\sigma_1$ and $\sigma_2$ directions to form macro-main cracks, while the expansion of other directions is inhibited.

3.2. Characterization Analysis of the Specimen Pore Structure under HPAB.
Taking the conditions without confining pressure as an example, the microstructures of specimens at different positions from the blasthole under HPAB were characterized and analyzed. The pore parameters of the specimen before HPAB were used as the control group. The 3D reconstruction model is an effective means to characterize the distribution of real complex pore geometric space topological structure inside the medium. Therefore, the damage evolution characteristics and disturbance law at different positions under HPAB can be revealed from the microscopic point of view. 3D reconstruction models at different positions under HPAB are shown in Figure 8. Based on the 3D reconstruction model, the influence of HPAB on the pore size distribution and porosity is analyzed.

3.2.1. Influence of HPAB on the Pore Size Distribution.
The PNM can accurately and equivalently represent the geometrical spatial topology and distribution characteristics of pores. Therefore, the PNM is used to analyze the evolution law between the pore and throat at different positions from the blasthole after the HPAB test. The distribution of pore size in different positions under HPAB is analyzed by the statistics of the equivalent radius of the pore, length of the throat, and equivalent radius of the throat in the PNM. Comparison of specimen pore parameters at different positions under HPAB is shown in Table 5. The pore size distribution and throat size comparison at different positions under HPAB are shown in Figure 9.

The conclusions drawn from Table 5 and Figure 9 are as follows:
Compared with the control group, after HPAB the number of pores increased by 24.80, 12.88, and 5.59%, respectively; maximum equivalent radius of pore increased by 62.34, 42.60, and 15.43%; the average equivalent radius of pore increased by 48.82, 26.00, and 13.15%, respectively; the number of throats increased by 12.96 times, 4.13 times, and 1.48 times, respectively; maximum equivalent radius of throats increased by 52.15, 49.57, and 7.13%, and maximum channel length of throat increased by 56.06, 34.96, and 28.10%, respectively. In the control group, the average equivalent radius of pore in the range of 40–60 $\mu$m is the highest, accounting for 28.88%. The proportion of the equivalent radius of the pore in the range of 40–60 $\mu$m is decreased under HPAB. However, the equivalent radii of the pore of 25 and 100 mm away from the blasthole is the highest in the range of 80–100 $\mu$m, accounting for 29.18...
and 24.60%, respectively. The equivalent radius of the throat and channel length of the throat are concentrated in the range of 10–60 μm and 150–400 μm, respectively.

After the HPAB, the number and equivalent radius of pores and throats in the near zone have increased significantly, indicating that HPAB has a strong influence on the pore structure of the specimen. On the one hand, the stress wave generated by HPAB destroys the original pore structure and generates a certain number of new pores, which helps to increase the total number of pores. On the other hand, the stress wave will dilate the pore/fracture width, extend the original pores/fractures, and induce the evolution of originally closed pores to semi-closed pores and open pores. With the increase of the distance from the blasthole, the number of pores and microscopic cracks (throats) in the specimens in the middle and far zones decrease significantly. The HPAB has different effects on the specimens at different positions, and the damage degree of influence of the specimens depends to a large extent on the distance from the blasthole.

3.2.2. Effect of HPAB on Coordination Number. Coordination number is an important parameter reflecting the connectivity of pore geometry space topology. Coordination number is positively correlated with pore connectivity. The coordination number proportion of REVs at different locations under high-pressure gas blasting is shown in Figure 10.

As can be seen from Figure 10, in the control group, the maximum pore-throat coordination number in REVs is 6, and the proportion of pore-throat coordination numbers is mainly distributed in the range of 0–1, among which the proportion of pore-throat coordination number 0 is 80.14%. The pores with a coordination number of 0 can be considered isolated pores. The pore characteristics often show that the pore volume and area are small, basically disconnected from other fractures, and have little contribution to gas flow. In the 25 mm away from the blasthole after HPAB, the maximum pore-throat coordination number in REVs is 26, and the proportion of pore-throat coordination numbers is mainly distributed in the range of 0–8, among which the proportion of pore-throat coordination number 0 is 13.92%. Compared with the control group, the maximum pore-throat coordination number increased by 3.33 times, and the proportion of pore-throat coordination number 0 decreased by 82.63%. The increase in coordination number indicates that the connection between pores and throats is closer, which further shows that the HPAB can improve the three-dimensional pore structure and form three-dimensional channels with better connectivity.

However, with the increase of distance from the blasthole, the stress wave decays rapidly. The weak stress wave and high-pressure air have little influence on the pore structure in the middle and far zones. The maximum pore-throat coordination number and the concentration range of coordination number proportion in REVs show a decreasing trend. The maximum coordination numbers in REVs with 100 and 250 mm distance from the blasthole are 13 and 8, respectively. The proportions of pore-throat coordination numbers 0–8, among which the proportion of pore-throat coordination numbers 0–3, respectively. The proportions of pore-throat coordination number 0 are 42.36 and 61.59%, respectively. The stress wave generated by HPAB induces the formation of fractures between the connected isolated pores, which reduces the proportion of isolated pores and improves the connectivity between pore structures.

3.2.3. Effect of HPAB on Porosity. Porosity refers to the ratio of the material pore volume to the total volume, which is an important indicator reflecting the internal pore structure of materials. Through the porosity statistics of REV in the control group and different ranges (25, 100, and 250 mm away from the blasthole) after HPAB, the porosity comparison is shown in Figure 11.

![3D reconstruction model of different positions under HPAB.](image-url)
According to Figure 11, the average porosities of the control group, 25, 100, and 250 mm from the blasthole after HPAB are 7.53, 26.21, 15.47, and 11.09%. Compared to the control group, 25, 100, and 250 mm from the blasthole after HPAB increased by 248.07, 105.44, and 47.28%. Figure 6 shows that the stress wave generated by HPAB has a great influence on the pore morphology. In the control group, the internal pores of the specimen are mostly closed pores with a large random distribution, which is the main reason for low permeability. After HPAB, the pore development and expansion near the blasthole are mainly affected by stress wave, and the closed pores are transformed into semi-closed pores and microcracks in the specimen. With the increase of the distance from the blasthole, the stress wave encounters different wave impedance interfaces during the propagation process, resulting in the stress wave attenuating rapidly and forming a weak stress wave. The pore expansion in the middle and far regions is mainly caused by weak stress waves and high-pressure air penetration.

As the distance increases, the pore fissure expands slowly, resulting in the decrease of porosity.

Through formula fitting, it is found that the relationship between the porosity of REV and the distance from the blasthole decreases in a power function trend. The fitting equation is shown in Formula 1.

\[ l = \alpha \cdot \varphi^\beta \]  

(1)

In the formula, \( l \) is the distance between the porosity of REV and the blasthole (unit: mm); \( \varphi \) is the porosity of REV; and \( \alpha \) and \( \beta \) are correction coefficients.

Formula 1 is used to calculate the porosity of REV and the distance from the blasthole to obtain the disturbance range of high-pressure gas blasting. The porosity at different positions from the blasthole after HPAB is shown in Table 6. It is found that the maximum disturbance range of HPAB is 687 mm away from the blasthole, that is, the influence range can reach 114 times of the blasthole radius.

Figure 9. Comparison of pore size and throat dimensions at different positions under HPAB. (a) Pore size comparison and (b) pore size ratio. (c) Contrast the equivalent radius of throats and (d) contrast channel length of throats.
4. CONCLUSIONS

In this paper, the propagation law of the stress field in coal under HPAB is studied by using the HPAB system. The evolution characteristics of the pore structure in coal at different positions after HPAB are analyzed by using industrial CT and 3D reconstruction technology, and the following conclusions are drawn:

1. Through the HPAB test, it is found that there is no fracture zone around the blasthole with or without confining pressure. Without confining pressure, the crack direction is disordered. On the contrary, the crack expands along the \( \sigma_1 \) and \( \sigma_2 \) directions with confining pressure, while the expansion of other directions is inhibited. Compared without confining stress, the radial strain attenuation index decreases by 11.97% and the lateral strain attenuation index increases by 15.36% under confining pressure.

2. The 3D visualization of the microscopic pore structure inside the specimen is realized by constructing a 3D reconstruction model. It is found that the stress wave has a great influence on the pore structure in the near area through the 3D reconstruction model. Compared with the control group, 25 mm from the blasthole, the number of pores increased by 24.80%, the pore size range increased from 40–60 to 80–100 \( \mu \text{m} \), the number of throats increased by 12.96 times, the maximum equivalent radius of throats increased by 52.15%, and the maximum channel length of throat increased by 56.06%. The maximum pore-throat coordination number increased by 3.33 times, and the proportion of pore-throat coordination number 0 decreased by 82.63%. With the increase of the distance, the stress wave has little influence on the pore structure in the middle and far zones.

3. Through the porosity statistics of REVs before and after HPAB, it is found that REV has low porosity and poor connectivity before HPAB. The porosity of the specimen is increased by HPAB. With the increase of the distance from the blasthole, the porosity decreases in a power function trend. Through formula fitting calculations, the maximum disturbance distance under HPAB can reach nearly 110 times the blasthole radius.

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Table 6. Porosity at Different Positions from the Blasthole under HPAB

| porosity/% | Before HPAB | 25mm from blasthole | 100mm from blasthole | 250mm from blasthole |
|------------|-------------|---------------------|----------------------|---------------------|
| 26.21      |             |                     |                      |                     |
| 15.47      |             |                     |                      |                     |
| 11.09      |             |                     |                      |                     |
| 7.53       |             |                     |                      |                     |
| distance from blasthole/mm | 25 | 100 | 250 | 687 |

(a) Comparison of porosity (b) Relationship between average porosity and distance from the blasthole

Figure 10. Comparison of coordination numbers at different positions under HPAB.

Figure 11. Comparison of porosity at different positions under HPAB. (a) Comparison of porosity and (b) relationship between average porosity and distance from the blasthole.
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