Study on the Technology of Enhancing Permeability by Millisecond Blasting in Sanyuan Coal Mine

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To reduce gas disasters in low permeability and high-gas coal seams and improve gas predrainage efficiency, conventional deep-hole presplitting blasting permeability increasing technology was refined and perfected. The numerical calculation model of presplitting blasting was established by using ANSYS/LS-DYNA numerical simulation software. The damage degree of coal and rock blasting was quantitatively evaluated by using the value range of the damage variable $D$. According to the actual field test parameters of coal seam #3 in the Sanyuan coal mine, $D_{lim} = 0.81–1.0$ was the coal rock crushing area, $D_{lim} = 0.19–0.81$ was the coal rock crack area, and $D_{lim} = 0–0.19$ was the coal rock disturbance area. By comparing and analysing the damage distribution nephogram of coal and rock mass under the influence of different millisecond blasting time interval and the blasting effect of simulation model, the optimal layout parameters of multilayer through cracks were obtained theoretically. And, the determined parameters were tested on the working face of the 1312 transportation roadway in coal seam #3 of the Sanyuan coal mine. The permeability effect was compared and analysed through the analysis of the gas concentration, gas purity, and mixing volume before and after the implementation of deep-hole presplitting blasting antireflection technology, as well as the change of gas pressure, attenuation coefficient, permeability coefficient, and other parameters between blasting coal seams. The positive role of millisecond blasting in reducing pressure and increasing permeability in low permeability and high-gas coal seam were determined.

1. Introduction

Coal seam gas predrainage technology is considered to be one of the most effective measures to prevent coal mine gas disasters [1]. However, with increasing mining depth, the gas pressure of the coal seam increases and the permeability decreases, which seriously affects the gas predrainage effect. In engineering practice, the deep-hole presplitting blasting permeability increasing technology can produce multiple cracks in the coal body of a low permeability coal seam forming an underground fracture network channel, which can greatly improve the gas drainage efficiency and reduce or even eliminate the hidden dangers in the gas mining process [2–5].

Research on deep-hole presplitting blasting in high-gas coal seams began in the last century. Paine et al. [6] established the corresponding mathematical model by taking the change in gas generated by blasting holes and the change in ground stress before and after blasting as variables and summarized the corresponding expression and solution method. Roy et al. [7] carried out field experimental research on blasting drilling data parameters explosion parameters, and gas risk by using new blasting technology. Singh et al. [8] studied the technology of controlled blasting to increase the permeability of a partially collapsed coal face caused by deep-hole presplitting. Chen et al. [9] proposed the deep-hole presplitting blasting for weakening thick hard roofs to mitigate strong strata behaviours. Aliabadian and Sharafisafa [10] investigated the effect of presplitting on the generation of a smooth wall in a rock domain under the blasting process in a continuum rock mass. Chen et al. [11] drew the
following conclusion through experimental research: when the blasting control hole is in the blasting fracture zone of the goaf, the development direction of the crack can be effectively controlled, which can not only meet the requirements of blasting but also improve the gas drainage efficiency. With the rapid development of computer technology, numerical simulation has become an important means to study the theory and technology of rock blasting. Valiappan et al. [12] analysed and discussed the detailed situation of rock blasting by using the finite elements calculation program software. Chu and Yang [13] used the relevant knowledge of mechanics to analyse the loss fracture criterion of coal mass after blasting. The results show that the stress wave can not only help the extension of primary fractures but also accelerate the generation of a small number of new cracks, which plays a role in pressure relief for enhancing the permeability of the coal seam. Xu et al. [14] analysed various factors that may affect the permeability enhancement effect of presplitting blasting by means of finite element software simulation, which has practical significance for the field application of presplitting blasting. Xue and Teng et al. [15] used five different initial fractured permeability to study the influence of the initial permeability on extraction efficiency. The results show that the higher the initial fracture permeability is, the faster the fracture formation rate is. At the beginning of production, the 5 types of initial permeability vary greatly. Xue and Liu et al. [16] analysed the damage mechanism and crack propagation process of coal, and the results show that the evolution process of permeability and elastic modulus is consistent with the evolution process of damage. The failure of coal unit leads to the decrease of elastic modulus and bearing capacity and also leads to the increase of permeability.

The abovementioned scholars have performed some research on the presplitting blasting technology. However, the existing theoretical knowledge of controlled blasting is based on rock masses as the analysis object of experimental research. At present, coal and gas in mines are in the same space, and they complement each other as a whole. If we do not consider the existence of gas in the coal seam and only study the coal and rock mass as a single solid medium, some errors exist compared to the actual situation. Therefore, in view of the technical problem of difficult gas drainage in the 1312 working face of coal seam #3 in the Sanyuan coal mine of China, a new technology of deep-hole presplitting blasting with millisecond blasting as the core is proposed by using solid fluid coupling method, and the blasting scheme is optimized by simulating different millisecond blasting time intervals. The results of field test and comparative analysis show that the blasting has achieved the expected effect, which has a certain reference significance for the gas control of similar coal mines in the same area.

2. Mathematical Model and Boundary Conditions

2.1. Mathematical Model. Solid basic theory and a variety of algorithms are the foundation of the powerful function of LS-DYNA. The following is a brief introduction to its basic theory [17–19].

2.1.1. Momentum Conservation Equation.

\[
\frac{\partial \sigma_{ij}}{\partial x_j} + \rho f_i = \rho x_i, \quad (1)
\]

where \( \sigma_{ij} \) is the stress vector, \( x \) is the acceleration of the particle (m (s\(^{-2}\))), \( \rho \) is the gas density (kg (m\(^{3}\))\(^{-1}\)), and \( f_i \) is the mass volume force.

The displacement boundary conditions shall meet the following requirements:

\[
x_i = \bar{x}_i, \quad (2)
\]

where \( \bar{x} \) is the displacement function on the displacement boundary.

The stress boundary conditions shall meet the following requirements:

\[
\sum_{j=1}^{3} \sigma_{ij} n_i = \bar{T}_i, \quad (3)
\]

where \( n_i \) is the configuration boundary and \( \bar{T}_i \) is the force load on the boundary.

2.1.2. Conservation Equation of Mass.

\[
\rho = j \rho_0, \quad (4)
\]

where \( \rho \) is the gas density (kg (m\(^{3}\))\(^{-1}\)), \( \rho_0 \) is the initial density (kg (m\(^{3}\))\(^{-1}\)), and \( j \) is the relative volume.

2.1.3. Energy Conservation Equation.

\[
E^* = V_s S_{ij} \varepsilon_{ij} - \left( P_g + q^* \right) V, \quad (5)
\]

where \( E^* \) is the energy, \( V \) is the configuration volume (m\(^3\)), \( S_{ij} \) is the deviator stress (MPa), \( \varepsilon_{ij} \) is the strain rate tensor, \( P_g \) is the pressure (MPa), and \( q^* \) is the volume viscous resistance (Pa).

2.2. Selection of Material Model and Determination of Parameters

2.2.1. Material Selection of the Coal Model. We more accurately express the large deformation failure mechanism of coal and rock under dynamic loading, and elastic-plastic dynamic material is used for the coal material. Detailed material parameters are shown in Table 1.

2.2.2. Material Selection of the Air Model. The Unit * MAT_NULL air material model provided in the program is selected in this paper, and the equation of state can be expressed as equation (6). The * EOS_LINEAR_POLYNOMIAL keyword in the system is used to define the equation of state:

\[
P = C_0 + C_1 \mu + C_2 \mu^2 + C_3 \mu^3 + (C_4 + C_5 \mu + C_6 \mu^2) Q, \quad (6)
\]

where \( C_1, C_2, C_3, C_4, C_5, \) and \( C_6 \) are the material parameters and \( Q \) is the internal energy per unit volume (GPa). Detailed air material parameters are shown in Table 2.
2.2.3. Damage Variable D. The damage equation is as follows:

\[ E = (1 - D)E_0, \]

where \( D \) is the damage variable, \( E \) is the elastic modulus of the damaged element, and \( E_0 \) is the elastic modulus of the lossless element.

When the shear stress reaches the Mohr–Coulomb criterion damage threshold,

\[ F = \sigma_\text{f} - \sigma_\text{f} = \frac{1 + \sin \psi}{1 - \sin \psi} \geq f_\text{cr}, \]

where \( F \) is the shear stress (MPa), \( \sigma_\text{f} \) and \( \sigma_\text{f} \) are static and dynamic failure strengths (MPa), \( \psi \) is the angle of internal friction (°), and \( f_\text{cr} \) is the compressive strength (MPa).

The damage variable \( D \) is expressed as

\[ D = \begin{cases} 0, & \varepsilon < \varepsilon_{\text{c}0}, \\ 1 - \frac{f_\text{cr}}{E_0}, & \varepsilon_{\text{c}0} \leq \varepsilon \leq \varepsilon_\text{r}, \\ 1, & \varepsilon \geq \varepsilon_\text{r}, \end{cases} \]

where \( f_\text{cr} \) is the compressive residual strength (MPa), \( \varepsilon_{\text{c}0} \) is the maximum compressive strain, and \( \varepsilon_\text{r} \) is the residual strain.

The permeability coefficient of the corresponding unit is expressed as follows:

\[ \lambda = \begin{cases} \lambda_0 e^{-\beta_1 \varepsilon_\text{c}}, & D = 0, \\ \xi \lambda_0 e^{-\beta_1 \varepsilon_\text{c}}, & D > 0, \end{cases} \]

where \( \lambda_0 \) is the air permeability coefficient \((\text{m}^2/(\text{MPa}^2 \cdot \text{d}^{-1}))\), \( \xi \) is the increasing factor of the permeability coefficient \((\text{m}^2/(\text{MPa}^2 \cdot \text{d}^{-1}))\), \( \beta_1 \) is the gas pressure coefficient, and \( \beta_2 \) is the stress influence coefficient.

When the element reaches the damage threshold of tensile strength \( f_\text{cr} \),

\[ \sigma_\text{c} \leq -f_\text{cr}. \]

The damage variable \( D \) is expressed as follows:

\[ D = \begin{cases} 0, & \varepsilon \leq \varepsilon_{\text{c}0}, \\ 1 - \frac{f_\text{cr}}{E_0}, & \varepsilon_{\text{c}0} \leq \varepsilon \leq \varepsilon_\text{tu}, \\ 1, & \varepsilon \geq \varepsilon_\text{tu}, \end{cases} \]

where \( f_\text{cr} \) is the tensile residual strength (MPa), \( \varepsilon_\text{r} \) is the residual strain, and \( \varepsilon_{\text{c}0} \) is the maximum tensile strain.

The corresponding unit permeability coefficient is described as follows:

### Table 1: Rock material parameters.

| Name          | Coal rock density | Elastic modulus | Poisson’s ratio | Tensile strength | Compressive strength | Cohesion | Internal friction angle |
|---------------|------------------|-----------------|-----------------|------------------|----------------------|----------|------------------------|
| Value         | 1.42 g/cm         | 0.855 GPa       | 0.323           | 1.909 MPa        | 10.848 MPa           | 1.142 MPa| 40°                     |

### Table 2: Air material parameters.

| Name          | C_0 | C_1 | C_2 | C_3 | C_4 | C_5 | C_6 | Q        |
|---------------|-----|-----|-----|-----|-----|-----|-----|---------|
| Value         | 1.29 E^{-5} | 0   | 0   | 0   | 0.4 | 0.4 | 0   | 0.025   |

| Density Unit g/cm | C_0 | C_1 | C_2 | C_3 | C_4 | C_5 | C_6 | Q |
|-----------------|-----|-----|-----|-----|-----|-----|-----|---|
| g/cm            | g/cm | g/cm | g/cm | g/cm | g/cm | g/cm | g/cm | GPa |

\[ \lambda = \begin{cases} \lambda_0 e^{-\beta_1 \varepsilon_\text{c}}, & D = 0, \\ \xi \lambda_0 e^{-\beta_1 \varepsilon_\text{c}}, & 0 < D < 1, \\ \xi^2 \lambda_0 e^{-\beta_1 \varepsilon_\text{c}}, & D = 1 \end{cases} \]

where \( \xi \) is the increasing factor of the permeability coefficient \((\text{m}^2/(\text{MPa}^2 \cdot \text{d}^{-1}))\).

**Damage constitutive model of coal in combination of coal and rock under dynamic load:**

\[ \sigma = \frac{(1 - D)E_1}{E_1 + \delta E_2} + \frac{\eta}{dt} \]

where \( \sigma \) is the damage constitutive model in three-body combination of coal and rock under dynamic load.

\[ \lambda = \begin{cases} \lambda_0 e^{-\beta_1 \varepsilon_\text{c}}, & D = 0, \\ \xi \lambda_0 e^{-\beta_1 \varepsilon_\text{c}}, & 0 < D < 1, \\ \xi^2 \lambda_0 e^{-\beta_1 \varepsilon_\text{c}}, & D = 1 \end{cases} \]

where \( \xi \) and \( \beta_1 \) are the constants, \( \varepsilon \) is the strain, and \( D \) is represented by equation (9).

### 2.3. Boundary Condition. When LS-DYNA is used to simulate deep-hole presplitting blasting, the following boundary conditions are applied to the numerical model according to the actual situation and the relevant needs of the simulation: the upper boundary of the model will be affected by the self-weight stress of the coal and rock mass. It can be expressed as follows:
\[ q = \gamma g H, \]

where \( q \) is the top pressure (kN/(m\(^2\))\(^{-1}\)), \( \gamma \) is the average bulk density of the coal seam (kN/(m\(^2\))\(^{-1}\)), \( g \) is taken as 1.35 t/(m\(^3\))\(^{-1}\), \( H \) is the buried depth of the coal seam (m), and \( H \) is taken as 900 m.

\[ q = 900 \times 9.8 \times 1.35 = 11907 \text{ kN} / \text{m}^2 = 11.907 \text{ MPa}. \]

To optimize the simulation, the pressure \( q \) on the upper boundary is set as 12 MPa.

2.4. Construction of the Numerical Model. Based on the actual situation of 1312 working face in No. 3 coal seam, the numerical model of double blasting hole was established with the size of 25 m × 25 m, and the calculation was carried out by solid fluid coupling. It was divided into 1000 × 1000 units, as shown in Figure 1. In this paper, the in situ stress of No. 3 coal seam is 15 MPa, which is obtained according to the underground measurement of No. 3 coal seam. In the numerical simulation in this paper, 15 MPa is directly set according to the actual situation, and the lateral pressure coefficient is set to 1.5, that is, the horizontal stress is 20 MPa. Horizontal constraints were added at both ends of the model and fixed at the bottom to move vertically. Because the test site was an infinite space, and the size of the numerical simulation model was limited, the problem analysis could only be carried out in a limited area. Therefore, adding nonreflection boundary conditions around the model could effectively eliminate the limitation of the model boundary.

3. Analysis of Numerical Simulation Results

3.1. Simulation Analysis of Hole Spacing Optimization in Millisecond Blasting. In the process of deep-hole presplitting millisecond blasting, when the tangential tensile stress of each point on the connecting line of adjacent blasting holes is greater than or equal to the tensile strength of the coal and rock, the crack propagation between boreholes will form a connection near the centre of the line of two holes. To achieve the best blasting effect, it is necessary to optimize the hole spacing of multi-hole blasting. To test the penetration effect between boreholes, the coal damage coefficient \( D \) was used to characterize the stress characteristics of the medium.

The penetration of cracks between holes with different hole spacings is shown in Figure 2. By observing the final development morphology of the cracks in the damage nephogram of different hole spacing, it can be seen that when the distance between adjacent holes is 5.5–6.0 m, the cracks between holes can form through. When the distance between adjacent holes is 5.0 m, the damage area \((D = 0.81 – 1)\) between the two holes is large, resulting in a large area of crushing area. To sum up, if the hole spacing is too large, the stress wave superposition effect will be weakened, and the adjacent holes cannot be connected smoothly. If the hole spacing is too small, it will cause a large area of coal fragmentation. Therefore, 5.5 m is selected as the best spacing to ensure the through effect of cracks and save cost for the project.

3.2. Simulation Analysis on Delay Time Optimization of Millisecond Blasting. This paper studies the influence of delayed blasting on the permeability enhancement effect by simulating the different initiation times of blasting holes to seek the best millisecond blasting time. According to field observations and research, the commonly used differential interval time is 15–75 ms, usually 25–30 ms [20,21]. Considering the actual situation of the Sanyuan coal mine and taking the millisecond time of the high-precision detonator as the standard, the millisecond blasting time is set as 0, 17, 25, and 42 ms, and the numerical model experiment is carried out in four groups.

Figure 3 shows that a stress intersection will occur at a certain time after two blasting holes are detonated successively. Therefore, when the time interval of millisecond blasting is different, the distribution range of damage will be different. Taking Figure 3(a) with a delay time of 0 ms as the control group, the crushing area of damage degree \( D \) is basically the same, which is smaller than that of double hole simultaneous blasting. The results show that although delayed blasting cannot change the energy produced at the moment of explosion, the stress produced by blasting can be superimposed better by the time difference, and the action time on the medium can be prolonged to achieve the best blasting effect. It is not difficult to see from Figure 3 that when the millisecond blasting time interval is 25 ms, the most of coal body damage degree \( D \) is concentrated in the range of 0.19–0.81. The results show that when the interval of millisecond blasting is 25 ms, the development of coal and rock fissures is better, the effect of stress wave on medium is stronger, and the blasting effect is the best, which is helpful for gas drainage. Combined with the actual situation, the time interval of millisecond blasting is set as 25 ms.

3.3. Influence of Control Hole on the Millisecond Blasting Effect. In the actual blasting engineering, to improve the fracturing effect of coal and rock masses and reduce the cost, in addition to considering the above condition parameters, the role of the control hole is also particularly important. Based on the results of a previous study, the influence of the
control hole is analysed by numerical simulation. Two groups of simulation experiments were established. The distance between holes was 5.5 m, and the interval of millisecond blasting was 25 ms. The control holes were taken as the control variables. The simulation results are shown in Figures 4 and 5.

It can be seen from Figures 4 and 5 that after blasting, the effect range of stress produced by blasting is different with or without the influence of the control hole, and the damage range is wider due to the control hole. Especially when the blasting is carried out to 210 us, a large range of cracks will appear in the coal body under the two groups of experiments. However, the damage area with the control hole was larger than that without the control hole, and the stress was more concentrated. The results show that the control hole can not only control the direction of energy transfer but also improve the comprehensive effect of blasting, so that the stress action time is longer and the coal fracture development is more sufficient.

In the process of millisecond shaped charge blasting, the superposition effect of new free surface and stress wave is the key factor to promote the expansion of blasting cracks and the formation of derived cracks. The coal undergoes two blasting actions in a short time, and the second blasting makes use of the residual stress field formed by the first blasting to increase the...
density of blasting cracks. The explosion stress wave diffracts at the tip of fracture surface, and multiple reflections and superposition occur between fracture surfaces to form derived fractures. The control hole effect of the post blasting hole makes the tensile stress field near the hole wall form, which is conducive to the formation of cracks in the direction of energy accumulation. The micro difference time and the spacing between the holes are important factors affecting the characteristics of the explosion fracture expansion. Under the condition of the other conditions unchanged, the joint action of the micro difference time and the spacing of the blasthole determines the development of the explosive fracture. When the propagation distance of the stress wave generated by the first blasting hole in millisecond time is less than the distance between the two blasting holes, the superposition of the explosion stress wave in the coal body between the two blasting holes is conducive to the formation of cracks.

4. Field Industrial Test

4.1. Overview of the Test Sites. The test site is located at the 1312 transport roadway working face of coal seam #3 in the Sanyuan coal mine. The working face faces 1310 in the east, Shangqin village in the south, Changzhi South Station in the
4.2. Investigation on Permeability Enhancement Effect of Deep Hole Presplitting Millisecond Blasting

4.2.1. Determination of Relevant Parameters of Blasting Drilling. The test was carried out at a 400 m distance from the working face of 1312 transport roadway in No. 3 coal seam of the Sanyuan coal mine. The first group was the conventional blasting group, which constructed three blasting holes with the drilling spacing of 5.5 m, and the distance between the observation hole and the blasting hole was 2.25 m. The first group was a conventional blasting group. Three blasting holes were constructed with a spacing of 5.5 m. The conventional blasting method of simultaneous blasting was adopted for the experiment. The blasting holes were numbered #0, #1, and #2. The second group was millisecond blasting group. Three blasting holes were also constructed, the drilling spacing was 5.5 m, and the millisecond blasting time was set as 25 ms. The blasting holes were numbered as #7, #8, and #9, and the blasting was started from the #7 blasting hole in turn. The third group was the natural extraction group. Four natural drainage holes were constructed, numbered #14, #15, #16, and #17. Meanwhile, in order to avoid the influence of seismic shock wave, the three groups of experiments were separated by 35 m. The layout of the boreholes was shown in Figure 6. After the completion of borehole sealing, the drainage pipeline, drainage concentration, and drainage flow detection equipment should be installed to conduct gas drainage for 30 days. The permeability enhancement effect of deep-hole presplitting millisecond blasting with optimized parameters was determined by investigating the variation in natural gas emissions, coal seam permeability coefficient, and presplitting blasting cracking effect.

4.2.2. Natural Gas Emission Characteristics of Borehole. Observation hole #11 and common extraction hole #15 of the 1312 working face of coal seam #3 were selected to measure the natural discharge flow of boreholes. Through the integration of monitoring data, the attenuation curves of boreholes #11 and #15 were fitted, as shown in Table 3 and Figure 7.

According to the comparison of the natural gas emission law of #11 millisecond blasting observation borehole and #15 normal drainage borehole in Table 3, it can be seen that after millisecond blasting, the attenuation coefficient of gas flow in borehole decreases from $\alpha_{15} = 0.10966 \text{ d}^{-1}$ of #15 hole to $\alpha_{11} = 0.03548 \text{ d}^{-1}$ of #11 hole, i.e., $\alpha_{11} = 0.3235\alpha_{15}$, which indicates that the attenuation intensity of gas emission in borehole is reduced by 67.65% after the implementation of deep-hole presplitting millisecond blasting technology in 1312 working face, which means that the pore structure of coal body is changed by presplitting millisecond blasting, which is conducive to the continuous gas drainage.

After measuring the natural discharge flow of observation hole #11 and ordinary extraction hole #15, these two holes should be blocked to prevent them from being in an open discharge state to avoid affecting the blasting hole and surrounding extraction hole.

4.2.3. Test on Change of Coal Seam Permeability Coefficient. The arrangement of boreholes for measuring the permeability coefficient of the coal seam is shown in Figure 8, and the parameters are shown in Table 4. To obtain the accurate permeability coefficient, all coal mines in China adopt the method of underground measurement. The calculation formula is shown in Table 5 below. Where $A^*$ and $B^*$ can be calculated by the actual parameters obtained by measurement.

According to the calculation formula of the permeability coefficient [22], the permeability of the original coal seam is increased from $0.0852 \text{ m}^2(\text{MPa}^{-2}\text{d}^{-1})$ to $2.565 \text{ m}^2(\text{MPa}^{-2}\text{d}^{-1})$ to $3.278 \text{ m}^2(\text{MPa}^{-2}\text{d}^{-1})$ after deep-hole presplitting millisecond blasting, which is more than 30 times higher than that of the original coal seam, and the coal seam permeability is greatly improved.

4.3. Comparison of the Gas Drainage Effect. The most direct purpose of deep-hole presplitting blasting is to make a large number of cracks in coal, so as to improve the permeability of coal and rock mass. Therefore, the curve was drawn by monitoring and recording the changes in gas concentration, gas purity, and gas mixture parameters in the gas drainage pipeline to judge the gas drainage effect before and after blasting. The observation time was 40 days. The gas concentration is shown in Table 6.

It can be seen from Table 5 and Figure 9 that the gas concentration of the first group of conventional blasting observation holes fluctuates between 23.3% and 39.7%, and the average gas concentration is 25.58%. The second group of millisecond blasting observation hole gas concentration in 28.4%–48.9%, and the average gas concentration was 37.60%. The gas concentration of the third group fluctuates from 15.0% to 23.6%, and the average gas concentration is 17.44%. The average gas concentration of conventional blasting is 1.47 times higher than that of natural drainage, and the average gas concentration of millisecond blasting is 2.16 times higher than that of natural drainage. The period of gas drainage is longer and the drainage effect is better.

It can be seen from Figure 10 that the gas purity range of single hole in the first group of conventional blasting observation holes #3 to #6, fluctuates between 0.054 and 0.096 m$^3$·min$^{-1}$, and the average borehole purity is 0.0715 m$^3$·min$^{-1}$. In the second group of millisecond...
Table 3: Results of natural gas gushing from a 100-meter borehole of the working face.

| Borehole number | Gushing law \( q_t = q_i e^{-\alpha t} \) | Initial gas emission intensity \( q_i \) | Attenuation coefficient of natural gas flow in the borehole | \( \alpha \) |
|-----------------|---------------------------------|-------------------------------|---------------------------------|----------------|
| #11             | \( q_i = 0.4175 e^{-0.03548t} \) | 0.4175                        | 0.03548                          | 0.03548        |
| #15             | \( q_i = 0.1045 e^{-0.10966t} \) | 0.1045                        | 0.10966                          | 0.10966        |

Figure 6: Schematic diagram of drilling construction at the test site.

Figure 7: Characteristics of natural gas emissions from 100 boreholes. (a) Fitting curve of gas emission and (b) fitting curve of gas emission.

Figure 8: Schematic diagram of the drilling of coal seam permeability coefficient construction at the test site.
It can be seen from Figure 11 that the range of gas mixture in single hole of the first group of conventional blasting observation holes #3–#6, fluctuates between 0.40 and 0.82 m³/min⁻¹, and the average mixing amount of boreholes is 0.6094 m³/min⁻¹. In the second group of millisecond blasting, the single hole gas mixture of observation holes #10–#13, varies from 0.56 to 1.45 m³/min⁻¹, and the average single hole gas mixture is 0.8425 m³/min⁻¹. In the third group of natural drainage holes #14–#17, the single hole gas drainage volume fluctuates between 0.05 and 0.35 m³/min⁻¹, and the average borehole mixing amount is 0.1975 m³/min⁻¹. The results show that the average gas mixture of the conventional blasting group is 3.21 times that of the natural drainage group and that of the millisecond blasting group is 4.73 times that of the natural drainage group.

In summary, after the implementation of deep-hole presplitting millisecond blasting, the cracks in the coal body are extended, which greatly improves the coal seam gas drainage.
Figure 9: Comparison of gas concentration in borehole.

Figure 10: Single hole gas scalar comparison.
The presplitting blasting causes irreversible new cracks in coal. This shows that deep-hole presplitting millisecond blasting technology is effective in promoting gas drainage in the Sanyuan coal mine.

5. Conclusions

(1) The damage degree of coal rock blasting is quantitatively evaluated by using the value range of damage variable $D$. According to the actual field test parameters of coal seam #3 in the Sanyuan coal mine, when $D_{lim}$ is equal to 0.81–1.0, it is a coal rock crushing area. When $D_{lim}$ is equal to 0.19–0.81, it is a fracture zone. When $D_{lim}$ is equal to 0–0.19, it is a coal rock disturbance area.

(2) The blasting model under different millisecond blasting time parameters is established, and the blasting parameters are optimized by using ANSYS/LS-DYNA software. The blasting cracking effect is analysed by observing the cloud chart of coal damage distribution. Taking the distribution characteristics of the coal blasting damage area as the evaluation index, the hole spacing of millisecond blasting is determined to be 5.5 m, the time interval of millisecond blasting is controlled at 25 ms, and the permeability enhancement effect is better.

(3) According to the results of numerical simulation, the best blasting parameters are tested on-site. The results are as follows: after millisecond blasting, the attenuation coefficient of borehole gas flow is reduced from 0.10966 d$^{-1}$ to 0.03548 d$^{-1}$. The attenuation intensity of borehole gas emission is reduced by 67.65%. The permeability of original coal seam is increased from 0.0852 m$^2$·(MPa$^{-2}$·d)$^{-1}$ to 2.565 m$^2$·(MPa$^{-2}$·d)$^{-1}$, which is more than 30 times higher. Compared with conventional blasting and millisecond blasting, it can be concluded that the average gas concentration of drilling hole is increased by 1.47 times and 2.16 times by conventional blasting and millisecond blasting, respectively; the average gas purity is increased by 3.21 times and 4.73 times; and the average gas mixing amount is increased by 3.09 times and 4.27 times. It is not difficult to see that the gas drainage effect of millisecond blasting is better than that of conventional blasting.

Data Availability

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

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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