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Pertinence Study on the Permeability and Mining-induced Stress of Coal Mass

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Abstract

Gas extraction is an effective measure for reducing gas accidents in the colliery; however, extracting gas in coal with low permeability is difficult. To obtain the influential law of mining-induced stress on the permeability of coal and improve the effect of gas extraction, this study took the 17218 face of Zhangji Coal Mine under Huainan Mine Industry Group as the engineering background to set the measurement station at both the return airway and haulage roadway of the face, establish the FLAC3D numerical calculation model, and comprehensively analyze the evolution laws of mining-induced stress, gas flow, gas extraction amount, and coal mass failure characteristic during the actual mining process at the face. Research results showed that during the actual mining process at the face, gas flow and mining-induced stress showed the same changing law, and the permeability of coal mass was controlled by mining-induced stress. The peak of coal stress at the side of the return airway, the degree of stress concentration, and its scope of influence were all large. The coal failure scope and degree at the side of the return airway were all large and the permeability of coal mass was high. The permeability of coal mass in the zone in which the stress was reduced at the face was the highest. The gas concentration could be significantly reduced if on-site technicians extract the gas in the stress reduction zone. The research findings enrich the theoretical research on coal permeability and provide the basis for effective gas extraction.

Keywords: Coal Mass, Permeability, Mining-induced Stress, Gas Flow, Failure Characteristic

1. Introduction

Gas is a kind of natural gas occurring in coal. In coal resource exploitation, a substantial amount of gas is poured into the mining space under the effect of mining-induced stress. The sudden release of gas easily causes gas explosion, coal and gas outburst, and other disasters and accidents. Numerous scientific researchers and on-site technicians have conducted long-term and in-depth exploration and gradually developed a set of gas control systems with gas extraction as the core to prevent gas-related accidents [1], [2]. Gas extraction has been successfully applied in numerous mining areas to significantly reduce the gas content in coal mass and prevent gas-related accidents [3], [4], [5], [6].

The permeability of coal mass is a key factor affecting the influence of gas extraction. Before coal mining, the coal mass will not be damaged or destructed under balanced loading. Given the small number of cracks within the coal mass, its permeability is generally low. The absence of a smooth channel for gas flow is not conducive to gas extraction. Mining disturbance breaks the original stress distribution balance of coal mass. Stress redistribution caused by mining leads to coal mass deformation, cracking, and even movement. Mining-induced stress can significantly increase the permeability of coal mass, which creates a conducive environment for gas extraction. Pertinence study on the permeability and mining-induced stress of coal mass has engineering application significance to gas extraction.

2. State of the art

Numerous local and foreign scholars have conducted a substantial amount of studies on the permeability of coal mass through theoretical model analysis, laboratory testing, and field measurement, thereby achieving rich results [7], [8], [9], [10], [11]. They have successively established various forms of coal permeability models with Palmer-Mansoori model [12], Shi-Durucan model [13], Cui-Bustin model [14], and Robertson-Christiansen model [15] as the representatives. These theoretical models provide a foundation for coal permeability calculation. However, the models usually have numerous assumptions; therefore, reflecting the actual situation of coal permeability is difficult. In laboratory testing research, Ma et al. [16] used the broken rock mass compaction and permeability test device to determine the permeability of broken coal mass through the compaction test. Perera et al. [17] examined coal permeability under different temperatures. A few scholars also established the test conditions according to the specific stress status of coal mass to carry out the test research on coal permeability under different stress conditions. For example, Liu et al. [18] simulated the uniaxial strain conditions in the laboratory to test the evolution law of the permeability of coal samples with pore pressure and confining pressure. Feng et al. [19] studied the change law of coal permeability with effective stress and coal matrix

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shrinkage under the uniaxial compression condition using the indoor pressure pulse decay method. Wei et al. [20] tested the permeability of loading coal that contains gas to study the differences and similarities in terms of permeability between coal briquette and raw coal, which both contain gas. The laboratory test studied various factors affecting coal permeability from several perspectives. However, the on-site mining conditions are different from laboratory test conditions; therefore, applying the research results of the laboratory test into engineering is difficult. Owing to the limited on-site condition in the coal field, the present practical measurement results on coal permeability are relatively limited. The on-site measurement results can reflect coal permeability; thus, research on coal permeability in the coal field need to be carried out. Thus, the paper took the geological and mining technical conditions of the 17218 face of Zhangji Coal Mine under Huainan Mine Industry Group to study the evolution laws of coal stress field, failure field, and gas flow through on-site measurement and numerical simulation and to analyze the pertinence between the permeability and mining-induced stress of coal mass with gas flow characterized by coal permeability.

The paper is arranged as follows. Part 2 introduces the research status of coal permeability. Part 3 provides the specific programs of on-site measurement and numerical simulation research. Part 4 analyzes the research results of coal mining-induced stress, gas flow, gas extraction amount, and failure characteristics. Part 5 presents the research conclusion.

3. Methodology

3.1 Geological Conditions of the Coal Seams

The west of the 17218 face of Zhangji Coal Mine under Huainan Mine Industry Group is the belt roadway at the north wing of No. 8 coal seam of the Beiyi mining area, and its south is the goaf of the 17228 face. A protective coal pillar with a width of 7 m exists at the goaf between the 17218 face and the 17228 face. The north of the 17218 face is an F216-5 fault, and its east is the solid coal. The slope of 17218 face is 1,484-m long, and its strike is 1,484-m long. The coal seam is 3.83-m thick on average with an average angle of 4°. The direct roof of the coal seam is sandy mudstone with an average thickness of 3.5 m. The direct bottom of the coal seam is sandy mudstone with an average thickness of 4.23 m. The old roof is fine sandstone with an average thickness of 10.0 m. Figure 1 shows the geological conditions of coal seams.

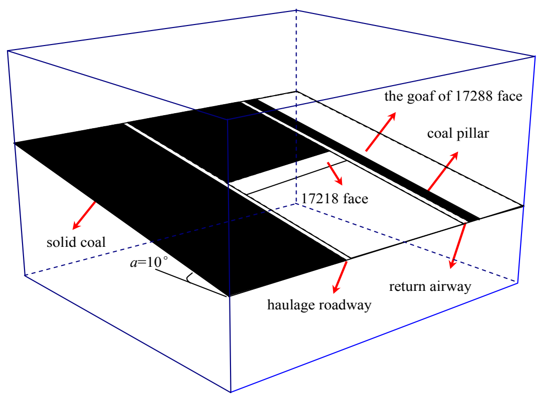


Fig. 1. Diagram of the Geological Conditions of Coal Seams

3.2 On-site Measurement Program

The detectors set up two stations at the return airway and haulage roadway of the 17218 face to detect the changes in mining-induced stress, gas pressure, and coal failure characteristics when mining in the working face. These two stations were 90 m and 120 m away from the face. The stress meter hole and the gas flow hole were drilled at each station. The stress meter hole was 10-m long with a diameter of 42 mm, and the gas flow hole was 30-m long with a diameter of 92 mm. The spacing between these two holes was 5 m. The detectors installed the stress meter and gas flow monitor through drilling. Along the advance direction of the face, the detectors conducted the bedding drilling at 5 m, 15 m, and 25 m away from the face. The holes were 10 m in depth and were 42 mm in diameter. Then, they used the mining omni-directional drilling peep instrument to observe the crack development of the coal mass. To detect the change in the amount of gas extraction, the detectors arranged bedding drilling holes at the return airway and haulage roadway of the face for gas extraction according to the mining technical conditions of 17218. The specific station layout is shown in Figure 2.

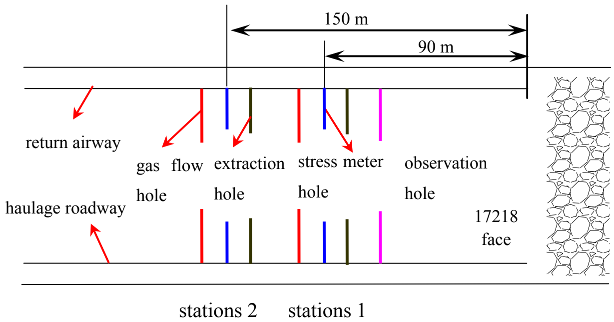


Fig.2. Diagram of the Station Layout

3.3 Numerical Simulation Research Program

The 3D calculation model of the 17218 face was established by using the numerical simulation software FLAC3D. The model was 541.8-m long, 500-m wide (slope), and 357.6-m high. The model included coal seam, roof strata, and floor strata with a 3.8-m-thick coal seam. The side of the model limited horizontal movement, and its bottom limited vertical movement. The vertical load was applied on the upper model. The weight of the overlying strata of the model was replaced by the vertical load. The calculation model is shown in Figure 3.

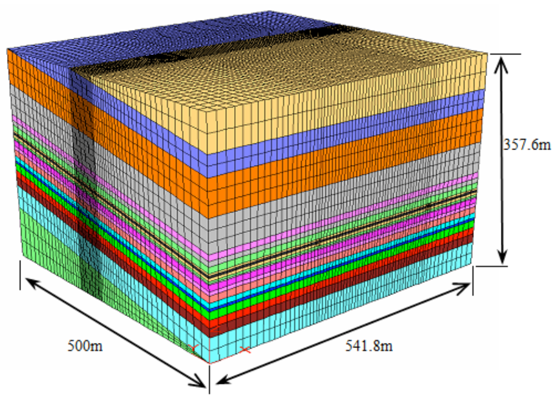


Fig.3. Numerical Calculation Model

In the calculation process, the Mohr-Coulomb yield criterion was used to determine whether the rock mass was damaged. If the mechanical state of the rock mass satisfied Formula (1), the rock mass was considered damaged.

$$f_s = \sigma_1 - \sigma_3 \frac{1+\sin\phi}{1-\sin\phi} - 2c\sqrt{\frac{1+\sin\phi}{1-\sin\phi}} \quad (1)$$

In the formula, σ_1 and σ_3 were the maximum and minimum principal stresses of the rock mass, respectively; and c and φ were the cohesive force and internal friction angle, respectively. When $f_s > 0$, shear failure occurred to the rock mass. In a usual stress state, the rock mass has low tensile strength; therefore, the tensile strength principle can be used to determine the occurrence of tension damage to the rock mass.

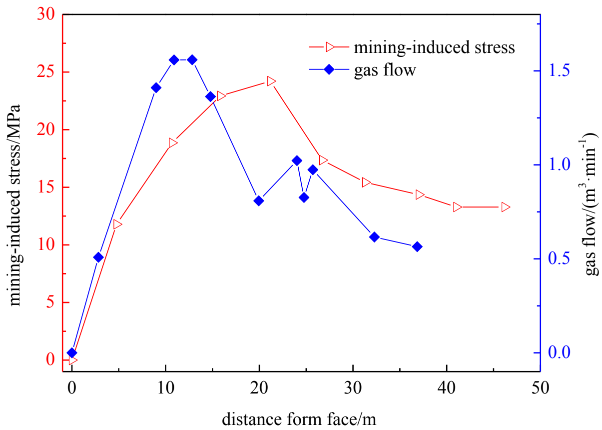
4. Result Analysis and Discussion

4.1 Measurement Result Analysis of Mining-induced Stress and Gas Flow of Coal Mass

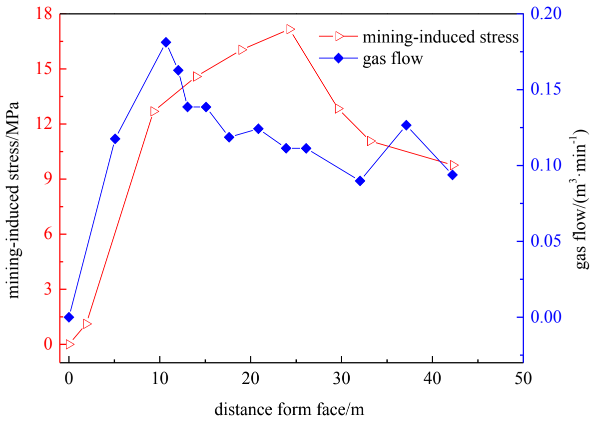
Based on the measurement results, Figure 4 shows the changing curves of mining-induced stress and gas flow of the coal mass. The following can be obtained after analysis.

In the mining process of coal seam, with the approach to the face, the mining-induced stress of coal mass at the return airway gradually increased first and reached a maximum of 24 MPa at 2 m away from the face. Then, the mining-induced stress rapidly reduced. The mining-induced stress of the coal mass at the haulage roadway showed an increasing and decreasing trend with a maximum of 17 MPa at 20 m away from the face. The coal mass at the return airway had the same change law as that at the haulage roadway; however, the peak of the former was larger, and its influential scope was wider.

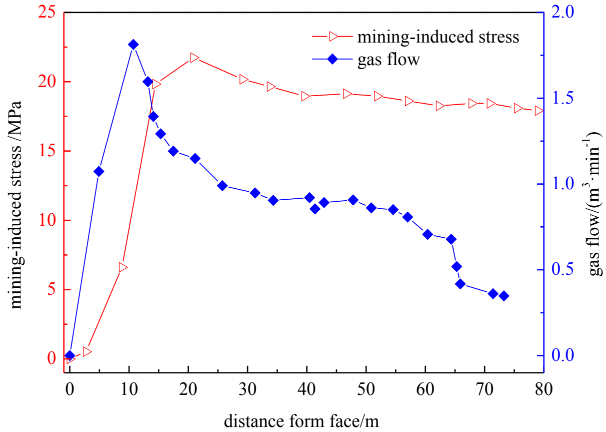
The measurement results of gas flow showed that with the approach to the face, the gas flows at both the return airway and haulage roadway showed an increasing and decreasing trend. The maximum gas flow at the return airway was approximately 2 m^3/min and that at the haulage roadway was about 1.8 m^3/min. The gas flow at the return airway was generally larger than that at the haulage roadway. Along the advance direction of the face, the change laws of gas flow and mining-induced stress of coal mass were consistent.



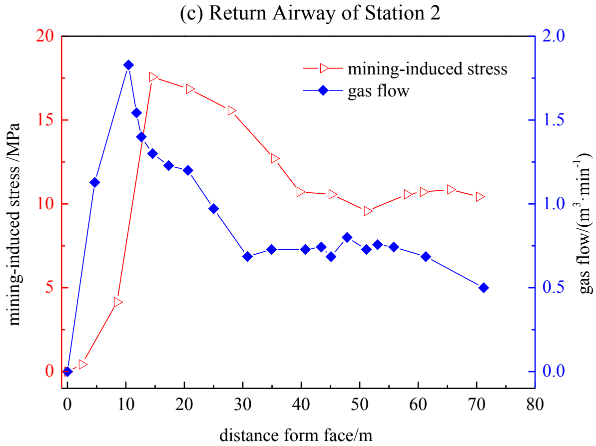
(a) Return Airway of Station 1



(b) Haulage Roadway of Station 1



(c) Return Airway of Station 2



(d) Haulage Roadway of Station 2

Fig.4. Change Curves of Mining-induced Stress and Gas Flow

Gas flow was sensitive to the mining-induced stress of coal mass. It changed with the mining-induced stress and was controlled by it. However, the locations of their peaks were different. The peak of the former was at approximately 10 m away from the face and that of the latter was at approximately 20 m away from the face; therefore, the peak of the former was behind that of the latter.

Gas flow was closely related to the permeability of coal. The permeability of coal could be characterized by the gas flow and could also be controlled by the mining-induced stress because gas flow changed with the mining-induced stress. The stress could enhance the permeability of coal and increase the gas flow.

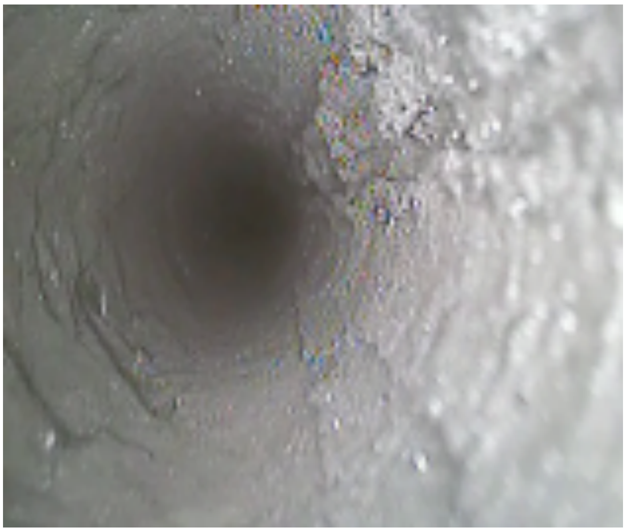
4.2 Measurement Result Analysis of Coal Failure Characteristics

Figure 5 showed the drilling peep result at different positions. According to the figure, both the development and failure degrees of coal fractures at both the return airway and haulage roadway gradually reduced with the increase of distance from the face. At the same distance from the face, the vertical and horizontal fractures of coal mass at the return airway developed well, and the penetration and failure degrees were high. The development and failure degrees of coal fractures at the haulage roadway were low.

4.3 Measurement Results Analysis of Gas Extraction Amount

The detectors discovered the gas flows in the drilling holes. According to the detection results, Figures 6 and 7 presented the change curves of single-hole gas extraction amount and total gas extraction amount, respectively.

(a) 5 m in Front of the Face at the Return Airway

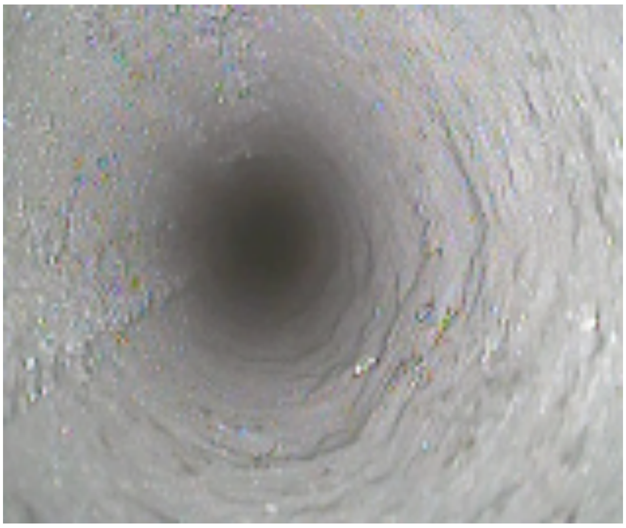


(b) 5 m in Front of the Face at the Haulage Roadway

(c) 15 m in Front of the Face at the Return Airway

(d) 15 m in Front of the Face at the Haulage Roadway

(e) 25 m in Front of the Face at the Return Airway



(f) 25 m in Front of the Face at the Haulage Roadway

Fig.5. Drilling Peep Results at Different Positions

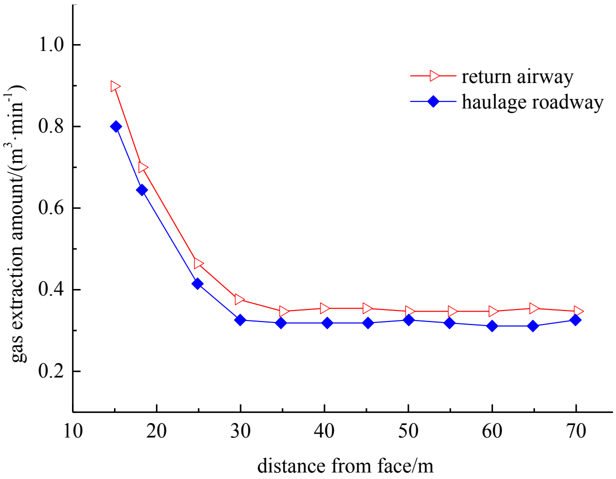


Fig.6. Change Curves of Single-hole Gas Extraction Amount

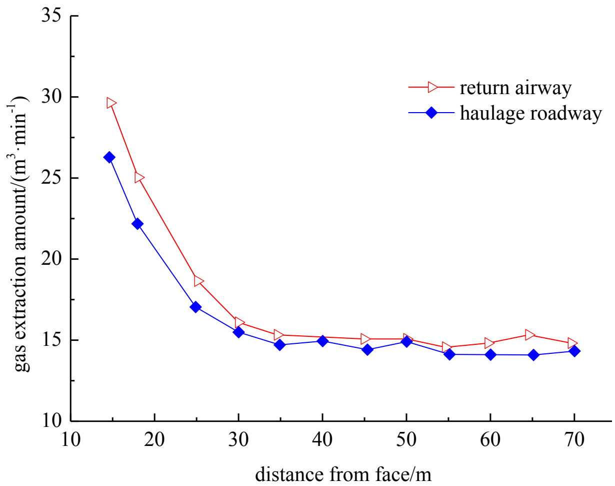


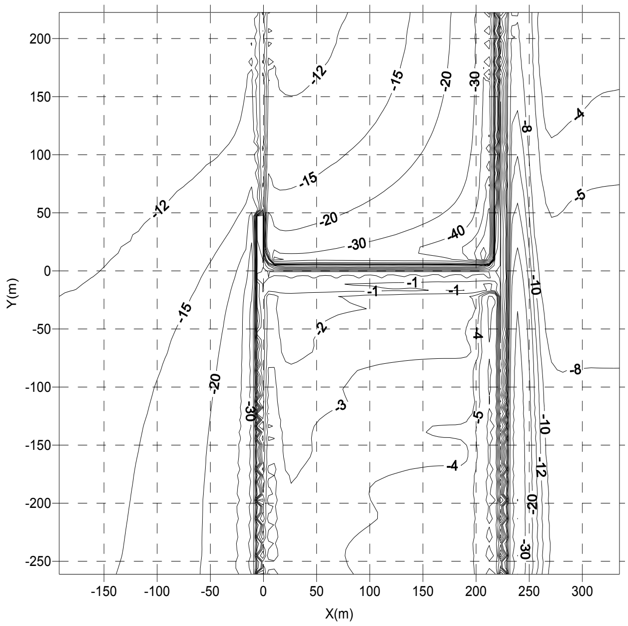
Fig.7. Change Curve of Total Gas Extraction Amount

Figures 6 and 7 show that gas extraction amounts from the bedding holes were different at different positions of the face. At positions far from the face, the gas extraction amount was small and the permeability of the coal mass was low, whereas the gas extraction amount was large and the permeability of the coal mass was high at the stress reduction zone of the face. Both the single-hole gas extraction amount and the total extraction amount at the return airway were larger than those at the haulage roadway, indicating the higher permeability of coal mass at the return airway.

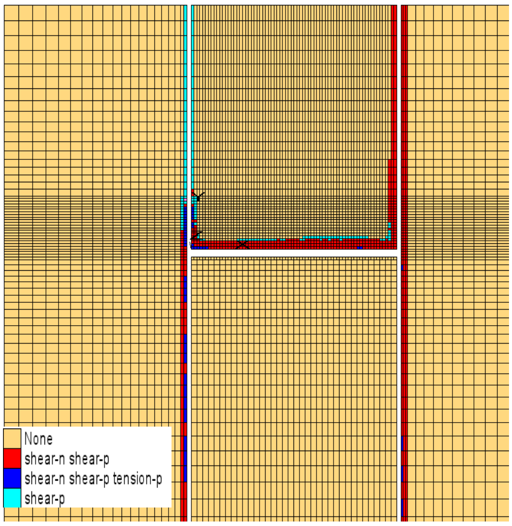
4.4 Numerical Simulation Result Analysis of Mining-induced Stress and Failure Characteristics of Coal Mass

According to the numerical simulation results, Figure 8 showed the distribution map of the stress fields and failure fields of coal mass. The figure shows that the coal stress gradually increased first with the approach to the face along with the advance direction of the face. Then, it slowly reduced after reaching the peak. The stress peak was located at the upper corner of the face. Under the effect of the mining-induced stress, the coal pillar set between the goaf of 17228 face and 17218 face were completely destructed. The coal mass at the return airway and the haulage roadway showed shear failure with local tension-shear failure. The failure scope of coal mass at the return airway was larger.

(a) Maximum Principal Stress Distribution in Coal Mass



(b) Vertical Stress Isoline in Coal Mass at the Face



(c) Failure Characteristic of Coal Mass at the Face

Fig.8. Stress Field and Failure Field Distribution Map of Coal Mass

Both the numerical simulation results and measured results of the failure characteristics of coal mass showed that the coal failure degree and scope at the return airway were larger and that coal permeability was higher. The plastic failure zone of coal mass was in the mining-induced stress reduction zone. The coal failure in the stress reduction zone was more serious. The gas content of coal mass could be significantly reduced if the on-site technicians extracted the gas in the stress reduction zone.

5. Conclusions

Reflecting the actual situation of coal permeability through the research results obtained by means of theoretical analysis and laboratory testing is difficult. To obtain the more accurate characteristics of coal permeability, the current study conducted on-site measurement research on the permeability of coal mass and carried out numerical simulation research on mining-induced stress and the failure characteristics of coal mass. The following conclusions are drawn.

(1) Mining-induced stress and the gas flow of coal mass showed an increasing and decreasing trend with the approach to the face. However, the peak of the gas flow was behind that of the mining-induced stress. Coal permeability was controlled by mining-induced stress.

(2) Both the peak of the coal stress and the coal failure scope at the return airway were large. The coal permeability at the return airway was higher than that at the haulage roadway. The failure characteristics of coal mass were related to mining-induced stress. The plastic failure zone was within the stress reduction zone.

(3) The coal permeability in the stress reduction zone of the face was the highest. The gas extraction amount could be significantly increased if the on-site technicians extracted the gas in the stress reduction zone.

This research studied the pertinence between the permeability and mining-induced stress of coal mass through on-site measurement and numerical simulation, which provided a basis for reasonable gas extraction. However, the present research has been applied only to the 17218 face of Zhangji Coal Mine. Further exploration is necessary for the promotion and application of the research results.

Acknowledgments

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