Research Article

A Study of the Laws of Abnormal Gas Emissions and the Stability Controls for Coal Mine Walls in Deeply Buried High-Gas Coal Seams

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At the present time, it is considered to be of major significance to study the gas emission law and stability controls of coal bodies in deeply buried high-gas coal seams. For this reason, in view of the specific problems of gas emissions caused by unstable rib spalling in coal mine walls, comprehensive research methods were adopted in this study, in order to conduct an in-depth examination of micropore structure parameters, gas desorption, diffusion laws, and coal stability levels. The results showed that the development degree of the pores above the micropores, as well as the small pores in soft coal seams, was better than those observed in hard coal seams. In addition, the gas outburst phenomenon was found to have more easily formed in the soft coal seams. The coal body of the No. 6 coal seam in the Xieqiao Coal Mine not only provided the conditions for gas adsorption but also provided dominant channels for gas diffusion and migration. The abnormal gas emissions of the No. 6 coal seam were jointly caused by the relatively developed pores above the small holes in the coal body, rib spalling of coal mine walls, and so on. The research results also revealed the evolution law of mechanical characteristics of the No. 6 coal seam under different water content conditions. It was found that the strength levels of the No. 6 coal seam first increased and then decreased with the increase in water content, and the water content level at the maximum strength of the coal seam was determined to be 7.09%. This study put forward a method which combined the water injection technology of long-term static pressure water injections in deep coal mining holes and real-time dynamic pressure water injections in shallower holes. Field experiments were successfully carried out.

1. Introduction

The high intensity mining of coal resources has gradually exhausted the coal resources of shallow coal seams in China [1–4]. Therefore, many mining areas have successively entered into deep mining processes for coal, such as the Huainan and Huaibei regions of China. However, with increase in coal mining depths, the mining environmental conditions have become more complex [5, 6]. For example, the higher levels of ground stress, gas pressure, gas content, and other phenomena have become important factors which may potentially induce such dynamic disasters as gas outbursts [7–16].

Coal and gas outbursts, as well as other dynamic disasters, are very complex coal and rock dynamic processes. These outburst events are the results of the comprehensive actions of stress, gas, and the characteristics of the coal bodies themselves [17, 18]. Therefore, during the processes of studying coal and gas outbursts, in addition to considering the control effects of the stress and gas levels on the outbursts, focus should also be paid to the influences of the coal bodies' characteristics on the outburst events, that is to say, the influence effects of the coal's own gas adsorption and desorption performances and the coal's stability with regard to the coal seam gas emissions [19–24].

At the present time, both Chinese researchers and international experts in the field have conducted many studies focused on gas emission and coal wall stability controls in high-gas coal seams. The majority of gas outburst accidents have occurred at the heading ends of mining roadways or at both ends of working faces. Since these areas are disturbed by mining activities, a general phenomenon of high stress concentration tends to exist. It has been confirmed that stress plays a significant leading role in gas outbursts [25] [26, 27].

It is known that the micropore structures of coal bodies are closely related to the coal's gas adsorption and desorption characteristics. The micropores in a coal body constitute the gas adsorption spaces. The micropores provide the spaces for capillary condensation and gas diffusion. Meanwhile, the mesopores and macropores constitute the gas seepage spaces. It has been observed that, with increase in pore sizes, the seepage process tends to change from a slow laminar flow to a strong laminar flow and then to laminar and turbulent mixed flows [20–28].

The physical and mechanical characteristics of coal have obvious influence effects on the laws of adsorption and desorption of coal gas. In addition, the laws of gas emissions for hard coal and soft coal are quite different. The stability of a coal body also has an important influence on the characteristics of the gas emissions. The rib spalling of the coal walls in a mine working face may cause the coal body to become soft. Subsequently, the cracks in the coal body will expand, and the area size of the exposed coal body will be increased. These actions provide dominant channels for gas emission and diffusion [29–35].

In the present study, based on the abovementioned analyses, previous studies mainly used a single method to study the appearance of coal gas gushing, and it was determined that the occurrences of gas outburst accidents in deeply buried coal seams have many influencing factors. However, at the present time, the comprehensive analysis regarding these multiple factors requires further investigation. Therefore, based on the research background of the rib spalling of coal mine excavation walls and the occurrences of gas transfinite accidents in the 21216 working face of the No. 6 coal seam of the Xieqiao Coal Mine (Huainan, China), this study adopted comprehensive research methods such as indoor tests, theoretical analyses, and field industrial tests in order to conduct in-depth research on the emission laws and stability controls of coal walls in deeply buried high-gas coal seams. The obtained research results potentially provide a foundation and basis for future improvements in high-gas seam and coal wall stability control measures.

2. Overview of the Engineering Geology

The coal seam examined in this study was the No. 6 coal seam of the Xieqiao Coal Mine. The No. 6 coal seam was located close to the No. 8 coal seam. These two coal seams were considered to be potential high-gas outburst coal seams. The average distances between the two coal seams were within 30 m, giving them the characteristics of an extremely close coal seam group. During the mining

processes, a ventilation roadway for the working face of the No. 6 coal seam was located under the goafs of the No. 8 coal seam. The location of the examined gas transfinite accident was in the working face 21216 of the No. 6 coal seam, as shown in Figure 1. The No. 6 coal seam and No. 8 coal seam both contained soft layers (hereinafter referred to as the soft coal). It was found that the physical and mechanical properties of the soft layers and the normal coal body (hereinafter referred to as the hard coal) were obviously different.

3. Analysis of the Micropore Structure Parameters of the Coal Seam

In order to study the abnormal laws of gas emissions in high-gas coal seams, the micropore structures of the coal body were analyzed. A Micromeritics ASAP 2460 multi-station specific surface area and porosity analyzer was used for the determination of the micropore structural parameters, as shown in Figure 2. In order to study the singularity of the gas emission law of the coal body in the No. 6 coal seam, the micropore structures of the soft and hard coals in both the No. 6 and No. 8 coal seams were compared and analyzed.

3.1. Specific Surface Areas and Pore Structure Parameters of Coal Body. In this study, the specific surface area parameters of the soft and hard coal bodies in the No. 6 and No. 8 coal seam were first tested. There were two types of specific surface area parameters: a BET specific surface area and a BJH specific surface area. The BET specific surface area represented the specific surface area of the micropores in the coal bodies. Meanwhile, BJH specific surface area represented the specific surface area of the micropores and larger pores in the coal bodies. The specific surface area of the micropores represented the ability of coal to absorb gas, while the small pores and larger pores represented the coal's gas diffusion and migration abilities.

Tables 1 and 2 detail the BET and BJH specific surface area test data of the two coal seams, respectively. Figure 3 shows the specific surface area comparison curves of the two examined coal seams. It can be seen in the figure that the BET specific surface area of the hard coal of the No. 6 coal seam was approximately 2.17 times than that of the hard coal of the No. 8 coal seam and 1.11 times than that of the soft coal of the No. 8 coal seam. In addition, the BET specific surface area of the soft coal of the No. 6 coal seam was found to be 4.28 times than that of the hard coal of the No. 8 coal seam and 2.19 times than that of the soft coal of the No. 8 coal seam. The BJH specific surface area of the hard coal of the No. 6 coal seam was approximately 3.22 times than that of the hard coal of the No. 8 coal seam and basically the same as the soft coal of the No. 8 coal seam. The BJH specific surface area of the soft coal of the No. 6 coal seam was determined to be approximately 6.54 times than that of the hard coal of the No. 8 coal seam and was twice than that of the soft coal of the No. 8 coal seam. Therefore, as can be seen from the above analysis results, it can be concluded that the BET and BJH

FIGURE 1: Schematic diagram for the spatial location relationship of the coal seam.

FIGURE 2: ASAP 2460 multistation type-specific surface area and porosity analyzer.

specific surface areas of the soft coal in both the No. 6 and No. 8 coal seams were larger than that of the hard coal. In addition, the BET and BJH specific surface areas of the hard and soft coal in the No. 6 coal seam were significantly larger than that of the No. 8 coal seam.

Therefore, the gas adsorption and desorption capacities of the No. 6 coal seam were obviously stronger than those of the No. 8 coal seam. This was found to be particularly true with regard to the gas adsorption and desorption capacities of the soft coal in the No. 6 coal seam, as shown in the dotted box in Figure 3. Therefore, it was suggested that more attention should be paid to the soft coal layers of each coal seam during the mining of working faces.

3.2. Analysis of the Relationship between the Pore Sizes and Specific Surface Areas and the Pore Volume. During the next steps of the present study, the increments of the pore diameters and specific surface areas along with the pore volume increments of the soft and hard coal of the No. 6 and No. 8 coal seams were compared and analyzed. The influence of pore size on gas adsorption and diffusion is different. Pore size and the hole below provide favorable conditions for gas occurrence, while pore size and the hole above provide space for gas diffusion and migration. The deep mechanism was that the volume of small hole and the hole below was smaller, which was more favorable for gas storage. However, the volume of the middle hole, large hole, or fracture was relatively large, which provides a superior channel for gas flow, and was more conducive to gas flow.

Figure 4 shows the relationships between the specific surface area increments and the pore diameters of the No. 6 coal seam. It can be seen in the figure that the pore specific surface area increments and the pore volume increments within the 3 to 70 nm pore diameter range of the hard coal of the No. 6 coal seam were relatively large, with many observed peak points. The pore specific surface area increments and the pore volume increments of the pore with diameters of 4 mm had reached the maximum value, which indicated that the pores of the hard coal of the No. 6 coal seam were relatively developed within that range (3 to 70 nm). The pore specific surface area increments and the pore volume increments were found to be relatively large in the pore diameter range of 100 to 300 nm, which suggested that the pores in that range are also relatively developed. Therefore, it was determined that the hard coal of the No. 6 coal seam not only contained relatively developed micropores but also was composed of both relatively developed small and large pores, which provided good gas adsorption and desorption conditions.

Figure 5 illustrates the relationship between the coal pore volume increments and the pore diameters of the No. 6 coal seam. It can be seen in the figure that the pore specific surface area increments and the pore volume increments within the pore size range of 2 to 100 nm in the No. 6 coal seam were relatively large, and there are many peak points observed. The pore specific surface area increments and the pore volume increments of the pore measuring 2 nm in size had reached the maximum value, which indicated that the soft coal pores of the No. 6 coal seam were relatively developed in the pore size range of 2 to 100 nm. In addition, the increment values of specific surface areas and the pore volume of the pores in the size range of 100 to 250 nm were also relatively large. That is to say, the pores in that range were found to be relatively developed. Therefore, the soft coal of the No. 6 coal seam not only contained relatively developed micropores but was also characterized by relatively developed micropores and larger pores, which provided good conditions for gas adsorption and desorption. It was found that when compared with the hard coal in the No. 6 coal seam, the increments of pore specific surface areas and the pore volume in the size range of 100 to 250 nm were larger, indicating that the conditions of gas diffusion and migration were superior in the soft coal of the No. 6 coal seam.

TABLE 1: BET specific surface areas of the different coal seams.

Pore structure parameters	No.	No. 6 hard	No. 6 soft	No. 8 hard	No. 8 soft
BET specific surface area (m^2/g)	1	1.987	3.7882	0.775	1.4581
	2	1.7895	3.1049	0.8103	1.6639
	3	1.6259	3.7332	0.8981	1.7318
	Average value	1.8008	3.5421	0.8278	1.6179

TABLE 2: BJH specific surface areas of the different coal seams.

Pore structure parameters	No.	No. 6 hard	No. 6 soft	No. 8 hard	No. 8 soft
BET specific surface area (m^2/g)	1	1.5354	3.3095	0.3781	1.2226
	2	1.6291	2.2912	0.534	1.6153
	3	1.2135	3.2919	0.4469	1.6384
	Average value	1.4593	2.9642	0.453	1.4921

FIGURE 3: Distributions of the BET and BJH specific surface areas of the different coal seams.

Figure 6 shows the relationship between the specific surface area increments of the coal and the pore diameters of the No. 8 coal seam. It can be seen from the figure that the pore specific surface area increments and pore volume increments of the hard coal pores in the pore size ranges from 2 to 4 nm and 30 to 70 nm in the No. 8 coal seam were relatively large, and there were many obvious peak points. The pore specific surface area increments and the pore volume increments of pores with diameters of 3.5 nm were observed to have reached the maximum value. The hard coal pores within the pore size range of 2 to 4 nm in the No. 8 coal seam were also well developed. However, the pore volume increments and the specific surface area values were found to be relatively smaller when compared with those of the No. 6 coal seam. The pores within the pore size range of 30 to 70 nm were found to be generally developed, and the pore surface area increments and the pore volume increment values of the pores within the pore size range of 100 to 240 nm were relatively large. Moreover, the pores in that range were also well developed, indicating that the hard coal pores in the No. 8 coal seam were not only conducive to gas

adsorption but also conducive to gas diffusion and migration.

Figure 7 shows the relationships between the specific surface area increments of the coal and the pore diameters of the No. 8 coal seam. It can be seen in the figure that the pore specific surface area increments and the pore volume increments of the soft coal pores in the pore size ranges of 2 to 8 nm and 15 to 100 nm in the No. 8 coal seam were relatively large, with many peak points observed. The pore specific surface area increments and the pore volume increments of the soft coal pores with a diameter of 3.5 nm had reached the maximum value, which indicated that the soft coal pores of the No. 8 coal seam were relatively developed in the aforementioned two pore size ranges. In addition, the increment values of the specific surface areas and the pore volumes of the pores in the range of 100 to 240 nm were found to also be relatively large. These results indicated that the soft coal pores within the pore size ranges of micropores and smaller pores were also well developed in the No. 8 coal seam. Therefore, it was confirmed that the soft coal of the No. 8 coal seam was not only conducive to gas adsorption but also to gas diffusion and migration. Also, when compared with the hard coal of the No. 8 coal seam, it was found that the soft coal of the No. 8 coal seam was not only more conducive to gas adsorption but also more conducive to gas diffusion and migration. However, it was found to be slightly less conducive than that of the soft coal of the No. 6 coal seam.

From the abovementioned experimental results, it can be seen that the increments of specific surface areas and the soft coal pore volumes in the micropore range of 0 to 100 nm were significantly higher than those of the hard coal. In addition, the increments of specific surface areas and the soft coal pore volumes in the micropore range of 100 to 300 nm were also higher than those observed for the hard coal. These findings indicated that the development degrees of the pores which were larger than the micropore range in the soft coal were greater than those of the hard coal. Therefore, it was determined that the gas adsorption and desorption conditions of the soft coal were superior to that of the hard coal.

In the present study, the corresponding specific surface area increments and pore volume increments of the soft and hard coal of the No. 6 coal seam within the ranges

FIGURE 4: Relationship between the specific surface area increments and the pore diameters of the No. 6 coal seam ($\text{\AA}$ is 10^{-1} nm): (a) hard coal; (b) soft coal.

FIGURE 5: Relationship between the coal pore volume increments and the pore diameters of the No. 6 coal seam ($\text{\AA}$ is 10^{-1} nm): (a) hard coal; (b) soft coal.

of 0 to 100 nm and 100 to 300 nm were found to be greater than those of the soft and hard coal of the No. 8 coal seam. Therefore, it was concluded that the No. 6 coal seam not only provided favorable conditions for gas adsorption but also provided superior channels for gas diffusion and migration. The influence effects of the coal pore distributions on the gas adsorption and diffusion are described in Table 3.

4. Laws of Gas Desorption and Diffusion

In this experimental study, the laws of the gas desorption and diffusion of the No. 6 and No. 8 coal seams were examined in detail. A 3H-2000PH high-pressure gas adsorption and desorption instrument was used in the experimental processes, as shown in Figure 8.

Figures 9 and 10 detail the change regularity of the gas desorption speed and gas desorption capacity, respectively. As shown in Figure 9, it was concluded that the gas desorption speed of the different coal seams in the various particle size ranges had been basically the same. In other words, the gas desorption speed of each coal seam had decreased with the increase in the desorption time, and the gas desorption speed had displayed a negative correlation with time.

During the initial gas desorption stage, the gas desorption speed was observed to drop sharply. Then, with the increasing duration, the gas desorption speed had gradually slowed down. For example, when the gas desorption time reached one minute, the gas desorption speed of some of coal seams tended to be 0, which indicated that the gas release speed was very fast and the gas

FIGURE 6: Relationship between the specific surface area increments of the coal and the pore diameters of the No. 8 coal seam ($\text{\AA}$ is 10^{-1} nm): (a) hard coal; (b) soft coal.

FIGURE 7: Relationship between the coal pore volume increments and the pore diameters of the No. 8 coal seam ($\text{\AA}$ is 10^{-1} nm): (a) hard coal; (b) soft coal.

TABLE 3: Influence effects of the coal pore distributions on the gas adsorption and diffusion.

Coal samples	Micropores	Small pores	Peak points of the specific surface areas and pore volumes increment (nm)	Influence effects on the gas of the hole distributions
Hard coal of the No. 6 coal seam	Developed 3–70 nm	Developed 100–300 nm	4	Conductive to gas adsorption and diffusion
Soft coal of the No. 6 coal seam	Developed 2–100 nm	Developed 100–250 nm	2	Conductive to gas adsorption and diffusion
Hard coal of the No. 8 coal seam	Relatively developed	Relatively developed 100–240 nm	3.5	Conductive to gas adsorption and diffusion
Soft coal of the No. 8 coal seam	2–4 nm 30–70 nm Relatively developed 2–8 nm 15–100 nm	Relatively developed 100–240 nm	3.5	Conductive to gas adsorption and diffusion

FIGURE 8: 3H-2000PH high-pressure gas adsorption and desorption instrument.

FIGURE 9: Variation law in the gas desorption speed.

FIGURE 10: Variation law in the gas desorption.

desorption time was short. Therefore, the initial gas desorption speed of the coal body had heavy impact effects on the gas emission results. As illustrated in the dotted line box in Figure 9, the initial gas desorption speed in the No. 6 coal seam was 1,993.2598 ml/min, and the initial gas desorption speed of the No. 8 coal seam was 1,893.0832 ml/min. Therefore, the initial gas desorption speed of the No. 6 coal seam was significantly higher than that of the No. 8 coal seam. Subsequently, the gas emission speed of the No. 6 coal seam was also significantly higher than that of the No. 8 coal seam. At the same time, it should be noted that the distance between the No. 6 and No. 8 coal seams was approximately 30 m, and the No. 8 coal seam had been mined out. It was observed in this study that, with the continued mining activities in the No. 6 coal seam, the goafs in the upper and lower sections of the coal seam may have potentially run through the No. 8

coal seam, leading to the flow of gas from the No. 8 coal seam goafs migrating into the No. 6 coal seam.

It is known that the initial gas desorption speed of a coal body represents the sudden gas emission speed at a project site. Therefore, according to this study's experimental results, the sudden gas emission speed of No. 6 coal seam was higher than that of the No. 8 coal seam, which indicated a higher potential for sudden gas emission, gas transfinite, and other mining accidents.

In the same time, the greater the desorption speed of gas, the greater the amount of gas desorbed from coal. On the contrary, if the gas desorption speed of coal body was smaller, the amount of gas desorbed from coal body was smaller. In this paper, we can see that the gas desorption rate and desorption rate of soft coal were higher than that of hard coal, and the gas desorption rate and desorption rate of #6 coal seam were higher than that of #8 coal seam.

5. Analysis of the Coal Wall Stability Control Mechanisms

The rib spalling of the coal mine walls in the working faces of high-gas coal seams may easily cause abnormal gas emissions. These abnormal emissions can potentially result in dangerously large amounts of accumulated gas, gas transfinite, and outburst accidents. Therefore, it has been confirmed that the rib spalling of coal mine walls is one of the important causes of gas accidents. Meanwhile, effective stability control measures for coal mine walls are important means of preventing gas transfinite and outburst accidents.

Previous related research results showed that reasonable injections of liquid into coal seams can strengthen coal bodies, as well as improve the stability levels and change the gas adsorption and desorption abilities of the coal. It has been found that liquid bridges can be formed between coal particles, after which liquid bridge forces may be produced. The contents of the applied bridge liquid determine the magnitude of the liquid bridge forces. In this study, the amount of the liquid bridging content in the coal particle gaps was expressed by the saturation S level. The term saturation referred to the percentage of liquid volume V_L in the coal particle gap volume V_T . The calculation method was as follows:

$$S = \frac{V_L}{V_T} \quad (1)$$

The connection mode of the liquid and coal particles was mainly dependent on the liquid saturation level. As shown in Table 4, the liquid bridges were divided into the following types in accordance with the determined saturation levels.

6. Law of the Influence of Moisture Content on the Stability of the Coal Bodies

Due to the strong hydrophilicity of coal particles, the costs related to water injections are greatly reduced, when compared with chemical injection materials. Moreover, water injections have been found to be safe and environmental friendly. Therefore, a coal seam water injection method was adopted to control the stability levels of the coal bodies in this study. However, it was found that the strength levels of the coal bodies under the different water content conditions had displayed obvious differences. Subsequently, this study first examined the strength levels of the different coal bodies under various water content condition scenarios. Due to the fact that the main failure mode of coal bodies in front of coal mine walls tends to be shear failure, this research study analyzed the strength characteristics of the coal bodies under different moisture content conditions through indoor shear experimentation. Then, the acquired results were compared, and the strength parameters of the different coal bodies under various moisture content conditions were analyzed.

6.1. Research Program. In this study's experiments, raw coal samples were selected from the 21216 working face of the No. 6 coal seam in the Xieqiao Coal Mine. The samples were

crushed and dried, and granular coal with a particle size less than 0.2 mm was screened out using a standard sieve. Then, 260 g of the screened granular coal was uniformly mixed with pure water of different qualities and then numbered. The direct shear apparatus and drying box used in the present study are shown in Figures 11 and 12, respectively. Then, shear failure experiments were carried out on coal bodies with different water contents. The experimental results were analyzed in order to obtain the change trends of the shear strength parameters for different coal seams with various levels of water content.

6.2. Strength Characteristics of Coal under Different Water Contents. Table 5 shows the shear strength index of the No. 6 coal seam under different water content conditions. In the table, S_1 , S_2 , S_3 , and S_4 represent the maximum shear stress levels corresponding to the different vertical stress under the same water content conditions, respectively.

The values of S_1 , S_2 , S_3 , and S_4 under the same water content condition were then linearly fitted, and the intercept obtained was the cohesion c . Meanwhile, the cohesion represented the strength index of the coal under the same water content condition. At the same time, the internal friction angles of the coal bodies under the aforementioned condition were also obtained. Figure 13 details the trends of the cohesion with the different water content levels. Therefore, it was concluded from the results shown in Figure 13 and Table 5 that the cohesion of the coal particles had not always increased with the increase in the moisture content when the water content levels had ranged within 2.02% to 18.83%. However, it was observed that the cohesion has first increased and then decreased with the increase in the moisture content. The moisture content level which had corresponded to the maximum cohesion was determined to be between 5.03% and 11.03%, and the moisture content at the maximum strength of the coal was 7.09%.

7. Coal Wall Stability Control Technology and Verification of the Effects

In accordance with the abovementioned research results, a combined method of water injection technology with long-term static pressure water injections in deep holes and real-time dynamic pressure water injections in shallow holes was proposed in the fourth section of this study. This combined method water injection technology using deep and shallow hole systems in coal seams was based on the characteristics of the known poor stability of coal bodies, along with the determination that rib spalling improvements and reinforcements of the coal bodies could easily increase the overall stability. The costs were greatly reduced when water injections were adopted, when compared with chemical material injections. Furthermore, the water injections were both safe and environmentally friendly processes. Figure 14 shows the layout of the deeply buried and shallow combined water injection boreholes in the examined coal seam. This study's specific implementation of the adopted technology was as follows. The long-term static pressure water injections

TABLE 4: Liquid saturation in the gaps between particles and the corresponding liquid bridge shapes.

Liquid saturation	Liquid bridge shapes	Schematic diagrams	Physical mechanisms
0	—		No liquid bridge force between particles
$S < 30\%$	Pendulum shape		Particles are connected by liquid bridges at the contact points; liquid bridges are thin
$30\% < S < 70\%$	Cable belt shape		Liquid bridges exist around the contact points; some particle gaps are filled with liquid resulting in increased adhesion
$S > 70\%$	Capillary shape		Gap between particles is almost fully filled with liquid; surfaces of the liquid are sunken; attraction between particles is obviously increased
$S > 100\%$	Slurry shape		Liquid pressure is equal to or greater than the air pressure; almost no adhesion exists between the particles

FIGURE 11: ZJ-type strain controlled direct shear apparatus.

FIGURE 12: Drying box.

TABLE 5: Shear strength index under different moisture content conditions.

No.	Water content (%)	S_1 (kPa)	S_2 (kPa)	S_3 (kPa)	S_4 (kPa)	Cohesion c (kPa)	$\tan\phi$	Angle of internal friction ($^\circ$)
1	2.02	9.353	16.056	31.566	60.404	0.246	0.156	8.889
2	2.79	8.963	15.004	30.592	58.066	0.491	0.153	8.699
3	5.23	8.379	16.173	30.865	60.404	1.161	0.148	8.430
4	7.09	9.548	15.978	32.735	60.599	2.126	0.147	8.368
5	7.81	7.338	13.364	27.876	51.366	1.285	0.126	7.204
6	9.02	7.989	16.757	31.176	65.081	1.713	0.144	8.194
7	9.13	8.689	13.835	30.787	55.773	1.624	0.137	7.790
8	11.03	8.574	16.562	29.618	63.522	1.850	0.147	8.340
9	13.16	8.768	15.393	30.592	61.963	1.364	0.144	8.205
10	13.37	7.775	12.471	28.059	50.806	1.339	0.125	7.125
11	13.47	8.311	12.471	29.618	53.178	1.277	0.131	7.480
12	15.02	8.963	15.588	29.812	59.235	0.491	0.153	8.699
13	15.56	5.266	13.250	27.669	48.453	0.811	0.122	6.950
14	18.83	7.529	13.250	27.669	54.387	0.382	0.135	7.694

FIGURE 13: Variation trends of the cohesion with different water content levels.

FIGURE 14: Layout of the deeply buried and shallow combined water injection boreholes in the examined coal seam.

of the deep holes (hole depth > 80 m) included injections of water into the coal bodies from ventilation and transportation roadways in the working faces of the mine. The distances between the water injection orifices of the ventilation roadways and the roof areas were controlled to within 0.8 m. The water injection orifices of the transportation roadways were located in the middle sections of the coal seams. The duration times of the water injections followed methods of both continuous all-day injections and intermittent water injections. The deep hole water injections were carried out 100 m ahead of the coal walls, and the water

injections were stopped at 20 m from the working face. The water injections of the shallow holes (hole depths < 8 m) were carried out from the coal walls to the coal bodies of the mine's working faces. The orifices were located between 0.5 and 1.0 m from the roof areas. The holes were constructed perpendicular to the coal walls or with slight angles of between 2° and 4° . The shallow hole water injection sealing devices extended into the holes by approximately 1.5 m. The water injection pressure was maintained at approximately 2 MPa. The water was injected twice a day for at least three hours each time. In the present study, following the implementations of the deep and shallow hole combined water injection technology, the overall stability levels of the coal bodies in the working faces were found to be greatly improved. In addition, the surrounding rock masses had been effectively controlled, and the advancing speed of the working faces was significantly enhanced. Therefore, effective improvements in mining efficiency had been achieved.

8. Conclusions

The present study first analyzed the characteristics of the structures of the micropores in the examined coal bodies. As a result, the mechanism of the abnormal gas emissions in the coal bodies had been successfully revealed. In addition, this study analyzed the mechanisms of the coal wall instability, adopted a method of indoor experimentation to study the influence laws of the various moisture content levels on the stability levels of the different coal bodies, and proposed an effective method using water injection technology to control the stability levels of the coal bodies. Also, field experiments were carried out to verify the accuracy of the proposed method. The following conclusions were obtained:

- (1) In this paper, the nature of abnormal gas emission in coal body was revealed by means of meso- and microstructure of coal body. Secondly, the method of coal seam water injection to control the coal wall was put forward, which has been well applied in the project site.
- (2) The development degrees of the soft coal pores larger than the micropore and small pore range were found

to be better than that of the hard coal. In addition, the soft coal bodies were observed to provide good conditions for gas adsorption and desorption processes. In the current study, the soft coal of the No. 6 coal seam not only provided favorable conditions for gas adsorption but also provided dominant channels for gas diffusion and migration. The abnormal gas emissions in the No. 6 coal seam were caused by the development of both small pores and larger pores in the coal bodies, as well as the effects of easy rib spalling in the coal walls.

- (3) The gas desorption speeds, gas desorption capacities, and initial gas desorption speed of the No. 6 coal seam were observed to be obviously higher than those of the No. 8 coal seam. Furthermore, the sudden gas emission speed of the No. 6 coal seam was determined to be higher than that of the No. 8 coal seam, which suggested that it was more likely to cause sudden gas emission hazards and transfinite accidents.
- (4) In the present study, the evolution laws of the mechanical characteristics of the No. 6 coal seam under various moisture content conditions were successfully revealed. It was found that the strength of the No. 6 coal seam had first increased and then decreased with the increase in water content. The water content level corresponding to the maximum cohesion ranged between 5.03% and 11.03%, and the water content level at the maximum strength of the coal seam was determined to be 7.09%. Therefore, in view of the problems related to the easy rib spalling of the coal mine walls, this study puts forward a method which combined the technology of long-term static pressure water injections in deep holes and real-time dynamic pressure water injections in shallow holes. Then, the proposed method was used to carry out field experiments. The results revealed that the proposed method had effectively enhanced the stability levels of the coal bodies, as well as greatly improved the advancing speeds of the working faces.

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 paper.

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References

- [1] E. Bai, W. Guo, Y. Tan, and D. Yang, "The analysis and application of granular backfill material to reduce surface subsidence in China's northwest coal mining area," *PLoS One*, vol. 13, no. 7, Article ID e0201112, 2018.
- [2] Q. Huang and J. Du, "Coupling control of pillar stress and surface cracks in shallow coal seam group mining," *Journal of China Coal Society*, vol. 43, no. 3, pp. 591–598, 2018.
- [3] Y. U. Bin, "Structural evolution of breaking roof group of multiple coal seams and its influence on lower coal seam mining," *Journal of China Coal Society*, vol. 40, no. 2, pp. 261–266, 2015.
- [4] X. Yang, G. Wen, L. Dai, H. Sun, and X. Li, "Ground subsidence and surface cracks evolution from shallow-buried close-distance multi-seam mining: a case study in Bulianta coal mine," *Rock Mechanics and Rock Engineering*, vol. 52, no. 8, pp. 5835–5852, 2019.
- [5] Z.-Q. Xiong, C. Wang, N.-C. Zhang, and G.-M. Tao, "A field investigation for overlying strata behaviour study during protective seam longwall overmining," *Arabian Journal of Geosciences*, vol. 8, no. 10, pp. 7797–7809, 2015.
- [6] X. Zhang, P. G. Ranjith, M. S. A. Perera, A. Ranathunga, and A. Haque, "Gas transportation and enhanced coalbed methane recovery processes in deep coal seams: a review," *Energy & Fuels*, vol. 30, no. 11, pp. 8832–8849, 2016.
- [7] M. S. A. Perera, "Influences of CO₂ injection into deep coal seams: a review," *Energy & Fuels*, vol. 31, no. 10, pp. 10324–10334, 2017.
- [8] W. Szott, M. Słota-Valim, A. Gołabek, K. Sowizdzał, and P. Łętkowski, "Numerical studies of improved methane drainage technologies by stimulating coal seams in multi-seam mining layouts," *International Journal of Rock Mechanics and Mining Sciences*, vol. 108, pp. 157–168, 2018.
- [9] L. Cheng, Z. Ge, J. Chen, H. Ding, L. Zou, and K. Li, "A sequential approach for integrated coal and gas mining of closely-spaced outburst coal seams: results from a case study including mine safety improvements and greenhouse gas reductions," *Energies*, vol. 11, no. 11, Article ID 3023, 2018.
- [10] A. Zhou and W. Kai, "A new gas extraction technique for high-gas multi-seam mining: a case study in Yangquan coalfield, China," *Environmental Earth Sciences*, vol. 77, no. 4, p. 150, 2018.
- [11] Z. Wang, G. Yin, Q. Hu, and H. Jin, "Inducing and transforming conditions from rockburst to coal-gas outburst in a high gassy coal seam," *Journal of Mining & Safety Engineering*, vol. 27, no. 4, pp. 572–575, 2010.
- [12] J. Tang, S. Yang, Y. Wang et al., "Experiment of coal and gas outbursts underground stress and gas pressure in deep mines," *Rock and Soil Mechanics*, vol. 35, no. 10, pp. 2769–2774, 2014.
- [13] Z. Li, *Study on Theory and Application of High Gassy Seam Rockburst*, Liaoning Technical University, Fuxin, China, 2007.
- [14] T. G. Zhang, "Prediction and control of coal and gas outburst in Pingdingshan mining area," *Journal of China Coal Society*, vol. 26, no. 2, pp. 172–177, 2001.
- [15] M. C. He, H. P. Xie, S. P. Peng, and Y. D. Jiang, "Study on rock mechanics in deep mining engineering," *Chinese Journal of Rock Mechanics and Engineering*, vol. 24, no. 16, pp. 2803–2812, 2005.

- [16] H. Cui, "Research on the prediction indexes of coal roadway heading face outburst and its critical value," *Journal of China Coal Society*, vol. 36, no. 5, pp. 808–811, 2011.
- [17] K. Wang, A. Zhou, G. Wei et al., "Study of formation and propagation characteristics of shock wave and gas flow of outburst at straight roadway," *Journal of Mining & Safety Engineering*, vol. 29, no. 4, pp. 559–563, 2012.
- [18] F. Zhang and T. Li, "Cognizance on compound dynamic disaster of coal and gas in deep mining," *Zhongzhou Coal*, vol. 4, pp. 73–76, 2009.
- [19] S. Valliappan and Z. Wohua, "Numerical modelling of methane gas migration in dry coal seams," *International Journal for Numerical and Analytical Methods in Geomechanics*, vol. 20, no. 8, pp. 571–593, 1996.
- [20] S. Valliappan and Z. Wohua, "Role of gas energy during coal outbursts," *International Journal for Numerical Methods in Engineering*, vol. 44, no. 7, pp. 875–895, 1999.
- [21] B. Zhao, G. Wen, H. Sun et al., "Similarity criteria and coal-like material in coal and gas outburst physical simulation," *International Journal of Coal Science & Technology*, vol. 5, no. 2, pp. 167–178, 2018.
- [22] S. Xue, L. Yuan, J. Wang et al., "A coupled DEM and LBM model for simulation of outbursts of coal and gas," *International Journal of Coal Science & Technology*, vol. 1, no. 2, pp. 22–29, 2015.
- [23] H. Zhang, L. Zhang, D. Wang et al., "Gas emission characteristics of tectonic coal and microscopic explanation of pore structure," *Journal of China Coal Society*, vol. 43, no. 12, pp. 3404–3410, 2018.
- [24] Y. Liu and M. Liu, "Effect of particle size on difference of gas desorption and diffusion between soft coal and hard coal," *Journal of China Coal Society*, vol. 40, no. 3, pp. 579–587, 2015.
- [25] J. Wang, J. Ning, P. Qiu, Y. Shang, and H. Shang, "Micro-seismic monitoring and its precursory parameter of hard roof collapse in longwall faces: a case study," *Geomechanics and Engineering*, vol. 17, no. 4, pp. 375–383, 2019.
- [26] Y. X. Wang, P. P. Guo, W. X. Ren et al., "Laboratory investigation on strength characteristics of expansive soil treated with jute fiber reinforcement," *International Journal of Geomechanics*, vol. 17, no. 11, Article ID 04017101.
- [27] H. Lin, H. T. Yang, Y. X. Wang, Y. L. Zhao, and R. H. Cao, "Determination of the stress field and crack initiation angle of an open flaw tip under uniaxial compression," *Theoretical and Applied Fracture Mechanics*, vol. 104, Article ID 102358, 2019.
- [28] S. Valliappan and W. Zhang, "Numerical modeling of methane gas migration in dry coal seams," *International Journal for Numerical and Analytical Methods in Geomechanics*, vol. 20, no. 8, pp. 571–593, 1996.
- [29] B. Zhao, G. Wen, H. Sun et al., "Similarity criteria and coal-like material in coal and gas outburst physical simulation," *International Journal of Coal Science & Technology*, vol. 5, no. 2, pp. 167–178, 2018.
- [30] Y. Zhao, Y. Zhang, W. Wang, W. Wan, and W. Ma, "Separation of elastoviscoplastic strains of rock and a nonlinear creep model," *International Journal of Geomechanics*, vol. 18, no. 1, 2017.
- [31] Y. Zhao, Y. Wang, W. Wang, L. Tang, and Q. Liu, "Modeling of rheological fracture behavior of rock cracks subjected to hydraulic pressure and far field stresses," *Theoretical and Applied Fracture Mechanics*, vol. 101, pp. 59–66, 2019.
- [32] B. Li, T. Li, N. Xu, F. Dai, W. Chen, and Y. Tan, "Stability assessment of the left bank slope of the baihetan hydropower station, southwest China," *International Journal of Rock Mechanics and Mining Sciences*, vol. 104, pp. 34–44, 2018.
- [33] B. Li, N. Xu, F. Dai, P. Xiao, and G. Zhang, "Dynamic analysis of rock mass deformation in large underground caverns considering microseismic data," *International Journal of Rock Mechanics and Mining Sciences*, vol. 122, Article ID 104078, 2019.
- [34] A. Li, F. Dai, N. Xu, G. Gu, and Z. Hu, "Analysis of a complex flexural toppling failure of large underground caverns in layered rock masses," *Rock Mechanics and Rock Engineering*, vol. 52, no. 4, 2019.
- [35] S. Xie, H. Lin, Y. Wang et al., "A statistical damage constitutive model considering whole joint shear deformation," *International Journal of Damage Mechanics*, 2020.