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Research Article

Application of Treatment for Deep Hole Drilling Debris in Gas-Rich Soft Coal Seams

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Hole accidents occurring in the drilling process and borehole collapse encountered in gas production are obstacles standing in the way of high efficiency of gas drainage through the outburst-prone soft coal seams in China. The fundamental testing data from existing suspending agents were combined to prepare a suspension in a specific density for testing debris disposal technology considering several adverse effects. Those effects include the sizeable residual volume of drilling debris, difficult debris disposal, the low effective utilization rate of drill holes, and the unideal extraction effect in drill holes with long-distance downward drill holes. The testing outcomes indicated that the suspension-aided debris disposal could contribute to the following aspects: discharging residual drilling debris out of the drill hole, rinsing the drill hole, preventing drilling debris from filling the coal seam, providing the adequate drill hole depth, and improving the effects of gas extraction. As a result, the gas production in shallow drill holes was increased by 40%, with gas concentration elevated by 21%. In addition, the scalar quantity and extraction concentration in the gas concentration of deep drill holes were increased by 84% and 260%, respectively. This study was undertaken to provide a specific reference for debris disposal work of deep drill holes for gas-rich soft coal seams.

1. Introduction

China was the greatest coal producer and consumer, separately occupying 51.6% and 50.8% for the world's coal in 2021. However, 754 coal mines in China are gas- and coal-herniated mines, and 48% of the state-owned coal mines are gas-rich mines. Gas hazards are still considered the most severe hazard that is threatening China's coal mine safety. Drilling boreholes through coal seams and extracting gas prior to underground mining are the dominating practices for avoiding gas explosions as well as other devastating disasters in underground mines. Nonetheless, the drainage of gas is highly complicated in gas-rich soft coal seams because of borehole instability possibly encountered in such soft seams. The primary challenges usually occur when dealing with the gas-rich soft coal seams that could potentially undermine many active coal mines in China.

The problem is that the borehole could produce more drilling debris during gas extraction when the stress is concentrated on the coal seam, thereby resulting in low gas extraction efficiency. Failed disposal of residual drilling debris in the drill hole will not only make it challenging to utilize the borehole completely but also hinder gas migration and block holes of the casing pipe, which will become serious under ponding conditions [1–4]. In addition, residual drilling debris in the drill hole will result in nonuniform negative pressure of extraction, reducing the radial scope of gas extraction to a certain degree, aggravating the formation of hole collapse, and degrading the gas extraction effect. In recent decades, the engineering method of hole depth increasing has been generally used to reserve the space for drilling debris in reservoir and mining engineering. However, the drilling depth is difficult to be increased in the drilling process of coal seams with gas-rich soft coal seams as well as remote coal seams under the influence of the power of drilling machine and drilling depth. As there is a significant amount of residual drilling debris in soft and loose coal seams, the drilling debris will significantly increase the drilling workload with the drilling depth. In addition, insufficient recognition of in situ drilling slurry depth leads to a certain blindness in the extension of drilling depth. Thus, the study of drill hole debris disposal will be highly valued in particular engineering applications [5–9].

With this motivation, many academic predecessors have investigated drilling debris disposal. Lu et al. [10] and Lin et al. [11] adopted high-pressure water to dispose of the drilling debris, and, as a result, a particular effect of applying high-pressure water was generated. However, the drilling debris could hardly be scoured out by high-pressure water because of the large particle size of drilling debris and nonradical debris disposal. Li [12] proposed a technology that protected drill holes by spraying foam to the shotcrete slurry along the borehole interior surface during the drilling process in the soft coal seam. This technology could mitigate drill hole collapse; however, coating a shotcrete slurry layer at the drilled coal seam influenced gas extraction. Gao et al. [13] investigated the drilling diameter effect on the air permeability of coal seam; they developed a new method by applying water-jetting technology for the cross-measurement of large-diameter drill holes.

Besides, the roadway's stability for coal seams of super deep mining depends significantly on the damaging behavior of the composite of both rock and coal under large in situ stress conditions. Chen et al. [14] conducted many experimental and numerical studies on the mechanical responses of a series of composites (the coal-rock, rock-coal, and rock-coal-rock) under triaxial compressive conditions with a range of confining pressure in between 0 MPa and 20 MPa. It was found that the elastic Young's modulus, the ratio of Poisson, and the maximum shear strength of the composite mass of both rock and coal increased with increasing the confining pressure. Zhao et al. [15] applied the theory of limit equilibrium and the inversion analysis of in situ monitored displacement to conduct a series of inversions of parameters and variables via commercial software of numerical simulation (FLAC3D). The outcomes of this study revealed that the location of the mine landslide was in a weakly evolved layer at an interface between highly weathered mudstone and sandstone. Later, Pan et al. [16] measured the physicomechanical properties of bedrock and silty clay layers by carrying out a series of triaxial and direct shear tests in their geomechanics laboratory, and they consequentially identified those properties significantly impacting the dump's stability. Their recommended values of soil's and rock's physical and mechanical properties were adequately presented in their study for geotechnical engineering practices. Zhao et al. [17] implemented many mechanical creeping tests on mudstone specimens under various stress conditions, concluding that the range of mudstone's long-term shear strength was between 8.0 MPa and 8.8 MPa, and the occurrence of steady creeping in slopes under the lower-stress conditions.

Even though much effort has been devoted to studying boreholes and well-drilling instability from many aspects mentioned above, the effect of increasing drilling depth on gas extraction has rarely been investigated so far. Since such a motivating research objective has been unresolved, the suspension-aided debris disposal method was therefore proposed in this in situ experimental study. This newly proposed method could discharge drilling debris to a certain degree to protect drill holes. A series of in situ experiments was performed to ensure that drill holes could serve for a significantly extended duration. The newly developed method was finally used to conduct a series of tests in the field.

2. Test Medium and Properties

2.1. Selection of Debris Disposal Medium. The fluid suspension in the floating process is usually used in mineral beneficiation and mineral processing. The standard dense media include heavy fluids, such as carbon tetrachloride, tribromomethane, and zinc chloride, as well as heavy suspensions prepared using silicon iron, galenite, magnetite, pyrite, and water. These heavy fluids have advantages, such as high density, low viscosity, and good stability. However, these fluids are inconvenient for recovery, and most are toxic or corrosive. In addition, heavy suspensions, such as silicon iron and galenite, are incredibly high that they cannot be extensively promoted. Therefore, magnet powder, which is a low-cost, nontoxic, and harmless dense-medium suspension, was selected as a debris disposal medium according to the drilling debris properties in the drill hole and previous practical applications in the field [18, 19]. The basic parameters of magnet powder and suspension are delivered in Table 1.

2.2. Stability of Suspension. Suspension is a two-phase medium made of a solid-liquid mixture. Its standing state results in the subsidence of suspending medium particles under the gravity effect and nonuniform vertical distribution of suspension density; thus, its flow state should be well regulated. Reducing particle size can improve suspension stability. Magnet with a particle size < 0.147 mm was taken as a dense medium in this test. Mechanical agitation or adding chemical reagents should be conducted to maintain suspension stability through the kinetic energy of vibration provided by a liquid pump.

2.3. Viscosity of Suspension. The dynamic viscosity of the magnet powder suspension presents three sectional changes with the increase of volumetric concentration, as shown in Figure 1. First, when the concentration was lower than 20%, the shear forces were slightly increased as the contact surface area between the medium particles and liquid was enlarged. As a result, the dynamic viscosity and concentration presented a relatively linear relation for concentration less than 25%. When the concentration was increased up to 40%, dynamic viscosity showed exponential growth with shear stress between medium interparticle and fluid. Finally, after the volumetric concentration reached over 40%, the suspension experienced structuring, so dynamic viscosity nearly presented a linear growth tendency. Accordingly, the volumetric concentration of the suspension was slightly oversized. In this study, the volumetric concentration for the field test was 25%.

Table 1: Basic parameters of magnet powder and magnet powder suspension.

Magnet powder				Magnet powder suspension			
Moisture content (%)	Magnetic content (%)	Total sulfur (%)	Density (10^3kg/m^3)	Dynamic viscosity ($\times10^{-3}$pa·s)	Density (10^3kg/m^3)	Volumetric concentration (%)	Particle size (mm)
7.6	95.57	0.18	4.67	4.89	1.95	25	<0.147

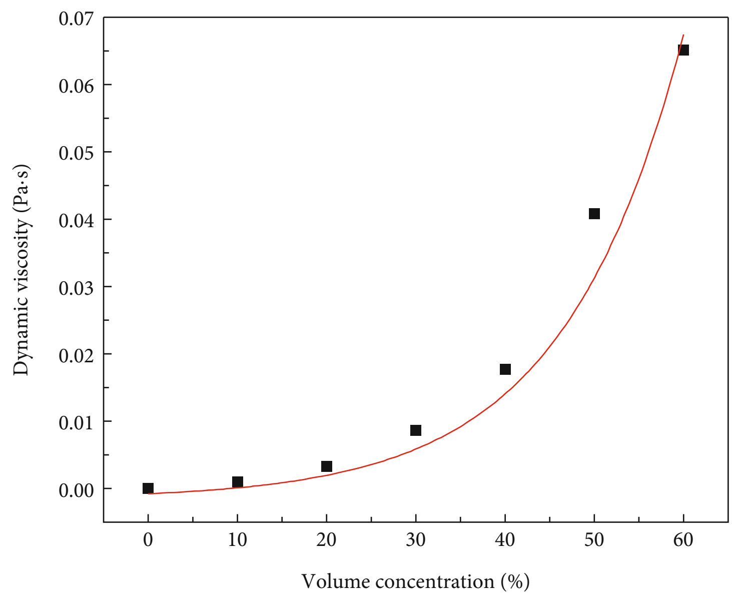

Figure 1: Relationship between suspension dynamic viscosity and volumetric concentration.

3. Field Test

Wulunshan Coal Mine in Guizhou exhibits a complex geological structure; the rock stratum at superficial parts is soft and loose. However, hard basalts were found at the deep seam floor. Jamming of drilling gear often takes place in the hard rock stratum after long-distance drilling by penetrating the coal seam because of the restriction in the performance of drilling machines. As a result, a significant amount of drilling debris was yielded in the drilling process. The interior wall of the drill hole could be easily destroyed. Also, the interior wall surface is rough, and the debris disposal resistance of compressed air is considerable. Hence, it was challenging to discharge drilling debris using the existing air compression-type debris disposal device carried by drilling equipment. Consequently, a significant amount of drilling debris was left in the drill hole, and the coal seam layer was buried by drilling debris, which directly influenced gas extraction. A comparative test was performed in the #1805 extraction roadway by selecting two pairs of drill holes. The arrangement is shown in Figure 2. The shallow drill hole was set in the #16 drill field. Drilling was stopped when debris disposal hole #16-6 was drilled to the front of the coal seam. The drilling depth of comparative hole #16-5 was extended for 1 m. The deep drill hole was set in the #12 drill field. Drilling was stopped when debris disposal hole #12-6 was drilled to the front of the coal seam. The drilling depth of comparative hole #12-5 was extended for 2 m. The drill hole parameters are given in Table 2.

3.1. Debris Disposal Technology. Figure 3 shows the schematic sketch of the suspension-aided hole-cleaning process. The uprushing fluid should be considered in selecting the flow direction. The uprushing flow velocity was contrary to the settling velocity of the added dense medium. When the uprushing flow velocity was equal to or greater than the settling velocity of maximum particles in the added dense medium, the suspension could reach a steady state. After drilling construction, the liquid injection and debris disposal pipes were installed correctly. The top opening of the borehole was sealed, and the suspension was then injected into the drill hole using a pulp pump. After the suspension entered the drill hole, drilling debris was suspended at the upper layer of the suspension under the effect of gravity–density difference, thereby forming a layered structure. As the suspension was continuously injected, the liquid discharged the drilling debris, which floated and filtered. Then, the suspension entered the box and was recycled. When the hole-cleaning work was completed, the water pipe was connected. Given that the particle size of the suspending agent was minimal, the suspending agent was gradually discharged with the upsurge of water flow. Finally, clear water was discharged using underground high-pressure gas, and the in-hole suspension was recycled. The entire hole-cleaning process of this test needed approximately 11 min.

3.2. Particle Size Analysis of Drilling Debris. The debris disposal in the shallow hole was relatively adequate. Thus, the drilling debris was sampled and sieved in the shallow hole

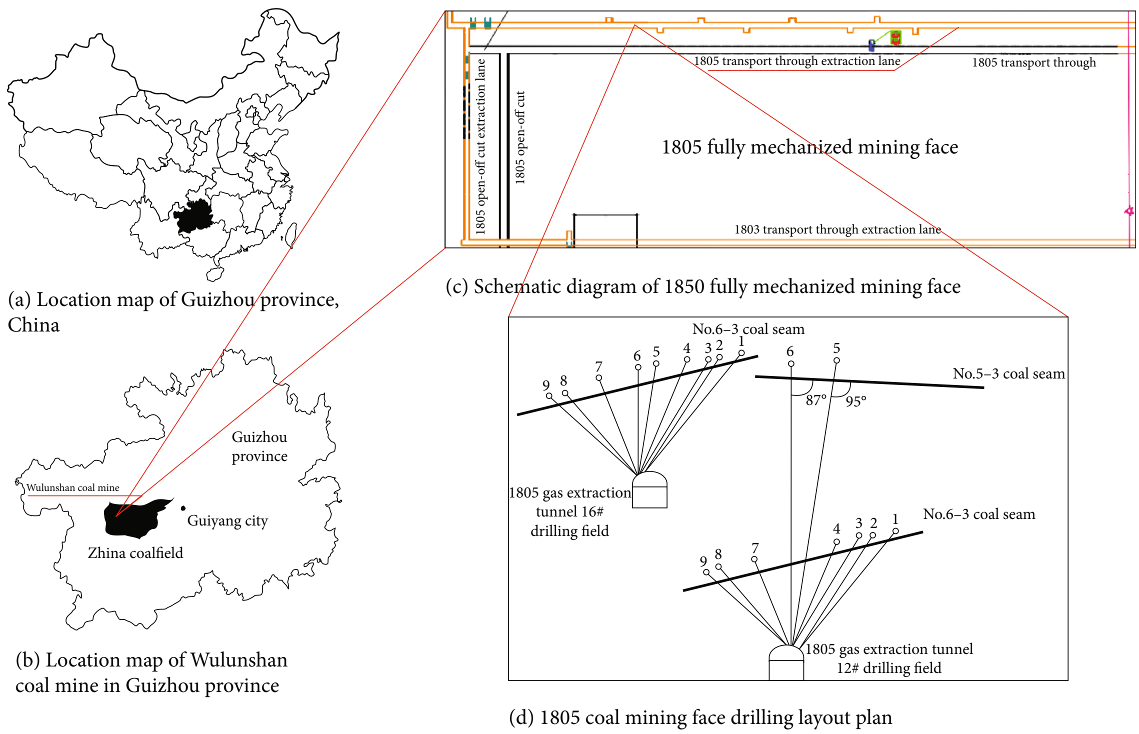

Figure 2: Layout drawing of drilling in the underground coal mine.

Table 2: Borehole construction settings and parameters.

Drilling number	Drilling depth (m)	Elevation of the coal seam (m)	The coal seam thickness (m)	Dip (°)
16#-6	21	19.6	1.4	87
16#-5	24	20.4	1.6	95
12#-6	74	72.2	1.8	87
12#-5	76	69.3	1.7	95

drilling process. The particle size distributions are presented in the form of histograms, as shown in Figure 4. The particle/grain size of the coal seam drilling debris in the drill hole was mainly within 2–5 mm, which accounted for approximately 42.22% of the significantly sizeable coal debris. In the deep hole, this drilling debris was of large mass and irregular shape, making it challenging to be discharged. The particle size of the drilling debris was larger than that of the coal debris. They were mainly flaky and massive, with particle sizes mainly being <2–5 mm, which accounted for 60.65%. These findings were attributed to the fact that the hardness of the rock stratum was relatively large, and the structure was relatively stable.

4. Analysis of Testing Results and Discussions

4.1. Comparison of Gas Extraction in Shallow Drill Hole. As shown in Figure 5, the extraction process presented the following four phases. (1) During the initial slow-rising phase (1–2 days), a certain amount of residual moisture was presented around the drill hole after the suspension discharged the debris. Thus, the moisture inhibited gas separation to a certain degree and hindered gas migration and diffusion. (2) During the rapid-rising phase (2–6 days), gas was continuously separated and rushed out, with the scattering and disappearance of the suspension. Hence, the quantity of gas extraction and concentration of extracted gas in the debris-discharged hole were close to those in the original drill hole. (3) During the stable phase (6–20 days), the quantity of gas extraction and the concentration of extracted gas in the debris-discharged hole were higher than in the original drill hole. After debris disposal, the drill hole extraction environment was improved, reducing the casing pipe's blocking probability. Drilling debris, inhibiting gas flow advection but facilitating gas diffusion, was not observed within a certain distance from the bottom part of the drill hole. This outcome was good for gas diffusion. Given that little residual drilling debris was left in the hole, the negative pressure of gas extraction was uniform, which reduced the probability of collapse to a certain degree. Therefore, the duration of the phase of steady-state was relatively long. (4) During the slow attenuating phase of debris disposal (after 20 days), the fluctuation of extracted gas concentration in the debris discharge hole was slower and weaker than in the original

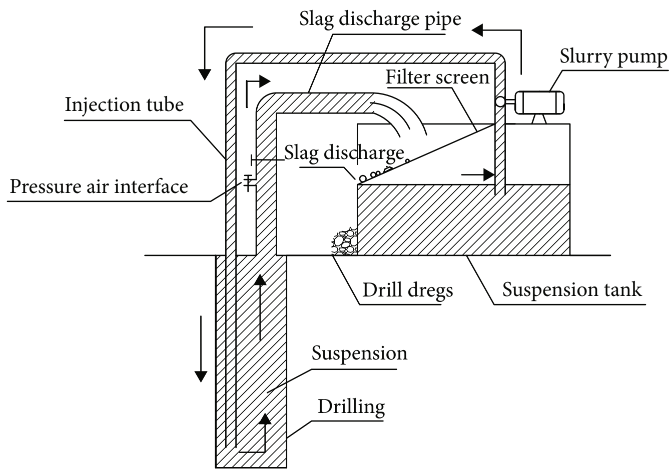

Figure 3: Schematic of the suspension-aided debris disposal.

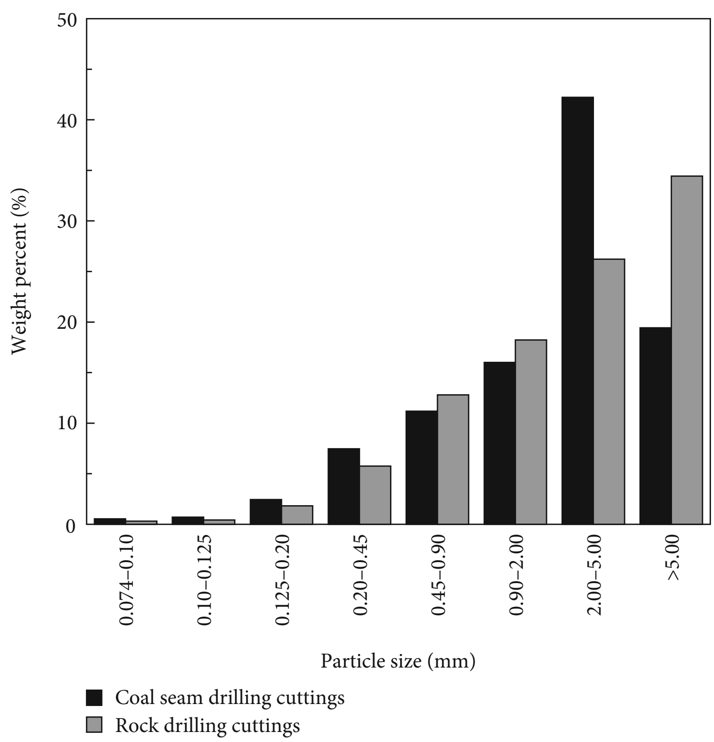

Figure 4: Particle size distribution of drilling debris for both rock layer and coal seams.

hole. Compared with the original drill hole, the quantity of gas extraction and concentration of extracted gas were increased by 40% and 21%, respectively, 30 days after debris discharge.

4.2. Comparison of Gas Extraction in Deep Drill Hole. As the comparisons given in Figure 6, the concentration of extracted gas and quantity of gas extraction increased significantly after deep drill hole debris disposal. The effects of drilling debris on gas extraction were deeply influenced by hole depth because much residual drilling debris was left at the deep hole bottom. Borehole drilling through the layer of coal seams was occasionally buried by coal and rock debris or partially buried. The gas migration resistance was considerable, which led to the turbulent vibration of drilling debris and gas vortices. As a result, the partial extraction kinetic energy was lost, and the blocking probability of the casing pipe was increased, which reduced gas extraction efficiency. After debris disposal, the floating debris on the inner wall surface of the drill hole was removed. As a result, the blocking probability of the casing pipe was reduced, and the gap between the rock stratum and coal seams was enlarged. Consequently, the negative pressure of gas extraction and contact area was enlarged, and the gas extraction

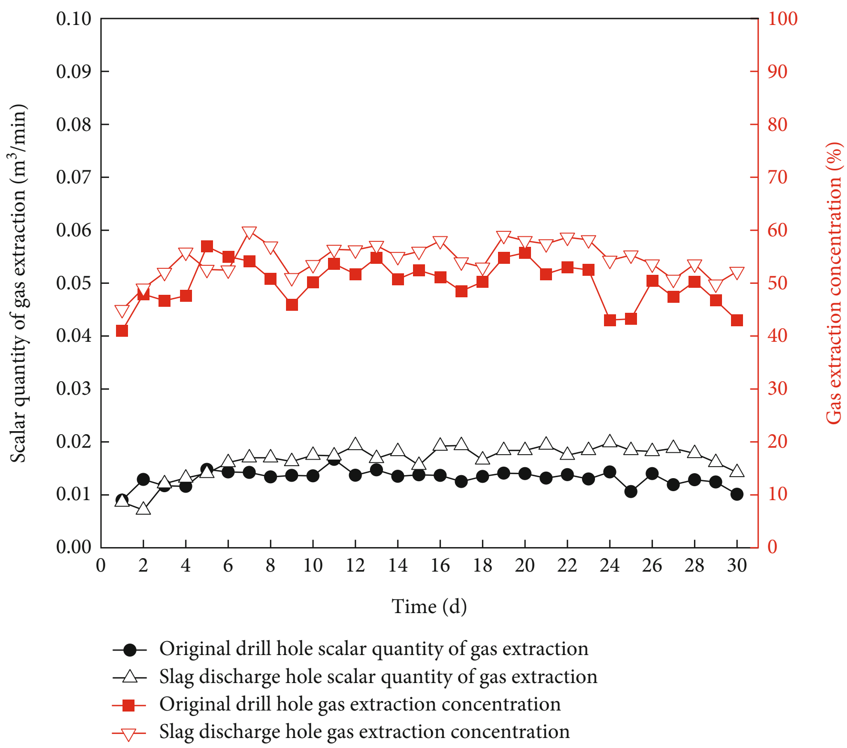

Figure 5: A comparison of extracted gas concentration and quantity of gas extraction in the shallow drill hole.

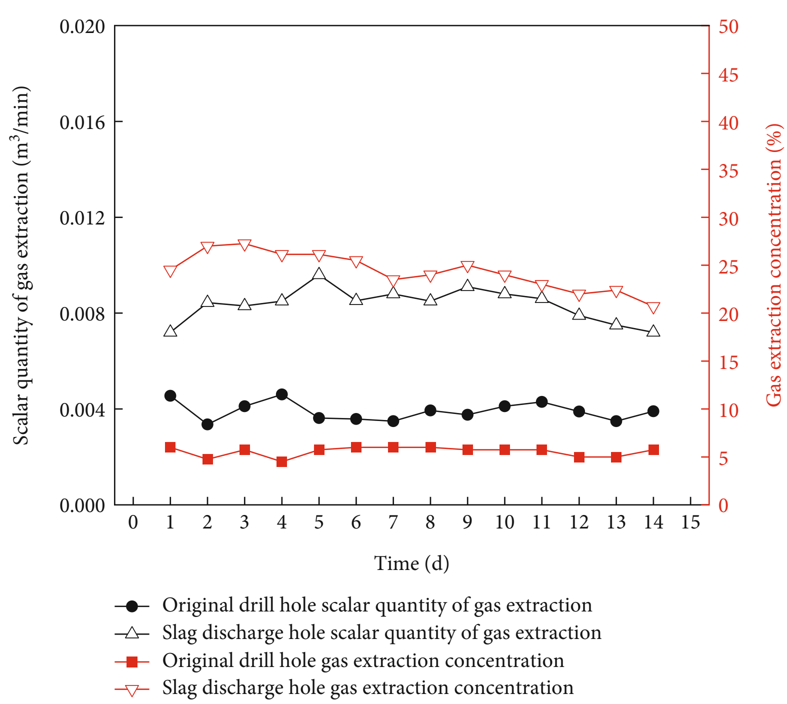

Figure 6: A comparison of the concentration of extracted gas and quantity of gas extraction in the deep drill hole.

effect was improved [20]. At 14 days after debris disposal, the extracted gas concentration and quantity of gas extraction were separately increased by 84% and 260%.

Last but not least, this work has only very intuitively analyzed the experimental outcomes regarding the gas extraction and gas flow regimes through porous media. Thus, it is necessary to further investigate the multiphase seepage through porous media consisting of rock and coal debris based on the advanced theory [21]. In addition, the experiments and numerical simulations in studying gas-

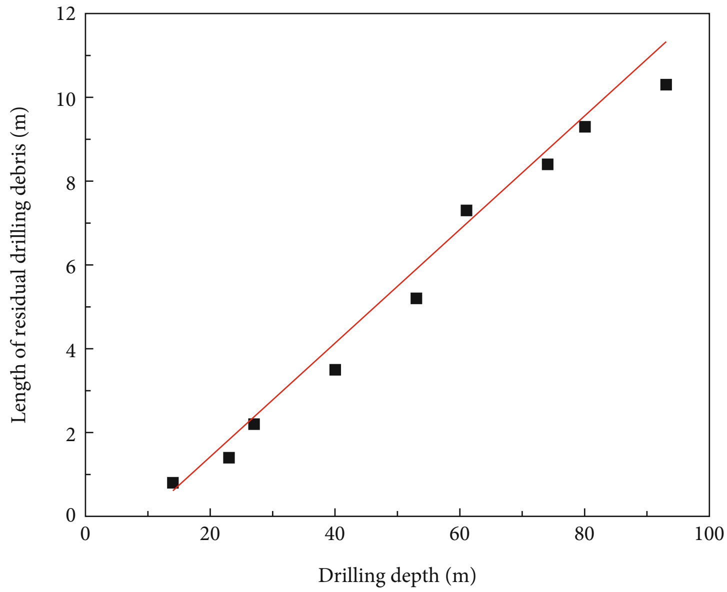

FIGURE 7: The linear relationship between the lengths of residual drilling debris and drill hole depths.

TABLE 3: The parameters of Equation (1) between the residual lengths for drilling debris and depth.

Linear fitting parameters	A	B	R^2
Fitting values	−1.302	0.129	0.987

water seepage and dynamic multiphase flow regimes at multiscale can bring more physical insights into gas extraction during underground mining and shed light on this research aim when gas and water phase is in either the continuous or nonconscious form [22, 23].

4.3. Relationship between Residual Volume of Drilling Debris and Depth. The geological conditions of the mine and the parameters of the drilling machine were combined to further study the relationship between the length of residual drilling debris and drill hole depth. Figure 7 shows the length of residual drilling debris and drilling depth evolution, and the measured data of the measuring points are fitted as follows:

$$\Delta L = A + B \cdot x, \tag{1}$$

where the ΔL is the length of residual drilling debris and the x is the drilling depth; the A and B are fitting parameters for this linear relationship. Table 3 provides the fitting parameters of Equation (1).

The testing outcomes indicated that the length of residual drilling debris increased as the drilling depth increased. The length of the residual drilling debris positively correlated with the drilling depth when using an air compression-type drilling machine for debris disposal with a diameter of 75 mm. As unveiled in Figure 7, the residual debris length was small, within 20 m of the drilling depth. When the drilling depth was up to 53 m, the length of residual drilling debris reached 5.2 m, and the residual rate was approximately 9.8%. When the drilling depth came to 93 m, the coal and rock debris formed gas vortices inside the drill hole because the debris disposal distance was much longer. Also, the length of the residual amount of debris in the drill hole reached 10.3 m under obstructing and adhesive actions of the rough inner wall. As a result, the residual ratio was 11.1%, and the effective drilling distance was actually only 82.7 m, significantly restricting the effective drilling depth. Therefore, the debris disposal method should be used to make the length of the extracted drill hole section reach an effective drilling distance under a restricted drilling depth.

5. Conclusions

(1)The adversary aspects, including unsatisfactory deep drill hole debris disposal, the rough drill hole wall at the soft and loose coal seam, difficulties in debris disposal, and other limitations existing in the downward drilling technology of coal mines, were all considered in this experimental study. In addition, debris disposal technology was optimized to ensure that the effective drilling depth could conform to technical requirements, thereby improving the effective utilization rate of drill holes

(2)The magnet powder commonly used in beneficiation and mineral processing was selected as the suspension for debris disposal in the drill hole. This selection was based on the fundamental properties of the drilling debris in the drill hole of the coal mine as well as the characteristics of the existing suspending agents combined

(3)The influences of debris disposal in shallow and deep drill holes on the effects of gas extraction were compared. The results showed that debris disposal in the shallow drill hole improved the gas-extracting environment to a certain degree and also increased the extracted gas concentration and quantity of gas extraction. Nevertheless, the gas extraction effect was significant for deep holes. Therefore, the debris disposal method could be utilized to reduce the drilling workload and jamming rate of the drilling machine. Furthermore, given the restriction from geological conditions and drilling machines, debris disposal measures could be taken to improve the utilization efficiency of drill holes and ensure qualified gas extraction length when the drill hole fails to reach the adequate depth

Data Availability

This article includes all the datasets used to underpin the research findings reported in this study.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgments

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