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Drill Cuttings Test of Coal Under Different Stresses and Characteristics of Coal Particle Distribution During Borehole Collapse

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Abstract: The drill cuttings method is a commonly used method for evaluating coal burst risk in mines. In engineering applications, due to the development of fractures in coal seams, borehole collapse can easily occur during drilling, which leads to a greater quantity of drill cuttings. This in turn affects the accuracy of the evaluation results of coal burst risk. Through laboratory tests on drill cuttings from intact coal and fractured coal specimens, the impact of coal stress and diameter of the borehole on the quantity of drill cuttings and the occurrence of borehole collapse was studied. When there is no collapse, the quantity of drill cuttings increases in proportion to the diameter of the borehole and the coal stress and has a power function relationship with the diameter of the borehole and an exponential function relationship with the coal stress. When the collapse occurs, the failure characteristics of coal specimens mainly present two forms. One is the cylindrical collapse area, and the other is the conical collapse area. Compared to normal drilling, there are notable changes in the particle size of drill cuttings after borehole collapse, and the characteristic value of drill cuttings size D50 increases significantly after the collapse of the borehole, which can be used to determine whether the borehole collapse occurs.

Keywords: coal burst; drill cuttings; borehole collapse; particle size; identification method

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1. Introduction

Coal burst is a common major dynamic disaster in the process of deep coal mining. As the depth of mining increases, both the frequency and intensity of coal bursts escalate dramatically [1–3]. High stress concentration is one important factor inducing coal bursts [4–6]. Therefore, the stress peak value and distribution characteristics of coal seams are often used as an important index for coal burst monitoring and early warning. The stress of a coal seam is often monitored by the drill cuttings method, borehole stress gauge, shock wave CT technology, and so on [7–10]. Among them, the drill cuttings method is one commonly used method for monitoring coal stress distribution and coal burst risk.

In the construction process of the drill cuttings method, small-diameter boreholes should be drilled in the coal seams. According to the quantity of drill cuttings discharged from the borehole and the dynamic phenomenon, the burst risk can be evaluated [11]. In terms of theoretical research, scholars have explored the relationship between coal

stress and the quantity of drill cuttings from various perspectives to establish a standard method for predicting coal burst [12,13]. Tang Jupeng et al. [14] used the Mohr–Coulomb criterion as the yield condition to carry out an elastic–plastic analysis of a deep coal body, and they pointed out that the amount of drill cuttings can be divided into two kinds: static drill cuttings and dynamic drill cuttings. The static drilling cutting amount is the solid core amount of the drilling coal body. The amount of dynamic drill cuttings is composed of three parts: the elastic deformation of the borehole, the elastic unloading at the junction of the elastic zone and the broken zone, and the expansion of the coal body in the broken zone of the hole wall. Regarding theory and laboratory test research on the drill cuttings method, Geng et al. [15] developed a theoretical calculation formula for drill cuttings in both the plastic zone and elastic zone of a roadway, and a correlation was established between the quantity of drill cuttings, the diameter of the borehole, and coal stress. Tang et al. [16] performed three-dimensional stress condition tests on coal specimens and studied the influence of drilling depth, coal stress, and drilling diameter on drill cuttings. Currently, most laboratory test studies on the drill cuttings method focus on intact coal specimens [17–21]. There are few quantitative comparative studies on drill cuttings characterization in intact and fractured coal specimens. There are many cracks in coal in the engineering site. When the drill cuttings method is tested in cracked coal in situ, the quantity of drill cuttings may increase sharply. According to the correlation between the quantity of drill cuttings and the coal stress, the stress value of the coal specimens calculated will be far greater than the normal value. This phenomenon is caused by the collapse of holes or the large stress of coal specimens during drilling. If the sudden increase in drill cuttings is caused by borehole collapse, there will be significant deviations or even misjudgments when using this drill cuttings data for burst risk assessment. Therefore, it is necessary to identify borehole collapse. However, there is no reasonable and effective method to determine whether a borehole collapse has occurred. Therefore, with the purpose of analyzing the influence of coal stress on the quantity of drill cuttings and investigating methods for identifying borehole collapse, drilling tests using intact coal and briquettes prepared from coal powder particles were carried out to study the influencing factors and coal failure characteristics during borehole collapse. Based on the correspondence between coal stress and the diameter of the borehole during collapse, a criterion for identifying borehole collapse was established. Additionally, the distribution and variation patterns of drill cutting particle sizes were analyzed, and a method for identifying borehole collapse was proposed.

2. Test Schemes and Methods

2.1. Coal Specimens Preparation

In this paper, drill cuttings tests were conducted on two types of coal specimens. For the intact coal drill cuttings test, specimens were prepared from raw coal, and the varying laws of the quantity of drill cuttings under the influence of the coal stress and diameter of the borehole were studied. In contrast, for the fractured coal drill cuttings test, specimens were fabricated using coal briquettes, with a focus on examining the response of drill cuttings during the drilling of complex fractured coal specimens. In this paper, the drill cuttings test of two kinds of coal specimens is mainly carried out. For the drill cuttings test I of complete coal specimens, the test piece is made of raw coal, and the varying laws of drill cuttings under the influence of coal stress and the diameter of the borehole are studied. The drill cuttings test II of fractured coal specimens takes briquette as the test specimen and focuses on the response law of drill cuttings in the drilling process of complex fractured coal specimens. The briquette specimens are made of pulverized coal particles with different particle sizes [22].

The intact coal specimens used in the intact coal specimen cuttings test I were selected from one Coal Mine in Jining, Shandong Province, China. The raw coal of these specimens was taken from the coal seam of the same working face and the same place, and the size of the coal specimens was 100 × 100 × 100 mm, as shown in Figure 1. The average elastic modulus, uniaxial compressive strength, and Poisson's ratio were 1.49 GPa, 39.8 MPa, and 0.31, respectively.

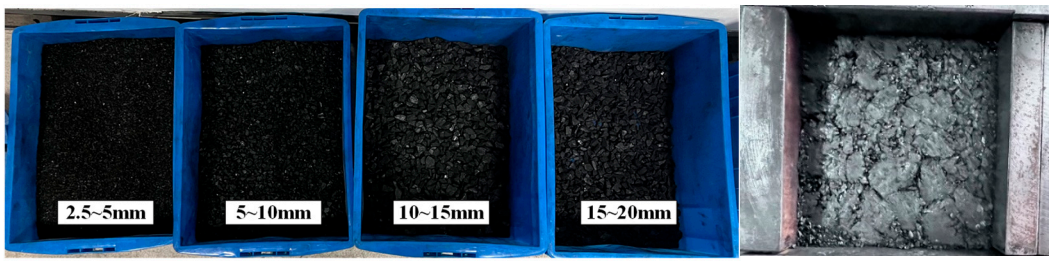


Figure 1. Intact coal specimens.

The test specimen in the fractured coal drill cuttings test is a briquette, which is pressed by pulverized coal particles with different particle sizes. The coal particles are crushed from the raw coal taken from the Coal Mine. The coal particle size is listed in Table 1. During the preparation of fractured coal specimens, coal particles of varying sizes were meticulously blended and evenly packed into a square box measuring 100 × 100 × 150 mm. Subsequently, coal specimens of dimensions 100 × 100 × 100 mm were crafted by subjecting them to a rock mechanics testing machine, operating at a controlled loading rate of 0.2 mm/min. This process was servo-controlled for 1 h under a stress of 20 MPa, equivalent to the in situ stress experienced by a coal seam buried at a depth of 800 m, as shown in Figure 2.

Table 1. Particle size distribution of coal particles [23].

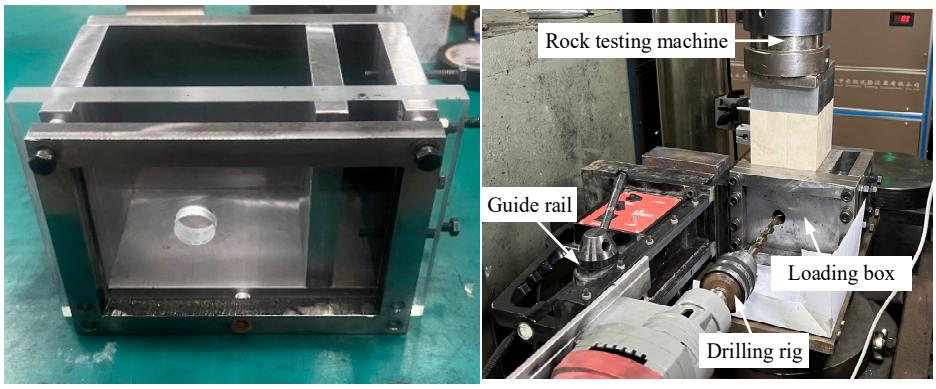
Coal Particle Size (mm)	2.5~5	5~10	10~15	15~20
Proportion of mass	27.5%	26.5%	24%	22%
Mass (g)	302.5	291.5	264	242



(**a**) (**b**)

Figure 2. Fractured coal pressed by (**a**) different size coal particles and (**b**) final specimen.

To simulate the stress conditions within deeply buried coal seams, a coal specimen drilling test apparatus has been designed, comprising a loading box and a drilling rig. The loading box serves to restrict the lateral displacement of the specimen, with a centrally located circular hole in the front bearing plate facilitating the passage of the drill pipe through the coal specimen. The drilling rig, equipped with a magnetic base and integrated guide rail, ensures precision and stability during the drilling process. The detailed setup for the drill cuttings test is shown in Figure 3.



(**a**) (**b**)

Figure 3. Drilling test of coal specimens in (**a**) the loading box and (**b**) drilling test apparatus.

The intact coal specimens or fractured coal specimens were placed in the drilling test apparatus, and the RLJW-2000 rock mechanics testing machine was used to perform axial loading with a speed of 0.2 mm/min. After loading to the designed stress value, servo control was carried out to keep the axial stress unchanged. Subsequently, the drilling rig was initiated to bore into the specimen, and upon the drill pipe's complete penetration through the specimen, the drilling process was halted. We then proceeded to gather the drill cuttings and weigh them accordingly.

For the coal drill cuttings test, four distinct initial stress conditions were designed, with each condition set at 10, 20, 30, and 40 MPa, respectively. Furthermore, under each of these initial stress levels, five borehole size drilling tests were conducted, featuring diameters of the boreholes D of 6, 8, 10, 12, and 14 mm, respectively.

2.2. Monitoring and Data Analysis Methods

In the test, in addition to collecting drill cuttings and weighing them as a whole, the distribution of particle size among the drill cuttings was determined by means of the screening method. The drill cuttings collected during drilling were screened according to seven particle size grades of 0~0.063 mm, 0.063~0.125 mm, 0.125~0.25 mm, 0.25~0.5 mm, 0.5~1 mm, 1~2 mm, and 2~4 mm, and the drill cuttings of each particle size grade were weighed. The particle size among drill cuttings was converted to the ratio of total drill cuttings.

The ratio of drill cuttings weighing data of different particle size grades can be statistically analyzed, and the particle size distribution histogram can be drawn. The logarithmic normal distribution function is fitted, as shown in Figure 4. The histogram of particle size distribution and the curve of normal distribution function can intuitively reflect the distribution law of each grade of drill cuttings under the influence of different factors. The cumulative curve of particle size distribution can be drawn, and the distribution range of particle size grades of D50 and D90 can be obtained under the influence of different factors. The distribution characteristics and variation forms of drill cutting sizes under different influencing factors can be further analyzed. In the context of cumulative particle size distribution, D50 is defined as the corresponding particle size at which the cumulative percentage of the sample reaches 50%, which is usually used to represent the average particle size; D90 is defined as the corresponding particle size at which the cumulative percentage of the sample reaches 90%, which is usually used to represent the particle size index of coarse particles.

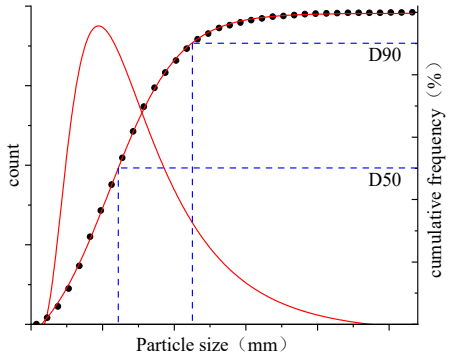


Figure 4. Particle size distribution diagram.

3. Test Results and Analysis

3.1. Drill Cuttings of Intact Coal Specimens with Different Diameters

The quantity of drill cuttings present in intact coal specimens at varying diameters of the boreholes is listed in Table 2. The quantity of drill cuttings produced is influenced by the diameter of the borehole, exhibiting a positive correlation. When the diameter of the borehole is 6 mm, the quantity of drill cuttings is 2.62 g. When the diameter of the borehole increases to 12 mm, the quantity of drill cuttings increases to 13.9 g; that is, when the diameter of the borehole increases 1 time, the quantity of drill cuttings increases by about 4.31 times. When the diameter of the borehole increases to 14 mm, the quantity of drill cuttings increases to 18.97 g; that is, when the diameter of the borehole increases by about 1.3 times, the quantity of drill cuttings increases by about 6.24 times. The quantity of drill cuttings is positively correlated with the diameter of the borehole as a power function, as shown in Figure 5.

Table 2. Drill cuttings amount of coal under different diameters of the borehole.

Stress (MPa)	Diameter of the Borehole (mm)	Drill Cuttings Amount (g)		
		Specimen ①	Specimen ②	Mean Value
10	6	2.1	3.14	2.62
10	8	6.09	5.9	5.995
10	10	8.57	8.38	8.475
10	12	13.92	13.88	13.9
10	14	18.89	19.05	18.97

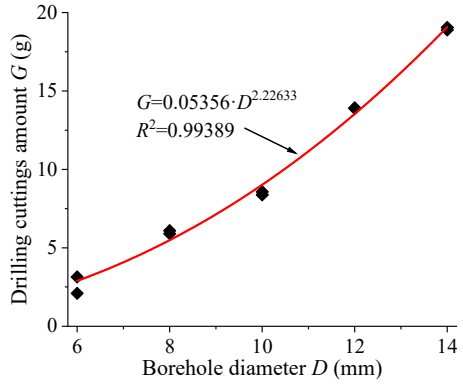


Figure 5. The relationship between diameter of the borehole and drill cuttings amount.

3.2. Drill Cuttings of Intact Coal Specimens Under Different Stresses

The quantity of drill cuttings in the intact coal specimens at varying coal stress is listed in Table 3. The quantity of drill cuttings increases with the increase in coal stress.

When the stress applied to the coal falls within the range of 0 to 30 MPa, the maximum increase in the quantity of drill cuttings does not exceed 10% for every 10 MPa increase in coal stress. However, when the coal stress reaches 40 MPa, there is a substantial jump in the drill cuttings amount, with an increase of approximately 44.44% compared to that at 30 MPa. It is important to note that the uniaxial compressive strength of the coal specimens is 39.8 MPa. When the specimens undergo plastic deformation, there is a significant surge in the quantity of drill cuttings. As shown in Figure 6, an exponential positive correlation exists between the quantity of drill cuttings and the stress applied to the coal specimens.

Table 3. Drill cuttings amount of coal under different coal stresses.

Stress (MPa)	Diameter of the Borehole (mm)	Drill Cuttings Amount (g)		
		Specimen ①	Specimen ②	Mean Value
10	10	8.57	8.38	8.475
20	10	8.56	8.63	8.595
30	10	8.8	9.47	9.135
40	10	13.42	12.97	13.195

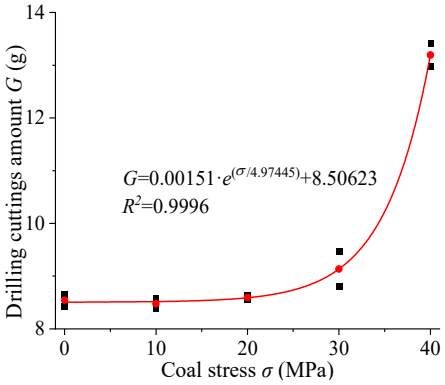


Figure 6. Relationship between coal stress and drill cuttings.

3.3. Drill Cuttings of Fractured Coal Specimens

For fractured coal specimens, with low stress or a small diameter of the borehole, the quantity of drill cuttings gradually increases with the increase in coal stress or the diameter of the borehole, which is similar to that of intact coal specimens. However, the quantity of drill cuttings is greater, as shown in Table 4, indicating that the existence of coal cracks can increase the quantity of drill cuttings. When the coal stress or the diameter of the borehole exceeds a certain value, the quantity of drill cuttings increases suddenly, and the drill cuttings continue to discharge under the condition of non-stop drilling. After the drill pipe is extracted, an obvious borehole collapse phenomenon can be observed, as shown in Figure 7. When the coal stress is 20 MPa, the borehole collapse occurs when the diameter of the borehole is 14 mm, and the quantity of drill cuttings is about 3 times that of the non-collapse borehole. When the coal stress is 30 MPa, the borehole collapse occurs when the diameter of the borehole reaches 10 mm, and the quantity of drill cuttings is about 2~4 times that of the non-collapse borehole. When the coal stress is 40 MPa, the borehole collapse occurs when the diameter of the borehole is 8 mm, and the quantity of drill cuttings is about 3~8 times that of the non-collapse borehole.

When the strength of coal specimens is low and there are many internal cracks, borehole collapse can occur during drilling operation. For the same coal specimens, the occurrence of hole collapse is contingent upon both the diameter of the borehole and the stress. When the diameter of the borehole remains constant and the stress in the coal specimens exceeds a specific threshold, borehole collapse can occur even in specimens that

had previously resisted it. Conversely, maintaining a constant stress level while enlarging the diameter of the borehole can likewise precipitate borehole collapse. Laboratory tests have yielded a criterion formula for predicting such collapses, as shown in Figure 8. If the combined stress and diameter of the borehole coordinates fall above the criterion curve, the occurrence of borehole collapse is imminent.

Table 4. Drill cuttings amount of fracted coal specimens.

Stress (MPa)	Drill Cuttings Amount (g)				
	***D* = 6 mm**	***D* = 8 mm**	***D* = 10 mm**	***D* = 12 mm**	***D* = 14 mm**
10	4.33	9.73	12.98	18.74	26.49
20	6.38	10.72	14.91	22.67	78.85 (Collapse)
30	6.68	18.02	167.05 (Collapse)	102.6 (Collapse)	77.57 (Collapse)
40	14.46	125.39 (Collapse)	63.61 (Collapse)	100.52 (Collapse)	85.1 (Collapse)

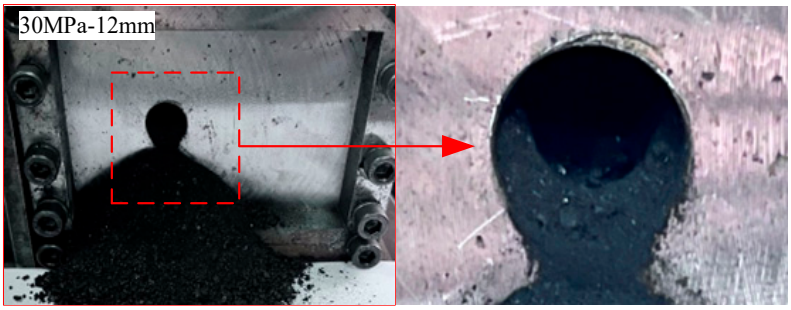


Figure 7. Drill cuttings accumulation at the borehole opening during collapse.

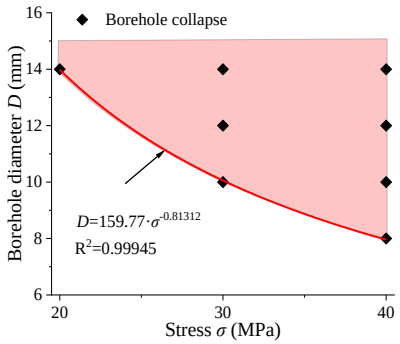


Figure 8. The relationship between diameter of the borehole and coal stress during borehole collapse.

3.4. Characteristics and Modes of Borehole Collapse

The coal specimens are processed after the collapse, and the loose coal blocks around the borehole are cleaned, showing the scope and morphological characteristics of the collapse borehole, as shown in Figure 9. The range of borehole collapse area increases with the increase in the diameter of the borehole and coal stress. The radius of the borehole collapse zone is about 2~3 times that of the radius of the borehole, and some of the failure modes are similar to the cylindrical shape. For example, when the coal stress is 40 MPa and the diameter of the borehole is 14 mm, the borehole collapse zone of the cylindrical shape is from the opening of the borehole to its end. When collapse occurs, it is generally the combined effect of higher coal stress and a larger diameter of the borehole, and the increase in coal stress expands the range of the cylindrical borehole collapse zone. Another failure mode of collapse is similar to the cone, such as the collapse zone when the coal stress is 40 MPa and the diameter of the borehole is 8 mm. Some specimens exhibit intact coal at the

borehole opening, while internal collapse occurs within, such as the collapse area when the coal stress is 30 MPa and the diameter of the borehole is 14 mm.

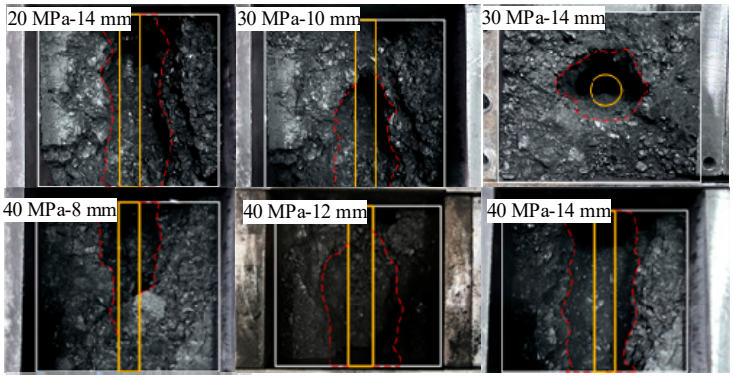


Figure 9. Borehole collapse patterns of coal under different stresses and diameters of the boreholes.

3.5. Particle Size Distribution of Drill Cuttings in Fractured Coal Specimens

In the previous study on the variation law of drill cuttings during normal drilling, the compressive strength of the selected intact coal specimen is large, and the internal cracks of the specimen are fewer, so it is difficult to collapse. Therefore, the fractured coal specimen pressed by pulverized coal particles is used. The fractured coal specimen is disturbed by the drilling process, and the collapse of pulverized coal particles leads to a sharp increase in the amount of drill cuttings. In the fractured coal specimen drill cuttings tests, when a borehole collapses, it can be observed that there is a notable increase in the size of the particles of drill cuttings. In order to compare the particle size characteristics of drill cuttings in normal drilling and borehole collapse in a quantitative manner, the quantity of drill cuttings in different particle size ranges is statistically analyzed.

When the diameter of the borehole is 10 mm, the histogram of the particle size distribution of the drill cuttings during normal drilling and during the collapse is shown in Figure 10. Gauss curve fitting is performed to obtain the geometric mean of the particle size of the drill cuttings, and the geometric mean is used to represent the average particle size of drill cuttings. The average particle size of drill cuttings is 0.616 during normal drilling, and it increases to 1.26 during borehole collapse. During normal drilling, the characteristic value of D50 is 0.42, and the characteristic value of D90 is 2. When the hole collapses, the D50 eigenvalue increases to 0.62, and the D90 eigenvalue increases to 2.51, indicating that the particle size of the drill cuttings increases when the hole collapses.

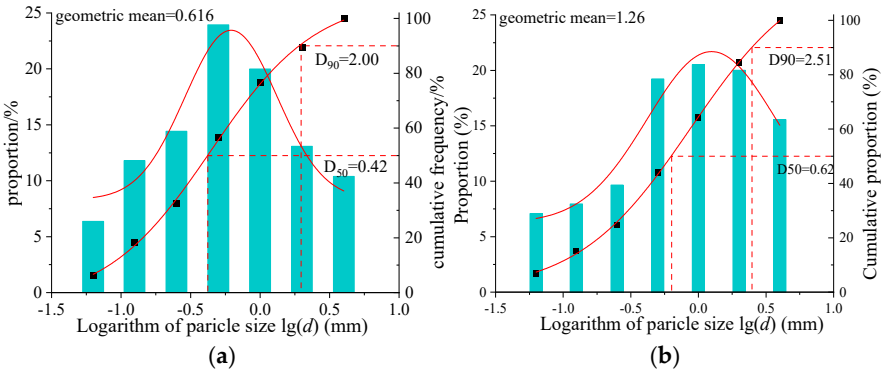


Figure 10. Particle size distribution of drill cuttings (**a**) during normal drilling and (**b**) during borehole collapse.

In the fractured coal specimen drill cuttings tests, the statistics of D50 under different diameters of the boreholes and coal stress are shown in Figure 11. It is evident that the

value of D50 is less than 0.5 during normal drilling. The value of D50 increases obviously after the borehole collapse, and the value is 0.53~0.79. Therefore, the occurrence of borehole collapse can be assessed by evaluating the D50 value of the drill cuttings.

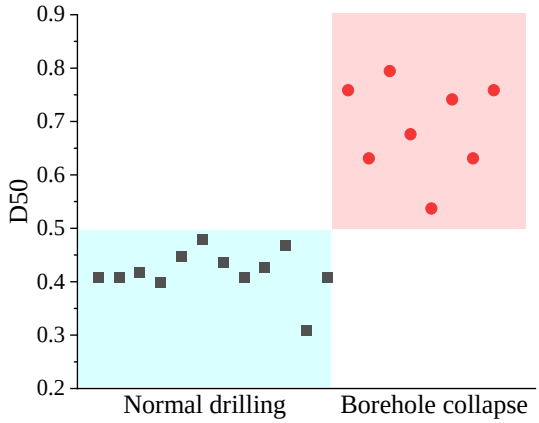


Figure 11. D50 value of drill cuttings during normal drilling and borehole collapse.

4. Discussion

In the drilling construction with a drilling rig, the drilling form is mainly the cutting action of the drill bit. Under the cutting action of the drill bit, the coal seam is cut and ground into small particles. Due to the large drilling depth of the drill cuttings method, during the drilling process of the drill pipe, in addition to the cutting effect between the drill bit and the bottom of the borehole, the high-speed rotating drill pipe also shakes and cuts the borehole wall. When the coal borehole wall is relatively intact with little cracks, the borehole wall is slowly deformed under the stress. The drill pipe grinds the borehole wall to produce small coal particles. When the fracture of the coal seam around the borehole is more developed and the stress concentration is high, the borehole may collapse. When the borehole collapses, the coal on the borehole wall peels off. The peeled coal block is hit and cut by the high-speed rotating drill pipe, which generates pulverized coal with larger particles, resulting in a sudden increase in the quantity of drill cuttings.

When the borehole collapses, the overall particle size of the drill cuttings increases significantly, and the proportion of large-grained drill cuttings increases. Therefore, it can be judged whether the borehole collapse occurs according to the change in the particle size of the drill cuttings. When the quantity of drill cuttings increases sharply during the drilling process, the particle size of the drill cuttings is analyzed. If the particle size of the drill cuttings increases significantly, it can be judged that the borehole collapses. If the particle size of the drill cuttings does not increase significantly, the stress at the current depth of the borehole should be great.

During the drilling operation in the coal seam, whether the borehole collapse occurs can be judged by the amount and the particle size of the drill cuttings. When the borehole collapse occurs, the drill cuttings data from this borehole are not suitable for evaluating the risk of coal bursts. A new position should be selected nearby to re-drill the borehole. When drilling to the depth of the collapse location in the previous borehole, the construction personnel should reduce the drilling speed, reduce the disturbance of the drilling to the coal body, and prevent the recurrence of the borehole collapse phenomenon, so as to ensure the smooth progress of the drilling operation.

5. Conclusions

(1) When the intact coal specimen is normally drilled, the quantity of drill cuttings increases in proportion to the diameter of the borehole, showing a power function

relationship. The quantity of drill cuttings increases in proportion to the coal stress, showing an exponential function relationship.

(2) When the borehole collapse occurs, the coal at the borehole wall pours into the borehole, resulting in a sharp increase in the quantity of drill cuttings. The failure characteristics of the borehole collapse are divided into two forms. One is the cylindrical collapse area, and the other is the conical collapse area.

(3) The distribution and variation law of drill cuttings particle size are positively correlated with coal stress and diameter of the borehole. When there is no collapse, the characteristic value of drill cuttings particle size D50 is in the range of 0.31~0.47, with an average value of 0.39. When there is collapse, the characteristic value of D50 increases to 0.53~0.79, with an average value of 0.66.

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Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Conflicts of Interest: Authors Cunwen Wang and Dongdong Zhang were employed by the company Shandong Energy Group Co., Ltd. Author Shudong He was employed by the company China Coal Technology & Engineering Group Chongqing Research Institute. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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