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Research Article

A New Method for Predicting Coal and Gas Outbursts

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In view of the fact that coal and gas outbursts are difficult to predict, a new method for predicting coal and gas outbursts was proposed based on occurrence mechanisms of coal and gas outbursts relating to coal mass strength, gas pressure, and *in situ* stress. The method revealed that the rate of occurrence of coal and gas outbursts in mines was 5% to 10% and gas pressures for coal and gas outbursts in shallow and deep mines in China were greater than 0.74 and 0.6 MPa, respectively. The prediction index for coal and gas outbursts based on the gas factor was the gas desorption index of drilling cuttings (K_1), which is referred to the gas content desorbed from the coal mass in the first minute of drilling. The prediction index for coal and gas outbursts based on coal mass strength was the thickness of a soft layer that could be twisted into powder by hand. Based on many cases of coal and gas outbursts, the critical thickness of the soft layer was found to have been 0.2 m. The prediction index for coal and gas outbursts based on *in situ* stress was the weight of drilling cuttings, which represented the mass of drilling cuttings per linear metre of boreholes with diameters of 42 or 75 mm. Finally, the new prediction method and prediction index critical values for coal and gas outbursts were verified based on industrial application tests. This method has been widely applied on-site and obtained good prediction results.

1. Introduction

From the perspective of energy demand, the dominance of coal in the energy structure will not change in the near future in China. The proportion of coal consumption will remain at about 50% for a long time and about 80% of this coal is mined in underground wells. In recent years, with the large-scale exploitation of coal, mining depth of mines in the central and eastern China has rapidly increased and extends to the deep parts at the rate of nearly 20 m per year. Western resources have also been developed in a large area, with coal production increasing in these regions, such as Shaanxi Province, the Inner Mongolia Autonomous Region, and the Xinjiang Uygur Autonomous Region. This leads to an increasingly serious threat posed by dynamic disasters, such as coal and gas outbursts, to safe production in coal mines. Statistical data in recent years show that although a series of effective measures have been taken to prevent disasters and accidents in coal mines, the number of outburst-prone mines still increases by hundreds every year [1], and the number of outburst accidents and deaths has not decreased significantly. Therefore, effectively preventing gas accidents in coal mines, especially coal and gas dynamic disasters represented by coal and gas outbursts, has been the primary task of engineers working in the field of coal mine safety.

The mechanism of occurrence of coal and gas outbursts refers to the cause, condition, and process of initiation, excitation, development, and termination of coal and gas outbursts. The comprehensive theory of action is generally accepted in terms of occurrence mechanism and prediction of coal and gas outbursts. The representative theories include energy theory, theory of crushing wave, theory of uneven stress distribution, theory of initiation centre, the rheological hypothesis of Zhou and He [2], the spherical shell destabilisation concept of Jiang and Yu [3], instability theory of flow fixation coupling of Liang et al. [4], and the catastrophe theory of Wang and Yu [5]. In addition, the stick-slip mechanism of Guo and Han [6], dimensional analysis method of Zheng [7], mechanical theory of Hu et al. [8], deductive method of Xian et al. [9], hierarchical control theory of geological structure of Zhang [10], main controlling geological body theory of the authors [11], and key structure body theory of Shu et al. [12] are also included. Other scholars have done physical simulation experiments of coal and gas outbursts [13–25], Xu et al. [13] have obtained that the exposed area of coal seam has some effect on coal and gas outburst; Tang et al. [14] have obtained that high-pressure gas is not only outbursting power but also damage power for powdered coal; Zhang et al. [15] have investigated the distribution and characteristics of gas pressure and stress ahead of the crosscut uncovering the closed type tectonic fracture zone; Lei et al. [16] have acquired the frequency characteristics in the four stages; Zhao et al. [17] have designed the simulation test system of coal and gas outburst including single gas pressure test machine and gas pressure and ground stress comprehensive test machine; Nie et al. [18] have conducted an artificial outburst with absorption equilibrium pressure of 0.30 MPa and inducing pressure of 0.53 MPa; Li et al. [19] have studied the judgment criterion of the comprehensive effect for coal body stress and gas pressure; Wang et al. [20] have studied the influences of gas adsorption on coal and gas outburst; Wang et al. [21] have established a model of energy conditions and a model of intensity assessment for outburst and have verified the model with real cases; Li et al. [22] have established the prediction models of outburst energy and taken Pingdingshan mining area as an example; Xu et al. [23] have analyzed the evolution process of temperature-pressure-stress during outburst; Wen et al. [24] have analyzed the theoretical requirements of the over-kilometer deep mining environment on the indexing requirements of the outburst simulation system loading capacity, system stiffness, gas pressure, and temperature and have proposed its critical indicators; and the outburst simulation tests have verified theories of relevant mechanisms of occurrence. Hu et al. [25] used the drilling cuttings index to predict coal and gas outbursts; Dong [26] used the drilling cuttings index and acoustic emission index to predict coal and gas outbursts; Li et al. [27] predicted coal and gas outbursts based on spatial chaos theory using gas desorption index of drill cuttings; Tang et al. [28] used the expansion energy of the initially released gases to predict coal and gas outbursts; Chen et al. [29] studied an FDA-based multiple indicators discriminant model of coal and gas outburst and applied the discriminant model to predict coal and gas outbursts; Qiu et al. [30] used electromagnetic signals to predict coal and gas outbursts; Li et al. [31] used the acoustic emission index to predict coal and gas outbursts; Dong et al. [32] used the gas concentration extraction indices to provide an early warning of atypical outbursts. Wang et al. [33] used the microseismic index to predict coal and gas outbursts; Lu et al. [34–36] have studied the microseismic location method and multiparameter characteristics of microseismic events. Current predictions of coal and gas outburst mainly depend on indices related to drilling cuttings, initial velocity of gas emission from a borehole, thickness of the soft layer, coal temperature, gas concentration extraction, acoustic emissions, and microseismic event counts. Research results have been adopted in relevant laws and regulations, such as Coal Mine Gas Grade Appraisal Method, Detailed Rules and Regulations for Prevention, and Control of Coal and Gas Outburst and Coal Mine Safety Regulation.

Although much research has been conducted on the mechanism of occurrence and prediction of coal and gas outbursts, how to use indices of gas pressure, drilling cuttings index, initial velocity of gas emission from borehole, thickness of soft layer, precursor signals, and so on to predict coal and gas outbursts is rarely reported. Aiming at this scientific problem, a new method for predicting coal and gas outbursts based on the mechanism of occurrence thereof was proposed in terms of coal mass strength, gas pressure, and *in situ* stress. By means of theoretical analysis, laboratory experiments, mathematical treatment, and industrial testing, coal and gas outbursts were predicted. Moreover, the method has been verified on-site.

2. A New Method for Predicting Coal and Gas Outbursts

For the new method for predicting coal and gas outbursts, many approaches such as theoretical analysis, laboratory experiments, mathematical treatment, and industrial testing were used to predict coal and gas outbursts. The method revealed that the rate of occurrence of coal and gas outbursts in mines was between 5% and 10% and gas pressures for coal and gas outbursts in shallow and deep mines separately were above 0.74 and 0.6 MPa in China [37]. During field measurement in a mining roadway, the prediction indices for coal and gas outbursts in the mine were determined according to geologic tectonic region, presence or absence of precursor areas of outbursts, changes before and after taking measures for preventing outbursts, and percentages of indices (i.e., normalised values thereof). The generally used prediction indices included gas desorption of drilling cuttings (K_1), weight of drilling cuttings (S), initial velocity of gas emission (q), and thickness of a soft layer.

The prediction index for coal and gas outbursts based on gas factor was gas desorption index K_1 of drilling cuttings, which denoted the gas content desorbed from the coal mass in the first minute of drilling. Firstly, the relationship between K_1 and gas pressure P was established through adsorption and desorption experiments in the laboratory and the initial prediction index critical value of K_1 was determined at gas pressures of 0.6 and 0.74 MPa during outbursts in the mine. Secondly, K_1 data were collected through *in situ* testing. When the proportion of a certain value among the collected data was 30% (considering a triple safety factor) [26], the value was taken as the initial prediction index critical value of K_1. Thirdly, in accordance with that value of K_1 corresponding to outburst precursors collected *in situ*, the initial prediction index critical value was determined. The smallest value of the three was taken as the prediction index critical value of coal and gas outbursts in the coal seam. The prediction index for coal and gas outbursts based on coal mass strength was the thickness of the soft layer that could be twisted into powder by hand. Based on many cases of coal and gas outbursts, the prediction index critical value of the thickness of the soft layer was 0.2 m [37]. Furthermore, the prediction index for coal and gas outbursts based on *in situ* stress was the weight of drilling cuttings, which indicated the weight of drilling cuttings per linear metre of boreholes with diameters of 42 or 75 mm. Firstly, through the industrial test conducted on-site, the data pertaining to the weight of drilling cuttings were collected. If the proportion of a certain value accounted for 30% of the collected data [26] (considering a triple safety factor), the value was adopted as the initial prediction index critical value of the index. Secondly, according to the weight of drilling cuttings corresponding to outburst precursors collected *in situ*, the initial prediction index critical value was determined. The smaller one of the two was the critical value of prediction index of coal and gas outbursts in the coal seam. Finally, the new method for predicting coal and gas outbursts and critical values were verified based on industrial application.

Compared with other methods, the new method is simple and practical.

3. Case Study: A New Method for Predicting Coal and Gas Outbursts

3.1. Overview of the Mine. The No. 2 well in Enhong Coal Mine, Yunnan Province, China, has been in production since 1958, with a designed production capacity of 6×10^5 t/a and the actual production capacity of about 4×10^5 t/a. It is a coal and gas outburst mine.

The mine is mainly controlled by the Cathaysian tectonic system. Primary structures in the mine including fault from Fuyuan County to Mile City, fault from Yingshang Township to A'gang Township, and Enhong compound syncline control the occurrence, metamorphism, and failure of coal-bearing strata.

The coal seams in the mine belong to the Late Permian Longtan Formation. The coal seams in the mine field extend about 6 km from southwest to northeast, while they dip about 3 km from the northwest to the southeast. The dip angle of the coal seams ranges from 5° to 12°. Of them, the C9 coal seam, containing low ash, low sulphur, and high calorific value coking coal, is mainly mined.

Inclined shaft development was used in the No. 2 well of Enhong Coal Mine. Two mining levels were set, that is, the levels at elevations of +1940 m and +1800 m. There were two mining areas, namely, the north wing and south wing. The stopping face in the south wing at the level of +1800 m was under active mining, while the mining in the north wing at the same level was about to be completed. About nine tunnelling faces were arranged in the mine. The stopping face was subject to longwall retreating mining along the strike and the coal blasting process, and the roof was controlled through the total subsidence method: blasting tunnelling technology and I-shaped steel supports were used in the tunnelling faces.

In the No. 2 well in Enhong Coal Mine, 23 coal and gas outbursts have occurred since 1980, with the maximum amount of outburst coal of 235 t and average amount of 16.55 t. The maximum amount of gas emitted was 8.3×10^4 m^3. The outburst sites showed elevation of +1932 to 1874 m at vertical distances of 120 to 416 m from the surface (Table 1).

The gas desorption index of drilling cuttings and critical values recommended by the Detailed Rules and Regulations for Prevention and Control of Coal and Gas Outbursts were adopted as the current prediction indices and critical values for the test working face of the mine. They are as follows: the thickness of the soft layer was 0.2 m, $K_1 = 0.5$ mL/g.min$^{1/2}$, and $S = 6$ kg/m (in a borehole with a diameter of 42 mm) or 18 kg/m (in a borehole with a diameter of 75 mm).

3.2. Determination of Parameters for Coal and Gas Outbursts in the C9 Coal Seam. By using the channel sampling method on-site, four samples were taken from the C9 coal seam: one from all levels and three from the soft layer. The gas parameters including proximate analysis of coal, initial velocity of gas emission, and Protodyakonov coefficient were determined in the laboratory (Tables 2 and 3).

The method for measuring pressure in boreholes was used on-site to determine gas pressures in the coal seam and other gas parameters (Table 4).

3.3. Determination of Sensitive Indices for Coal and Gas Outbursts in the C9 Coal Seam. In the process of field measurement of the mining roadway, based on the index indicating the presence or absence of precursor areas of outbursts and change therein before and after taking measures for preventing outbursts, the sensitivities of index K_1 of drilling cuttings desorption, S, and initial velocity q of gas emission were investigated. Finally, the gas desorption index K_1 of drilling cuttings was selected as the main prediction index. Considering the increase of burial depth and geologic tectonic zone, the weight$S$ of drilling cuttings was regarded as a reference index (Tables 5 and 6 and Figures 1 and 2).

According to Table 5 and Figure 1, the gas desorption index K_1 of drilling cuttings decreased to a significant extent (33% reduction); when the thickness of the coal seam changed likewise, the value of precursor areas of outbursts was large and measures for preventing outbursts were taken; namely, the index was sensitive to coal and gas outbursts.

Based on Table 6 and Figure 2, the index S of the weight of drilling cuttings reduced slightly when the thickness of the coal seam changed and values of precursor areas of outbursts were small after taking measures for preventing outbursts (e.g., drilling holes). This implied that the index was not sensitive to coal and gas outbursts; however, by taking the increase of burial depth and geological structural zone into account, the index S of the weight of drilling cuttings was considered as a reference index.

During the test, several tests were conducted for determining initial velocity q of gas emission: however, due to softness of coal seam, collapses in boreholes, and lack of a tight seal to such boreholes, test indices were generally small and the initial velocity of gas emission from boreholes could not be determined at most points; therefore, it was not used

Table 1: Statistics pertaining to times and intensity of outbursts in the mine.

Grade of outburst intensity (t)	Times of outburst		Outburst intensity		
	Times	Proportion (%)	Maximum amount of coal burst (t)	Average amount of coal burst (t)	Maximum amount of gas emitted ($10^4\,m^3$)
Submassive outburst (100 to 499 t)	2	8.7	235	186	3.3
Medium outburst (50 to 99 t)	2	8.7	94	72	3.4
Small outburst (<50 t)	19	82.6	39	12.4	8.3
Total	23	—	235	32.7	8.3

Table 2: Parameters including gas adsorption constant and proximate analysis of the C9 coal seam.

Coal seam	Sampling site	Proximate analysis (%)			True density, TRD	Apparent density, ARD	Porosity, F (%)	Gas adsorption constant	
		M_{ad}	A_d	V_{daf}				a	b
C9	Transportation roadway in the 121901 working face at the 1800 m level	0.43	8.74	22.31	1.37	1.20	12.41	20.5147	0.8480

Note: adsorption experiments were conducted at $t_S = 30°C$.

Table 3: Failure type in the C9 coal seam, initial velocity of gas emission, and firmness coefficient.

Coal seam	Sampling site	Outburst parameter		
		Failure type of coal seam	Initial velocity of gas emission, $\triangle P$	Protodyakonov coefficient, f
C9	Return air roadway in the 121901 working face	V	21	0.19
	Transportation roadway in the 121901 working face	V	23	0.18
	2# connection roadway in the 121901 working face	V	19	0.19

Table 4: Gas pressures in the C9 coal seam and other gas parameters.

Coal seam	Testing site	Gas pressure, P (MPa)	Gas content, Q (m^3/t)	Permeability coefficient, λ ($m^2/MPa^2.d$)	Attenuation coefficient of flow in borehole, $\alpha(d^{-1})$
C9	Floor drainage roadway at the 1800 m level	1.02	10.81	0.1341	0.111

as a predictive index for coal and gas outbursts and the test values are listed in Table 7.

During field investigation, the thickness of the soft layer was not obvious, so it was not used as a predictive index for coal and gas outbursts.

3.4. Determination of Critical Values of Sensitive Indices for Coal and Gas Outbursts in the C9 Coal Seam

3.4.1. Determination of Critical Value of Gas Desorption Index K_1 of Drilling Cuttings

(1) Preliminarily determining critical value of gas desorption index K_1 of drilling cuttings based on the modelled K_1–P relationship

The experimental process of assessing the K_1–P relationship model is as follows: coal samples with particle sizes between 1 and 3 mm were taken and degassed for 2 h using a vacuum pump. After that, the coal samples were pressurised to the predetermined gas pressure for adsorption, to allow the coal samples to absorb gas for 24 h. The gas pressure under equilibrium was recorded. After exposing the coal samples to the atmosphere for 1 to 2 min, the value of K_1 was determined. At least five experiments were conducted on each coal sample. By fitting these data, the K_1–P relationship model could be obtained. Figures 3–5 show the experimental results pertaining to the K_1–P relationship model for coal samples from different sites in the C9 coal seam in Enhong Coal Mine.

Table 5: Gas desorption index K_1 of drilling cuttings based on geological structure and precursor areas of outbursts.

Area	Failure type of the coal seam	K_{1max} index	Geological structure	Outburst precursor
Return air roadway in the 121901 working face	III, IV	0.56	Thinning of coal seam	—
Return air roadway in the 121901 working face	III, IV	0.83	Thinning of coal seam	—
Return air roadway in the 121901 working face	III, IV	0.89	Thinning of coal seam	—
Transportation roadway in the 121901 working face	III, IV	0.82	Thinning of coal seam	—
Transportation roadway in the 121901 working face	III, IV	0.95	Thinning of coal seam	—
Transportation roadway in the 121901 working face	III, IV	0.69	Thinning of coal seam	—
Transportation roadway in the 121901 working face	III, IV	0.80	Thinning of coal seam	—
Transportation roadway in the 121901 working face	III, IV	0.57	Thickening of coal seam	—
Transportation roadway in the 121901 working face	III, IV	0.83	Thinning of coal seam	—
Transportation roadway in the 121901 working face	III, IV	0.70	Thinning of coal seam	—
Transportation roadway in the 121901 working face	III, IV	0.85	Thinning of coal seam	—
Transportation roadway in the 121901 working face	III, IV	0.74	Thinning of coal seam	—
2# connection roadway in the 121901 working face	III, IV	1.01	Thinning of coal seam	—
2# connection roadway in the 121901 working face	III, IV	1.04	Thinning of coal seam	—
South return air roadway at 1800 m level	III, IV	0.72	Thinning of coal seam	Coal burst
Transportation roadway in the 121901 working face	III, IV	0.78	Thinning of coal seam	Emission after pulling the drill pipe out
2# connection roadway in the 121901 working face	III, IV	0.88	Thinning of coal seam	Emission after pulling the drill pipe out
2# connection roadway in the 121901 working face	III, IV	0.88	Thickening of coal seam	Emission after pulling the drill pipe out

Based on the K_1–P relationship model, the critical value of gas desorption index K_1 of drilling cuttings was preliminarily determined as 0.62 mL/g.min$^{1/2}$(gas pressure $P = 0.74$ MPa), as presented in Table 8.

(2) Preliminarily determining the critical value of gas desorption index K_1 of drilling cuttings based on percentages of data collected on-site

By cycling samples 109 times to collect prediction index K_1 on-site, the index and its percentages are shown in Figure 6 and Table 9; accordingly, when $K_{1max} \geq 0.7$ mL/g.min$^{1/2}$, the percentage was 29%.

(3) Determining initial critical value according to the K_1 value corresponding to outburst precursors collected during field testing

In accordance with Table 5, the minimum K_1 value corresponding to outburst precursors including coal burst and emission after pulling the drill pipe out collected during field testing was 0.72 mL/g min$^{1/2}$, so the value was used as the initial critical value of K_1.

By combining the initial critical values (0.62, 0.70, and 0.72 mL/g min$^{1/2}$ (occurrence of coal and gas outburst)) as separately determined from the K_1–P relationship model, data percentages, and outburst precursors, 0.60 mL/g min$^{1/2}$ was selected as the critical value of gas desorption index K_1 of drilling cuttings after numerical rounding of the data.

3.4.2. Determining the Critical Value of Index S of the Weight of Drilling Cuttings

(1) Preliminarily determining the critical value of index S of the weight of drilling cuttings according to percentages of data collected on-site

A total of 68 cycles were conducted *in situ* to collect values for S as a prediction index. The index and its percentages are demonstrated in Figures 7 and 8 and Tables 10 and 11: when $S_{max} \geq 3$ kg/m (in a borehole with a diameter of 42 mm), the percentage was 38%; for $S_{max} \geq 14$ kg/m (in a borehole with a diameter of

Table 6: Index S of the weight of drilling cuttings based on geological structure and precursor areas of outbursts.

Area	Failure type of coal seam	S_{max} index	Geological structure	Outburst precursor
Return air roadway in the 121901 working face	III, IV	1.4 (Φ42)	Thinning of coal seam	—
Return air roadway in the 121901 working face	III, IV	4.5 (Φ42)	Thinning of coal seam	—
Transportation roadway in the 121901 working face	III, IV	11 (Φ75)	Thinning of coal seam	—
Transportation roadway in the 121901 working face	III, IV	18.8 (Φ75)	Thinning of coal seam	—
Transportation roadway in the 121901 working face	III, IV	18 (Φ75)	Thinning of coal seam	—
Transportation roadway in the 121901 working face	III, IV	5.5 (Φ42)	Thickening of coal seam	—
Transportation roadway in the 121901 working face	III, IV	4.2 (Φ42)	Thinning of coal seam	—
Transportation roadway in the 121901 working face	III, IV	3.6 (Φ42)	Thinning of coal seam	—
Transportation roadway in the 121901 working face	III, IV	2.5 (Φ42)	Thinning of coal seam	—
Transportation roadway in the 121901 working face	III, IV	3.1 (Φ42)	Thinning of coal seam	—
2# connection roadway in the 121901 working face	III, IV	2 (Φ42)	Thinning of coal seam	—
South return air roadway at the 1800 m level	III, IV	2.2 (Φ42)	Thinning of coal seam	Coal burst
Transportation roadway in the 121901 working face	III, IV	2.5 (Φ42)	Thinning of coal seam	Emission after pulling the drill pipe out
2# connection roadway in the 121901 working face	III, IV	1.5 (Φ42)	Thinning of coal seam	Emission after pulling the drill pipe out
2# connection roadway in the 121901 working face	III, IV	2.7 (Φ42)	Thickening of coal seam	Emission after pulling the drill pipe out

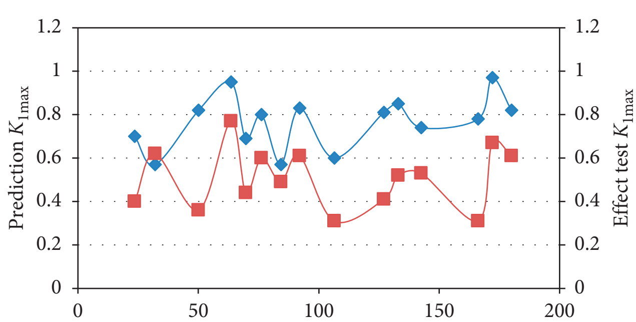

Figure 1: Changes of K_{1max} index before and after taking preventative measures in the transportation roadway in the 121901 working face.

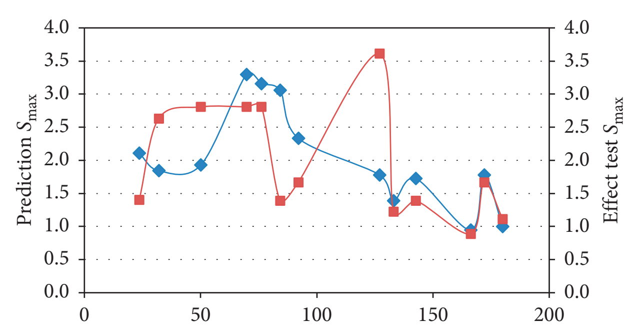

Figure 2: Changes of the index of S_{max} before and after taking preventative measures in the transportation roadway in the 121901 working face.

75 mm), the percentage was 39%. The initial critical values of the index S of the weight of drilling cuttings were determined as $S_{max} = 3$ kg/m (in a borehole with a diameter of 42 mm) or $S_{max} = 14$ kg/m (in a borehole with a diameter of 75 mm); however, the indices of the weight of drilling cuttings were generally small.

(2) Determining the initial critical value of S in accordance with data corresponding to outburst precursors collected during field testing

As listed in Table 6, the minimum S value corresponding to outburst precursors including coal burst and emission after pulling the drill pipe out collected

Table 7: Test of initial velocity q of gas emission.

Site	2	3	4	5	6	7	8	9	10
3# connection roadway at the 1800 m level	3.2	2.3	0.1	0.2	0.2	0	0.1	0	—
3# connection roadway at the 1800 m level	0.2	0.2	2	1.2	0.2	0.2	—	—	—
3# connection roadway at the 1800 m level	1.2	3.2	—	—	—	—	—	—	—
3# connection roadway at the 1800 m level	2.6	0.8	1.2	1	1	2	—	—	—
Transportation roadway in the 121901 working face	—	1.2	—	—	3.4	—	—	—	—
Transportation roadway in the 121901 working face	0.2	1	—	—	—	—	—	—	—

Table 8: Initial critical value of gas desorption index K_1 of drilling cuttings.

Coal samples	Sampling site	Initial critical value of gas desorption index K_1 of drilling cuttings (mL/g.min$^{1/2}$)	K_1–P relationship $K_1 = AP^B$	
			A	B
1	Return air roadway in the 121901 working face	0.62	0.7222	0.4948
2	Transportation roadway in the 121901 working face	0.69	0.8038	0.5122
3	2# connection roadway in the 121901 working face	0.67	0.7729	0.4961

Table 9: Distribution of percentages of prediction index K_{1max} during the test.

K_{1max} (mL/g.min$^{1/2}$)	Total times (109)	Percentage
≥0.1	109	100
≥0.2	107	98
≥0.3	96	88
≥0.4	70	64
≥0.5	61	56
≥0.6	44	40
≥0.7	32	29
≥0.8	20	18
≥0.9	7	6
≥1.0	4	4

Table 10: Distribution of percentages of prediction index S_{max} (Φ42 mm) during the test.

S_{max} (kg/m)	Total times (45)	Percentage
≥1	45	100
≥2	31	69
≥3	17	38
≥4	4	9
≥5	2	4
≥6	0	0

during field testing was 1.5 kg/m (in a borehole with a diameter of 42 mm). As no outburst precursors were observed for boreholes with a diameter of 75 mm, 1.5 kg/m (Φ42 mm) was regarded as the initial critical value of S.

Table 11: Distribution of percentages of prediction index S_{max} (Φ75 mm) during the test.

S_{max} (kg/m)	Total times (23)	Percentage
≥10	23	100
≥12	19	83
≥14	9	39
≥16	4	17
≥18	2	9

Table 12: Distribution of percentages of gas desorption index K_{1max} of drilling cuttings predicted during the field testing.

K_{1max} (mL/g min$^{1/2}$)	Total times (157)	Percentage
≥0.1	157	100
≥0.2	157	100
≥0.3	154	98
≥0.4	147	94
≥0.5	136	87
≥0.6	114	73
≥0.7	97	62
≥0.8	83	53
≥0.9	67	43
≥1.0	49	31

The initial critical values determined by combining with data percentages and outburst precursors and the S index were not sensitive to coal and gas outbursts in the C9 coal seam in this mine. Meanwhile, considering the increase of burial depth and the prevailing geological

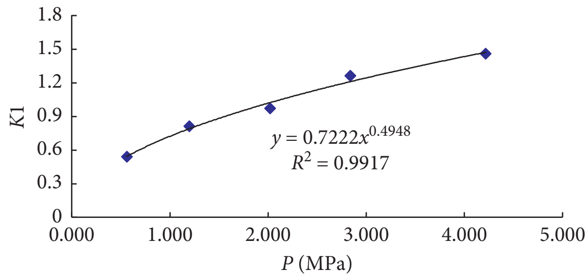

Figure 3: K_1–P relationship model in the return air roadway in the 121901 working face.

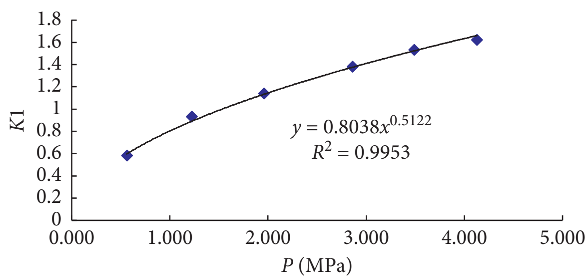

Figure 4: K_1–P relationship model in the transportation roadway in the 121901 working face.

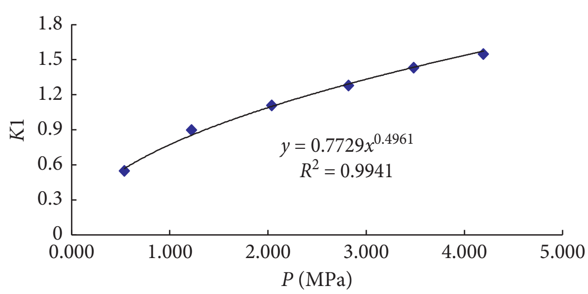

Figure 5: K_1–P relationship model in the 2# connection roadway in the 121901 working face.

structural belt, $S = 6$ kg/m (in a borehole with a diameter of 42 mm) or $S = 18$ kg/m (in a borehole with a diameter of 75 mm) could be selected as critical values.

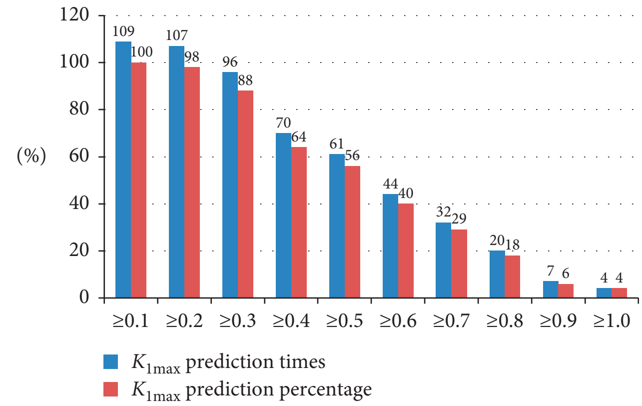

Figure 6: Distribution of $K_{1\max}$ during the test.

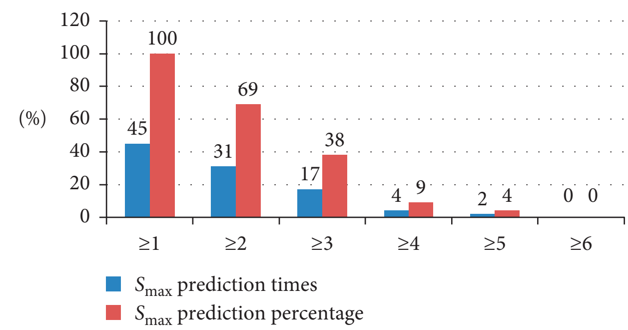

Figure 7: Distribution of $S_{\max}$ (Φ42 mm) during the test.

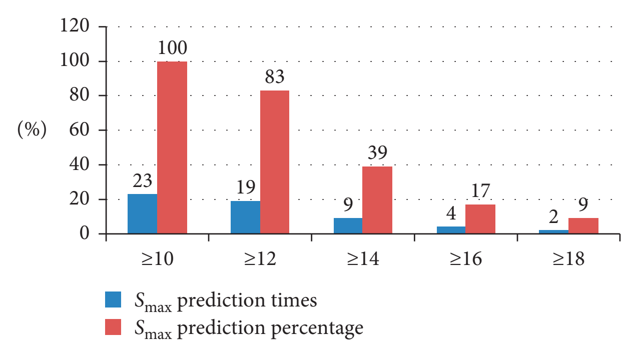

Figure 8: Distribution of $S_{\max}$ (Φ75 mm) during the test.

3.4.3. Situation during Application of Indices K_1 and S for Coal and Gas Outbursts. Based on the aforementioned research, gas desorption index K_1 of drilling cuttings was used as the main predictive index for coal and gas outbursts in the C9 coal seam in Enhong Coal Mine and its critical value was 0.6 mL/g.min$^{1/2}$. The auxiliary index was the index S of the weight of drilling cuttings, and its critical values were 6 kg/m (in a borehole with a diameter of 42 mm) or 18 kg/m (in a borehole with a diameter of 75 mm).

During field testing, 157 cycles were applied to collect values of K_1 and the percentages of the index are shown in Table 12 and Figure 9. It can be seen from the figure and the table that the percentage was 73% for $K_{1\max} \geq 0.6$ mL/g.min$^{1/2}$. Later, it was found that there was a large fault with the downthrow of 20 m near the 121901 working face, increasing the risk of an outburst. This further proved the sensitivity of the prediction index K_1 and the accuracy of its critical value.

During field testing, a total of 135 cycles were applied to collect the weight of drilling cuttings S. Percentages of the index are shown in Table 13 and Figure 10. The number of cycles exceeding the critical value was zero when $S_{\max} \geq 6$ kg/m.

During application, the roadway was safely tunnelled for about 1000 m according to the determined prediction indices for coal and gas outbursts, without a coal and gas outburst occurring.

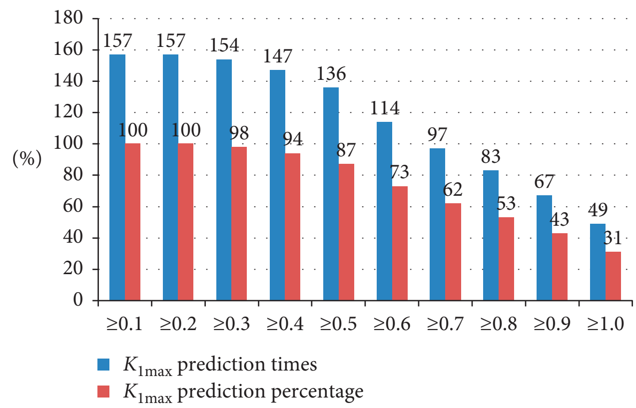

Figure 9: Distribution of range of gas desorption index K_{1max} of drilling cuttings predicted during field testing.

Table 13: Distribution of percentages of the index S_{max} (Φ42 mm) of weight of drilling cuttings predicted during field testing.

S_{max} (kg/m)	Total times (135)	Percentage
≥1	135	100
≥2	119	88
≥3	24	18
≥4	4	3
≥5	0	0
≥6	0	0

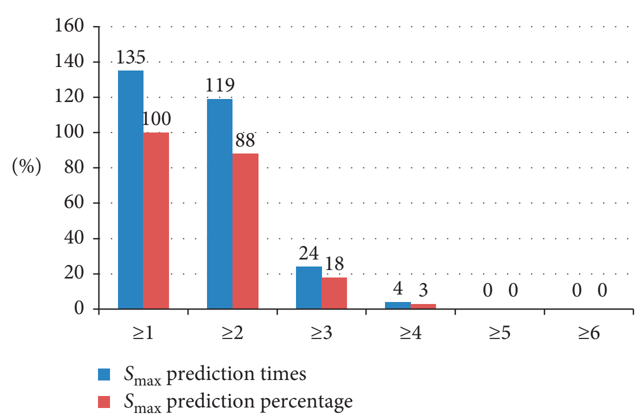

Figure 10: Distribution of range of the index S_{max} (Φ42 mm) of the weight of drilling cuttings predicted during field testing.

4. Conclusion

(1) Based on the mechanism of occurrence of a coal and gas outburst relating to coal mass strength, gas pressure, and *in situ* stress, a method for predicting coal and gas outbursts was proposed.

(2) During *in situ* measurement of the mining roadway, the specific prediction indices for coal and gas outbursts were determined according to indices including geological tectonic region, presence or absence of outburst precursors, changes before and after taking measures for preventing outbursts, and percentages of indices. The indices generally used were the gas desorption index K_1 of drilling cuttings, the weight$S$ of drilling cuttings, initial velocity q of gas emission, and thickness of the soft layer.

(3) By using the new method for predicting coal and gas outbursts, the main prediction index for coal and gas outbursts in the C9 coal seam in Enhong Coal Mine was the gas desorption index K_1 of drilling cuttings and its critical value was 0.6 mL/g min$^{1/2}$. The index S of the weight of drilling cuttings was used as the auxiliary index and its critical values were 6 kg/m (in a borehole with a diameter of 42 mm) or 18 kg/m (in a borehole with a diameter of 75 mm).

(4) The new method of coal and gas outbursts can greatly improve the technical level of coal and gas outburst personnel and the prediction accuracy of coal and gas outbursts.

Data Availability

The data supporting the conclusion of the article are shown in the relevant figures and tables in the article.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

Guowei Dong conceived and designed the experiments and wrote the paper; Xuanming Liang analyzed the data; Qixiang Wang performed the theoretical analysis.

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