Research Article

Experimental Study on Strength, Acoustic Emission, and Energy Dissipation of Coal under Naturally and Forcedly Saturated Conditions

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Coal seam water injection (CSWI) is an effective technology that is widely used for preventing rock burst in coal mines. To deepen the understanding of the mechanism of CSWI to prevent rock burst, new equipment was designed to prepare forcedly saturated coal samples in this study and a series of mechanical experiments was conducted to investigate the mechanical properties, acoustic emission (AE), and energy dissipation characteristics of the coal samples in natural, naturally saturated, and forcedly saturated states. The experimental results show that the forced saturation treatment can significantly improve P-wave velocity and water content of coal samples, as water can penetrate more into micropores and fractures. The forced saturation method also significantly promotes the deformation capacity of the coal sample and reduces the strength by 83.37%. The main reason of the bearing capacity decrease for the forcedly saturated coal samples is plastic yielding rather than brittle crack propagation and slip. The derivative of the volumetric dissipation energy was proposed to evaluate the outburst proneness. The forced saturation method significantly reduces the risk of sudden release of energy and is more effective in preventing rock burst in coal seams than the natural saturation method.

1. Introduction

Coal mass is a natural multiphase composite material that contains fractures and pores [1]. The mineral composition and microstructure of coal mass can be affected by water soaking which induces natural fracture propagation and softens the organic materials [2], resulting in the degradation in the physical and mechanical properties [3]. Therefore, CSWI is widely used in coal mines to prevent rock burst and coal wall caving in the longwall panel [4, 5]. As shown in Figure 1, the gob-side coal pillar bears high vertical stress in an approximately uniaxial compressive state and may experience coal burst by the joint induction of the high static load and the dynamic load caused by the hard roof breaking [6–8]. By injecting water into the coal pillar, its mechanical behavior and energy release characteristics would be changed to reduce the risk of coal burst.

Many studies have been conducted to understand the fundamental mechanical behaviors of water-saturated coal

and rock samples. It is well accepted that the quasistatic strength of rock decreases with respect to water saturation [9–15]. Colback and Wiid [16] found that the uniaxial compression strength (UCS) of water-saturated quartz sandstone can be reduced by approximately 50%. Vásárhelyi [17] analyzed the effects of water saturation on the static mechanical response of miocene limestone samples and proposed a relationship with petrophysic. Xiong et al. [18] conducted a series of Brazilian tests, uniaxial and triaxial compression tests to investigate the changes of mechanical properties of naturally saturated mudstone samples and suggested that the strength of naturally saturated rock samples was more sensitive to the confining pressure than that of dry samples. Zhou et al. [19] studied the influence of water content on mechanical properties of rock treated by both saturation and drying processes and demonstrated that the tensile strengths of the partially water-saturated rock samples with the same moisture content were different during saturation and drying processes due to different

FIGURE 1: Schematic of the mechanism of coal burst induced by high static load and dynamic load [6].

water distributions in samples. Zhang et al. [20] analyzed the effect of saturation on fracture strength and fracture energy of coal samples by the Brazilian tests. Yu et al. [21] employed a MTS electrohydraulic servo rock test system to examine the UCS and uniaxial tension strength of naturally saturated coal samples. Liu et al. [22] compared the microseismic signals during the failure process of dry and naturally saturated coal samples by using a self-developed microseismic wave monitoring system. Su et al. [23] analyzed the effects of natural saturation time on rock burst proneness. Wang et al. [6, 24, 25] investigated the mechanical responses and energy dissipation characteristics of naturally saturated coal samples under 3D coupled dynamic and static loads by an improved SHPB and the RMT-150 test system. Zhao et al. [26] compared the dynamic tensile strength of dry and naturally saturated coal samples and concluded that the indirect tensile strength of naturally saturated coal samples is higher than that of dry samples. Tang et al. [27] investigated the AE characteristics of naturally saturated coal samples during UCS tests. Additionally, the variations of P-wave velocity and waveform characteristics during the whole process of natural water absorption of coal and rock samples were also tested [28–31].

Previous studies that focus on the mechanical properties of water-containing coal samples under static or impact load just considered the natural saturation treatment on coal samples. In general, the naturally saturated coal samples are prepared by putting the original coal samples into water with approximately 0 MPa water pressure so that the samples absorb water naturally. The soaked coal sample can be considered as a naturally saturated coal sample when its weight stays unchanged. However, during the CSWI process, coal mass is subjected to a forcedly water-saturated process by injecting pressurized water into it. Therefore, the forced saturation process in field is significantly different from the natural saturation process in the previous studies, and it is necessary to investigate the differences in mechanical properties between the naturally and forcedly saturated coal samples for deepening the understanding of the mechanism of CSWI to prevent rock burst.

This study aims to investigate the differences in mechanical properties between the forcedly and naturally saturated coal samples. In this study, new equipment for preparing forcedly saturated coal samples was developed. A series of uniaxial compression tests was conducted to identify the mechanical properties of the coal samples under different water-saturated states, including the natural state without soaking, the naturally saturated state, and the forcedly saturated state. In addition, AE monitoring was used to reflect damage characteristics during the UCS tests, and the differences in energy dissipation characteristics were analyzed.

2. Experimental Work

2.1. Collection and Preparation of Coal Samples. The coal samples were all collected from the same longwall panel in the Huoerxinhe coal mine, No. 3 coal seam, of the carboniferous Taiyuan group in China, as shown in Figure 2. The main component of the No. 3 coal seam is anthracite, and its coal proximate analysis results are given in Table 1.

The coal samples were first processed to cylinders of 50 mm in diameter and 50 mm in length, and then they were polished to ensure that the nonparallelism of the top and bottom surfaces is less than 0.05 mm and that the surface evenness is less than 0.02 mm according to the International Society for Rock Mechanics (ISRM) specifications [32]. The processed coal samples were divided into three groups and further treated by different water saturation methods. Groups A, B, and C represent the natural, naturally saturated, and forcedly saturated coal sample groups, respectively, as shown in Figure 3.

The natural coal samples (Group A) were not treated by water and were just kept at 20°C–24°C and 40% relative humidity. The naturally saturated coal samples were prepared as follows. First, the coal samples in Group B were put into a plastic basin. Then, 2 cm deep pure water was added into the basin every 2 hours for a total of 4 times. When the final water level was at least 3 cm higher than the top surfaces of these coal samples, the basin was sealed with plastic wraps. After, the coal samples were weighed every 24 hours until the

FIGURE 2: Location of Huoerxinhe coal mine.

TABLE 1: Proximate analysis results of the anthracite used in this study.

Parameters	Values
Moisture, Mad	0.87%
Ash, Ad	9.42%
Volatile matter, Vdaf	6.38%
Fixed carbon, FC, d	84.80%
Char residue characteristic, CRC	2
Total sulfur, S _t , d	0.32%
Calorific value, Q _{gr} , d	31.63 MJ/kg
Hydrogen, Hdaf	2.47%

consecutive weight difference did not exceed 0.01 g and kept in water for 7 days. Finally, the coal samples were removed from the water for testing.

New equipment was designed to prepare the forcedly saturated coal samples, as shown in Figure 4. The instrument mainly consists of three parts: a sealed container, an air extractor, and a high-pressure liquid injection device. The sealed container is an iron cylinder of 65 cm in height and 25 cm in diameter with a wall thickness of 2 cm. The booster pump is driven by high-pressure air to supercharge the water flowing to the sealed container. The air pressure to drive the booster pump is 0.2–0.8 MPa and can generate ten times more hydraulic pressure through the booster pump. The vacuum pump is made by Fujiwara Corporation with a maximum vacuum degree of -0.098 MPa.

Specific steps taken to prepare the forcedly saturated coal samples are as follows. (1) Open the sealed container by the open valve and place the samples into the sealed container. (2) Seal the container using seal washer. (3) Make sure the water-injection pipe is full of water, then turn off the valves 1 and 2, and turn on valve 3. (4) Extract the air in the sealed container by the vacuum pump for at least 1 h and then turn off valve 3. (5) Turn on valve 1 and inject water into the sealed container using the booster pump. When the hydraulic pressure gauge shows the hydraulic pressure of 5 MPa, stop the injection of water and turn off valve 1. (6) Keep coal samples soaking in the sealed container for 4 hours and then remove them from the container.

2.2. Experimental Procedure and Instrument

2.2.1. Measurement of Water Content and P-Wave Velocity.

The prepared coal samples were first weighted to get the wet weight m_w , then dried in a drying oven at 105°C for 4 h, and finally weighted for the complete dry weight m_0 . The samples used for measuring water content were not used for the UCS tests. The water content, W , is calculated by

$$W = \frac{m_w - m_0}{m_w} \times 100\%. \quad (1)$$

The P-wave velocity of coal samples was examined before and after soaking by the UTA-2001A nonmetal ultrasonic nondestructive detector. The frequency range of this detector was 1–500 kHz and the maximum time range was 9999.9 μs . The wave transmission method was chosen to measure P-wave velocity. The ultrasonic excitation signal, generated by the acoustic signal transmission card, penetrated coal sample and was received by the ultrasonic reception sensor. The P-wave velocity, v , was calculated according to sample length and the time of ultrasonic emission and reception.

2.2.2. AE Measurement. The AE-win B 1.86 acoustic emission system was used to collect AE signal from the samples during UCS tests. The AE sensor that is mounted at the top of the experimental frame obtained the acoustic energy release characteristics resulting from fracturing during loading. An AE count was confirmed and recorded when the amplitude of the received acoustic signal exceeded a threshold value of 45 dB in the data acquisition system. The sampling frequency was set to 1 Msps.

2.2.3. Mechanical Experiment System for UCS Tests. UCS tests were performed to evaluate and compare the mechanical properties of the three kinds of coal samples. The RMT-150C rock mechanics servo testing machine was used in conjunction with the AE inspecting system to obtain the stress-strain data and AE signals. The testing frame stiffness of the RMT-150C testing machine was 5.0×10^9 N/mm. The

FIGURE 3: The photos of the collected coal masses and the prepared coal samples: (a) natural coal samples (Group A); (b) naturally saturated coal samples (Group B); (c) forcedly saturated coal samples (Group C).

FIGURE 4: Experimental setup for preparing forcedly saturated coal samples.

maximum load capacity was 1000 kN. The test range was 50 mm. Figure 5 shows the overall experimental setup. The loading rate used was 0.002 mm/s in each test. The hydraulic power system in Figure 5 was used for providing the compressive load onto the coal samples.

The stress-strain curve in the coal samples' elastic phase commonly is not straight line because coal is heterogeneous. There are many different modulus to represent the elastic modulus of coal samples, such as average modulus, secant modulus and tangent modulus [33]. The average modulus was selected in this study. The average modulus is the slope of the line between point M at which the stress is 70% peak stress and point N at which the stress is 30% peak stress, given by:

$$E_0 = \frac{\sigma_M - \sigma_N}{\epsilon_M - \epsilon_N}, \quad (2)$$

where E_0 is the average modulus, P_a ; σ_M and σ_N are the stress values at point M and N respectively, P_a ; ϵ_M and ϵ_N are the strain values at point M and N respectively.

3. Experimental Results and Discussion

3.1. Water Content. Table 2 shows the water content of the three types of coal samples. The water content is in the range of 1.48%–1.54% with an average value of 1.51% for the

natural coal samples, 1.94%–2.14% with an average value of 2.06% for the naturally saturated coal samples, and 4.05%–4.30% with an average value of 4.17% for the forcedly saturated coal samples. It can be found that the water content for the forcedly saturated coal samples is significantly higher than the natural and naturally saturated coal samples, indicating that the forced saturation treatment can drive water into more micropores and fractures, and therefore is more effective at changing the microstructure of coal samples than the natural saturation method.

3.2. P-Wave Velocity. Table 3 shows the P-wave velocity characteristics of the natural, naturally saturated and forcedly saturated coal samples. The average P-wave velocity values before soaking are 1449, 1499 and 1434 m/s for the natural, naturally saturated and forcedly saturated coal samples respectively, while the average P-wave velocity values after saturation for naturally saturated and forcedly saturated coal samples are 1623 m/s and 2117 m/s respectively. After saturation, the increase rate of P-wave velocity is in the range of 3.1%–9.2% for the naturally saturated coal samples, whereas 42.1%–55.6% for the forcedly saturated coal samples. The results suggest that P-wave velocity increases significantly more by the forced saturation treatment than by the natural saturation treatment.

FIGURE 5: Mechanical experiment system used to conduct UCS tests and AE measurements.

TABLE 2: Water content of three kinds of coal samples.

Type of coal sample	Sample ID	Water content (%)	Average water content (%)	Standard deviation (%)
Natural	A1	1.52	1.51	0.020
	A2	1.51		
	A3	1.54		
	A4	1.48		
	A5	1.50		
Naturally saturated	B1	2.12	2.06	0.090
	B2	2.14		
	B3	1.95		
	B4	1.94		
	B5	2.13		
Forcedly saturated	C1	4.30	4.17	0.092
	C2	4.24		
	C3	4.09		
	C4	4.05		
	C5	4.17		

It is noteworthy that the P-wave velocity and water content of natural and naturally saturated coal samples are both lower than those of forcedly saturated coal samples. The coal sample contains coal, air and water, and can be regarded as solid-gas-liquid multiphase material. Its P-wave velocity can be estimated by [34]:

$$v = \frac{1}{\sqrt{\beta\rho}} \quad (3)$$

where ρ is the density, kg/m^3 ; β is the compressibility factor which is the reciprocal of the bulk modulus, Pa^{-1} . β and ρ can be calculated by:

$$\begin{cases} \beta = n_c\beta_c + n_a\beta_a + n_w\beta_w, \\ \rho = n_c\rho_c + n_a\rho_a + n_w\rho_w, \end{cases} \quad n_c + n_a + n_w = 1, \quad (4)$$

where the subscripts c, a and w represent the parameters for coal, air and water respectively; n is volume proportion. In fact, n_a and n_w are significantly lower than n_c . β_c and β_w are much less than β_a ($\beta_a \approx 1.5 \times 10^4 \beta_w$), and ρ_c and ρ_w are much greater than ρ_a : $\rho_c \approx 1400 \text{ kg/m}^3$, $\rho_w \approx 1000 \text{ kg/m}^3$, and $\rho_a \approx 1.25 \text{ kg/m}^3$. Therefore, when $n_a > 0.1\%$, β and ρ can be estimated by:

$$\begin{cases} \beta \approx n_a\beta_a, \\ \rho \approx n_c\rho_c + n_w\rho_w \approx 1000(1 - n_a)\rho_a. \end{cases} \quad (5)$$

Substituting Equation (5) into Equation (3), P-wave velocity is obtained by:

$$v \approx \frac{1}{\sqrt{1000\beta_a\rho_a}} \cdot \frac{1}{\sqrt{n_a(1 - n_a)}}. \quad (6)$$

From Equation (6), it can be found that v and n_a are inversely proportional when $n_a < 0.05$. Because $n_w = 1 - n_c - n_a$, v and n_w are proportional when $n_a < 0.05$. The above analysis explains the mechanism of the effect of water and air on the P-wave velocity of coal sample, and indicates that the relative low P-wave velocity of naturally saturated coal samples is caused by the air in coal samples.

The dispersion of P-wave velocity after saturation of group C is lower than that of group B according to Table 3 and Figure 6. Because of the heterogeneity of air and water distribution in naturally saturated coal sample, the difference in P-wave velocity between each sample in group B is relative large. However, the forcedly saturated coal sample contains little air, and water penetrates more fully into the micropores by forced saturation treatment, so the water distribution is more homogeneous in forcedly saturated coal sample, which is reflected from the lower dispersion of P-wave velocity.

TABLE 3: P-wave velocity variation of three types of coal samples.

Type of coal sample	Sample ID	v_o (m/s)	v_s (m/s)	r (%)	v_{oa} (m/s)	v_{sa} (m/s)	v_{od} (m/s)	v_{sd} (m/s)
Natural	A1	1416	N/A	N/A	1449	N/A	87.55	N/A
	A2	1538	N/A	N/A				
	A3	1374	N/A	N/A				
	A4	1349	N/A	N/A				
	A5	1566	N/A	N/A				
Naturally saturated	B1	1416	1507	4.1	1499	1623	88.00	123.13
	B2	1538	1731	9.2				
	B3	1374	1444	3.1				
	B4	1566	1690	6.0				
	B5	1600	1742	6.6				
Forcedly saturated	C1	1515	2153	42.1	1434	2117	56.19	21.04
	C2	1470	2110	43.5				
	C3	1353	2105	55.6				
	C4	1434	2127	48.3				
	C5	1397	2092	49.7				

Note. v_o = P-wave velocity before soaking; v_s = P-wave velocity after saturating; r = increase rate of P-wave velocity; v_{oa} = average value of v_o ; v_{sa} = average value of v_s ; v_{od} = standard deviation of v_o ; v_{sd} = standard deviation of v_s .

FIGURE 6: Bar graph of P-wave velocity characteristics of naturally and forcedly saturated coal samples.

3.3. UCS Test Results. The UCS test results are listed in Table 4, and the stress-strain curves are illustrated in Figure 7. The strain rate was 4×10^{-5} in each test. The peak stress is in the range of 13.80–16.29 MPa with an average value of 14.67 MPa for natural coal samples, 8.03–10.19 MPa with an average value of 8.88 MPa for naturally saturated coal samples, and 1.54–3.36 MPa with an average value of 2.44 MPa for forcedly saturated coal samples. Compared to the natural coal samples, the average strength reduction rates of naturally and forcedly saturated coal samples reached 39.47% and 83.37% respectively. The average elastic modulus of naturally and forcedly saturated coal samples decreased by 36.80% and 89.22% respectively. The results indicate that the mechanical

strength of the forcedly saturated coal samples decreases more significantly than that of the naturally saturated coal samples.

Compared to natural coal samples, the average strain at peak stress and the average maximum strain of forcedly saturated coal samples increased by 16.39% and 41.72% respectively; however, the average strain at peak stress and the average maximum strain of naturally saturated coal samples decreased by 25.61% and 22.34% respectively. The results indicate that the naturally saturated coal samples from Huoerxinhe coal mine still show brittle failure characteristics, but the coal samples treated by forced saturation method are more similar to plastic materials.

4. AE Characteristics and Energy Dissipation

4.1. AE Characteristics. The results of AE counts are displayed in Table 5. The variations of AE counts and energy during loading are shown in Figures 8 and 9. In Table 5, the peak count is the maximum value of AE counts recorded during UCS test. The average peak counts of natural, naturally saturated and forcedly saturated coal samples are 67708, 3330 and 951 times respectively, and the average cumulative counts are 943094, 454688 and 118507 times respectively. Both the peak counts and the cumulative counts decrease in an order of natural, naturally saturated and forcedly saturated coal samples. It is generally believed that the acoustic signals are accompanied by microcracks generation and propagation, so the AE counts reflect the rupture situation in coal samples indirectly. The less the AE counts, the less the number of brittle cracks [33]. Therefore, the crack number of forcedly saturated coal samples is significantly less than the naturally saturated coal samples. According to Figure 9, the peak energy and cumulative energy of the forcedly saturated coal samples are much less than those of natural and naturally saturated coal samples, indicating the proportion of strain energy released in the form of brittle fracture generation is reduced by forced saturation treatment. Additionally, it is noted that the peak

TABLE 4: The UCS test results of natural, naturally saturated, and forcedly saturated coal samples.

Type of coal sample	Sample ID	σ_p (MPa)		ϵ_p (10^{-3})		ϵ_{max} (10^{-3})		E_0 (GPa)	
		E	A	E	A	E	A	E	A
Natural	A6	13.80		9.87		13.12		3.15	
	A7	16.29	14.67	10.90	10.19	15.75	13.52	2.47	2.69
	A8	13.91		9.80		11.68		2.45	
Naturally saturated	B6	8.42		7.42		9.69		1.44	
	B7	10.19	8.88	8.68	7.58	11.84	10.50	1.90	1.70
	B8	8.03		6.63		9.98		1.77	
Forcedly saturated	C6	1.54		13.72		19.96		0.13	
	C7	2.42	2.44	11.52	11.86	21.49	19.16	0.33	0.29
	C8	3.36		10.34		16.02		0.42	

Note. σ_p = peak stress; ϵ_p = strain at peak stress; ϵ_{max} = maximum strain; E_0 = elastic modulus; E = experiment value; A = average value.

FIGURE 7: The relationships between stress and strain of natural, naturally saturated, and forcedly saturated coal samples.

TABLE 5: Experimental results of AE tests.

Type of coal sample	Sample ID	Peak counts (times)		Cumulative counts (times)	
		Experimental value	Average value	Experimental value	Average value
Natural	A6	81008		985765	
	A7	55816	67708	1094713	943094
	A8	66300		748806	
Naturally saturated	B6	4771		380109	
	B7	2264	3330	509222	454688
	B8	2956		474733	
Forcedly saturated	C6	1150		71887	
	C7	829	951	117894	118507
	C8	875		165740	

count appears at the peak stress point for natural and naturally saturated coal samples, as shown in Figure 9(a) and Figure 9(c); however, the peak count and peak energy appear in the softening stage for the forcedly saturated coal samples, as shown in Figure 9(e). If the portion that is dissipated by brittle crack generation and slip decrease, the

portion that is dissipated by other means will increase. Because the forcedly saturated coal samples have stronger deformability according to Figure 7, it can be implied that the main reason of bearing capacity decrease for the forcedly saturated coal samples is plastic yielding rather than the brittle crack propagation and slip.

FIGURE 8: Variations of AE counts and cumulative counts with time of natural, naturally saturated and forcedly saturated coal samples. (a) Natural coal sample A8. (b) Natural coal sample A8. (c) Naturally coal sample B7. (d) Naturally coal sample B7. (e) Forcedly saturated coal sample C6. (f) Forcedly saturated coal sample C6.

FIGURE 9: Variations of AE energy and cumulative energy with time of natural, naturally saturated and forcedly saturated coal samples. (a) Natural coal sample A8. (b) Natural coal sample A8. (c) Naturally coal sample B7. (d) Naturally coal sample B7. (e) Forcedly saturated coal sample C6. (f) Forcedly saturated coal sample C6.

4.2. Analysis of Energy Dissipation. In fact, the failure process of coal samples is accompanied by the continuous absorption and dissipation of energy. The absorbed energy is mainly from the work done by the rock mechanical test system. A part of the absorbed energy is stored in the coal samples as elastic energy, while the rest of energy is dissipated through plastic deformation, fracture generation, friction and thermal radiation. It is assumed that there is no heat exchange between the coal samples and the environment during loading. According to the first law of thermodynamics, the volumetric absorbed energy, U , is [35]:

$$U = U_e + U_d, \quad (7)$$

where U_e is the volumetric elastic energy stored in the coal samples, P_a ; U_d is the volumetric dissipation energy, P_a .

For any point (σ, ϵ) on the stress-strain curve, U is the stress integral of the strain, which is the area of polygon O-B-C in Figure 10, given by:

$$U = \int_0^\epsilon \sigma d\epsilon. \quad (8)$$

The volumetric elastic energy is the area of the triangle A-B-C in Figure 10, calculated by [35]:

$$U_e = \frac{\sigma^2}{2E_u} \quad (9)$$

where E_u is the unloading modulus, P_a . For rock materials, the unloading modulus is nonlinear and usually is not equal to the loading elastic modulus in postpeak stage, but they are close because of the plastic hysteresis, so here it is assumed that E_u is approximately equal to E_0 [36].

The volumetric dissipation energy U_d can be obtained by substituting Equations (8) and (9) into Equation (7) and solving for U_d , given by:

$$U_d = \int_0^\epsilon \sigma d\epsilon - \frac{\sigma^2}{2E_u} \quad (10)$$

The derivative of U_d dissipation, $\dot{U}_d$, is defined as:

$$\dot{U}_d = \frac{\partial \left(\int_0^\epsilon \sigma d\epsilon - \left(\frac{\sigma^2}{2E_u} \right) \right)}{\partial t}, \quad (11)$$

where t is time, s.

Figure 11 shows the $U_d - t$ and $\dot{U}_d - t$ curves of natural, naturally saturated and forcedly saturated coal samples. From Figure 11(a), the maximum values of $\dot{U}_d$ are 65.68, 59.48 and 13.65 kJ/m³ for the natural, naturally saturated and forcedly saturated coal samples respectively. Compared to the natural coal samples, the maximum values of $\dot{U}_d$ for naturally saturated and forcedly saturated coal samples decreased by 9.44% and 79.22%. According to Figure 11(b), the maximum values of $\dot{U}_d$ are 5.46, 3.51 and 0.63 kJ/(m³·s) for the natural, naturally saturated and forcedly saturated coal samples respectively, which obviously shows that the forcedly saturated coal samples have a very low value of $\dot{U}_d$

FIGURE 10: Schematic of the energy components during UCS test.

compared to the others. The results indicate that the derivative of the volumetric dissipation energy can be used as an indicator to evaluate the outburst proneness, and the forced saturation method significantly reduces the risk of sudden release of energy and is more effective in preventing rock burst.

5. Conclusions

In this paper, a series of experiments was conducted to investigate the mechanical properties, AE characteristics, and energy dissipation of the natural, naturally saturated and forcedly saturated coal samples. According to the experimental results, the conclusions are drawn as follows:

- (1) The forcedly saturated coal samples have higher values of P-wave velocity and water content compared to the naturally saturated coal samples. The forced saturation method drives water into more micropores and fractures and is more effective at changing the solid framework of coal samples. The relative low P-wave velocity of naturally saturated coal samples is caused by the air in coal samples.
- (2) Compared to the natural coal samples, the average strength reduction rates of naturally and forcedly saturated coal samples reached 39.47% and 83.37% respectively. The naturally saturated coal samples from Huoerxinhe coal mine still show brittle failure characteristics, but the coal samples treated by forced saturation method are more similar to plastic materials.
- (3) Both the AE counts and AE energy decrease in an order of natural, naturally saturated and forcedly saturated coal samples. The main reason of bearing capacity decrease for the forcedly saturated coal samples is plastic yielding rather than brittle crack propagation and slip. The derivative of the volumetric dissipation energy can be used as an indicator to evaluate the outburst proneness. The forced saturation method significantly reduces the risk of

FIGURE 11: The unit volume dissipated energy variation of natural, naturally saturated and forcedly saturated coal samples under UCS tests: (a) $U_d - t$; (b) $\dot{U}_d - t$.

sudden release of energy and is more effective in preventing rock burst in coal seams than the natural saturation method.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

For this paper, Weng Wang put forward the research ideas; Shen Wang designed the article structure and wrote the paper; Huamin Li discussed the analysis process of experimental data with Shen Wang; Dongyin Li corrected the English words and the design flow in this paper; Weijie Yang collected the data from the experiments.

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