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An experimental investigation on acoustic emission characteristics of sandstone rockburst with different moisture contents

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Abstract

Rockburst occurred frequently during deep mining in China. The mechanism of rockburst is very complicated and related to many factors. In order to investigate the influence of moisture contents of rockmass on rockburst, we conducted a series of laboratory rockburst experiments of sandstone under three different moisture contents by the Modified True-Triaxial Apparatus (MTTA), in which the acoustic emission (AE) system was employed to monitor the internal damage of rock mass. A high-speed video camera was utilized to record the detail of rockburst. Based on the experimental results, the AE characteristics, such as AE count, AE energy, and AE frequency, were analyzed. The rockburst process, type, and intensity under different moisture contents were discussed. The research results show that with the increase of moisture contents, rock strength was softened, the elastic and the cumulative damage of the rock were reduced, resulting in a gradual decrease in AE cumulative counts and cumulative energy over the course of rockburst. This study provides an experimental basis and reference for better understanding to the rockburst mechanism and control.

Keywords: sandstone, rockburst, moisture contents, acoustic emission, mechanical characteristics

1 Introduction

Following the increase in mining depth, more frequent engineering disasters occurred in coal mines in China, such as surrounding rock large deformation, roof collapse, rockburst, coal and gas outburst, etc. [1–3]. In these disasters, rockburst is one of the most difficult to be controlled because of its sudden occurrence, unpredictability, and high energy release [4–8]. Rockburst problem has been a great concern in the past several decades [9–13]. With the development of research methods, many progresses in study of rockburst have been made in recent years [14–27]. The mechanism is very complicated, and related to rock lithology, rock mineral composition, the stress of surrounding rock, etc. From the micro perspective, microstructure of the rock and the crack growth play an

important role in rockburst happening. Rock as a kind of brittle material contains cracks and pores. Rock failure containing multiple defects is an important area of research in rock mechanics. Many scholars did a number of research works about the rock brittle failure and crack growth mechanisms for rocks containing multiple defects [28–34]. Lin et al. [35] studied crack growth and failure mechanism of granite material containing multiple defects under uniaxial compression. The result has an important meaning for actual engineering. Yang et al. [36] summarized the crack coalescence behavior of specimen containing multiple defects through numerical simulation and experimental study. Numerically simulated results are in accord with the experimental results. The moisture contents of rock can affect the strength and the microstructure of the rock, which has a significant influence on rockburst. This paper addressed the influence of different moisture contents to rockburst using AE technology.

AE can release elastic waves when micro-cracks are generated in a rock mass under high stress [37–39]. Researchers have done extensive work on AE characteristics in rock engineering in order to investigate evolution mechanisms and mechanic properties in the process of rock failure [40–42]. There are also some researches on the influence of different moisture content to rock mechanics properties using AE technology. Yao et al. [43] studied the strength loss of sandstone of moisture contents and AE characteristics under uniaxial compression. The results of AE characteristics experiment show that count peak of acoustic emission of sandstone samples corresponded to the peak stress under dry condition and lagged behind with the increase of moisture content which showed delaying characteristics. Motivated by these studies, researchers has been attempted to to predict and forecast the stability of such kind of sandstone roof. Zhang et al. [44] collected and studied the acoustic emission signal of sandstone for different moisture contents in the process of shear experiment, which showed that the frequency range of the AE signal of sandstone under in situ condition was more concentrated than sandstone samples with higher moisture content, and the peak of frequency was more apparent. Xu et al. [45] studied the AE of water-bearing sandstone in shear experiment, which showed that the shear stress of sandstone decreased with the increase of moisture content, and the AE activity and accumulated energy under the dry condition reached the peak value.

The aforementioned researches have deepened the understanding rock mechanics under different moisture contents, there is however a lack of researches on the effects of different moisture contents for rockburst. AE monitoring technology, as a kind of typical nondestructive monitoring method, has been widely used in indoor rock mechanics experiment [46–48], using AE to study the relations between water, rocks and acoustic emission under different moisture contents in the process of rockburst is very sparse. Therefore, in this paper we conducted the research on the

sandstone in Nanshan coal mine to study the influence of different moisture contents on rockburst using rockburst experimental system.

2 Experimental method and results

2.1 Engineering geological conditions

Nanshan coal mine is located in the middle of Hegang coalfield, Heilongjiang province, China (see Figure 1). The geological structure in this region, controlled by nearly NW stress field, is composed of about 200 faults including 20 faults with more than 20 m fault throw. Most of the fault strike is NE direction (see Figure 2). The mining history has been almost 80 years. At present, the mining depth is 530 m. Following the increase in mining depth, the rock burst occurred more frequently. The magnitude of the most serious rock burst is about 3.0 Richter scale. The surrounding of roadway was damaged very severely during the rock burst, and sometimes the coal and gas outburst happened.

2.2 Rock samples

Sandstone samples were taken from a ventilation roadway of –120 m level in Nanshan coal mine. Rockburst occurred frequently at the location where the samples were taken. The samples size are approximate 150 mm×60 mm×30 mm. Figure 3 shows one of these samples, #D-2. In order to evaluate the effect of moisture content on the rockburst, samples with three levels of moisture content were tested: dry (relative moisture content is 0.00%), natural (average relative moisture content is 0.43%) and fully saturated (average relative moisture content is 1.70%). Three samples are examined in each type of test. Physical and mechanical parameters and dimensions of samples are listed in Tables 1 and 2. X-ray diffraction results of mineral composition of samples are shown in Table 3. The SEM tests shows that the rock is also featured with fissures that are filled with silicates, clay minerals that are dominated by illite and I/S mixed layers and trace amount of mica and albite (see Figure 4).

Figure 1 Location of Nanshan coal mine.

Figure 2 Structure schematic diagram of Nanshan coal mine.

Figure 3 NanShan # D-2 sandstone: (a) Schematic of the sample; (b) photograph of the sample.

Table 1 Physical and mechanical properties of sandstone samples

Type of water saturation	Moisture contents (%)	Density (g/cm ³)	<i>E</i> (GPa)	UCS (MPa)
Dry	0.00	2.46	35.7	69.14
Natural	0.43	2.53	30.8	58.75
Fully saturated	1.70	2.56	26.8	41.34

Table 2 Dimension and density of sandstone samples

No.	Water state	Dimension (mm×mm×mm)	Quality (g)	Density (g/mm ³)	Moisture contents (%)
D-1	Dry	30.18×60.18×150.02	677.5	2.49	0
D-2		30.08×60.23×150.05	668.2	2.46	0
D-3		30.11×60.18×150.05	669.1	2.46	0
N-1	Natural	30.11×60.16×150.25	689.0	2.53	0.43
N-2		30.31×60.18×150.08	693.7	2.53	0.42
N-3		30.13×60.13×150.04	670.4	2.47	0.44
S-1	Fully saturated	30.24×60.07×150.15	697.7	2.56	1.63
S-2		30.30×60.25×150.18	707.1	2.58	1.55
S-3		30.32×60.03×150.12	699	2.56	1.70

Table 3 X-ray diffraction results of mineral composition of samples

No.	Mineral types and contents (%)						Clay mineral contents (%)
	Quartz	Potash feldspar	Plagioclase	Calcite	Dolomite	Siderite	
1	28.1	4.8	14.6	–	0.5	–	51.0
2	30.6	8.5	28.0	0.45	0.4	–	31.6
3	28.9	11.1	22.2	–	1.0	–	36.8
Average	29.2	8.1	21.6	–	0.6	–	39.8

2.3 Experimental method

Rock burst experiment was conducted using the Modified True-Triaxial Apparatus (MTTA) developed by He et al. [20], which can provide dynamic loading/unloading independently in three principal stress directions (see Figure 5). It is a unique system for rockburst testing, which includes a main machine, a hydraulic pressure controlling unit and a data acquisition apparatus that can record forces, displacements, acoustic emission and has a high speed digital camera recording unit.

During the rockburst experiment, stress was loaded to the rock sample on 3 directions and 6 faces using the hydraulic load control system. One surface of the sample can be unloaded immediately from the true triaxial compression condition, which simulates the excavation in the field.

According to in-situ stress regression curve of Nanshan coal mine (see Figure 6), the initial confining pressure corresponds to stress field at 539 m depth, with $\sigma_1=34$ MPa, $\sigma_2=23$ MPa and $\sigma_3=19.8$ MPa. The loading-unloading stress design is shown in Figure 7. The stress concentration after excavation was simulated by vertical loading with a stress that was the redistributed maximum tangential stress according to the Kirsch formula ($\sigma_{\max}=3\sigma_1-\sigma_3$).

2.4 Experimental observations

Rockburst observed in the laboratory typically can be characterized by four temporal stages. Stage 1, cracks forms and ejection of small particles appears sparsely at the surface of sample. Stage 2, more small particles are ejected at the top of the sample. Stage 3, large pieces of rock with a shape of sheet pop out at the top of the sample. Stage 4, the upper portion of sample is violently exfoliated and shot out, forming a large pit and making explosion sound.

Figure 8 shows the failure modes on six surfaces of rectangular sample with three different moisture contents aforementioned, which clearly exhibit the formation of cracks during stage 1 and the pit during stage 4.

Figure 9 presents a series photos captured by high speed photography, which shows the exfoliation and the subsequent explosive broking of upper part of the rock during stage 4.

Through the records and photos of D-2, we can see that there are cracks and small particles accompanied by partial ejection occurred in the surface of sample. For the sample of D-2, in 15 s, tiny particles ejected at the top. In 60 s, sheet ejection appears at the top of the sample, followed by a violent exfoliation of the upper portion and flying at higher speeds after broken, forming a large pit and accompanied by explosion sound. However, the sample of N-3 took shorter time to finish the whole process of rockburst. For the sample of N-3, in 11 s, tiny particles ejected at the top. In 24 s, sheet ejection appeared at the top of the sample, followed by a violent exfoliation of the upper portion and flying at higher speeds after broken, forming a large pit and accompanied by explosion sound. The explosion sound of N-3 is lower than D-2. The sample of S-1 has the shortest time to complete the whole process of rock burst. For the sample of S-1, there were also cracks and small particles accompanied by partial ejection occurred in the surface of sample. In 10 s, tiny particles ejected at the top. In 15 s, sheet ejection appears at the top of the sample, followed by a violent exfoliation of the upper portion and flying at higher speeds after broken, forming a large pit and accompanied by explosion sound. The explosion sound of S-1 is lowest in the three moisture contents.

Figure 4 SEM photos of the sandstone samples.

Figure 5 Modified true-triaxial apparatus (MTTA) and its periphery instruments. (a) Schematic of the MTTA (He et al., 2007), and (b) photograph showing the MTTA and its periphery monitoring instruments.

Figure 6 In-situ stress regression curve of Nanshan coal mine.

Figure 7 The loading-unloading stress design of samples.

Figure 8 Failure modes on six surfaces of rectangular sample after rockburst (or strength failure) for three samples of different moisture content: (a) dry, (b) natural, and (c) fully saturated.

Figure 9 Rockburst (or strength failure) captured by high speed video for three samples with different moisture content: (a) dry, (b) natural, and (c) fully saturated.

Figure 10 presents corresponding stress paths, which shows the critical stress of rockburst after two unloading events. The critical stresses of sample at the time of the occurrence of the rockburst are inversely proportional to moisture content of the sample, i.e. the lower the moisture content, the higher critical stresses. This is because that higher moisture content makes the rock softer. The rockburst of samples with different moisture contents also exhibit different intensity which is manifested in two ways: first, rock samples with lower moisture content were broken into smaller pieces in comparison with sample of higher moisture content. For the fully saturated sample, we observed peel off of fairly large pieces, which is quite untypical for rockburst. For typical rockburst, pieces usually rotate when they are peeled off from sample. Second, rockburst lasts for shorter time period for

samples with lower moisture content than that for sample with higher moisture content. The reason is that rockburst (or strength failure) is instantaneous energy release and failure process. Rock's elastic modulus of dry state is larger and has a better ability of accumulation of strain energy, and once such energy is release, it is more intense and destructive.

Figure 10 Measured stress paths towards the occurrence of rockburst (or strength failure) for three samples: (a) dry, (b) natural, and (c) fully saturated.

3 Analysis of AE characteristics

While Section 2.4 provides qualitative analyses of the different rockburst behavior for samples with different moisture contents, in this Section, we attempt to quantify the differences with AE signals. The PCI-2 AE system was employed to monitor the experiment, which is the latest product developed by the PAC company. The PCI-2 AE system consists of PCI-2 software system, the AE sensor and preamplifier. The system can record the AE waveforms and extract in real-time the characteristics of the AE data. Acquisition card of PCI-2 is equipped with broadband sensor. The frequency response range of broadband sensor is 100 Hz–1 MHz, the sampling rate is 2 Msps (Msps means million samples per second). The amplifier gain is 40 dB.

In the experiments of rockburst, cracking produces AE signals. During the data acquisition process, the magnitude of the AE data less than 50 dB is filtered by the AE hardware system in order to eliminate most of the electrical, instrumental and environmental noises. The threshold value of 50 dB is suggested by the operation manual of the PAC company under the laboratory testing conditions. A frequency domain filter, i.e. Gaussian high pass filter (GHPF) was employed to remove the rest of the noises. The GHPF is a robust and efficient high-band filter [49,50] and can remove the noises at high band while preserve the main characteristics of the signal at low band. Broadly speaking, the AE signals can be analyzed using two methods: the parameter analysis and waveform analysis method. The former involves statistical analysis of characteristics of AE signal parameters such as AE count, AE energy. The later uses a certain method to obtain AE source information according to AE signal waveform. In this paper, parameter analysis of the AE characteristics is employed. Because the strength and elastic modulus of rock samples decreases as the moisture content of rock sample increase, and internal crack and its propagation are distinct under different moisture content, the parameters for AE characteristics of rockburst

are different. Utilizing four characteristics of AE signals collected during the rockburst experiment: AE count, AE cumulative count, energy and cumulative energy, we can quantify the effect of moisture content of the rockburst. Combined with waveform analysis, which is important for the study of rockburst under the different moisture contents.

3.1 AE energy release

Figure 11 shows the AE counts and cumulative AE counts and Figure 12 shows AE energy and cumulative AE energy for three samples with different moisture content. The values of cumulative count and accumulative energy are listed in Table 4.

Figure 11 AE count and total AE count of the rockburst (or strength failure) for three samples: (a) D-2, dry; (b) N-3, natural; and (c) S-1, fully saturated.

In general, no matter what moisture content the sample has, AE counts keep rising over the course of loading/unloading at the different stress level. However, AE signal is sporadic (see Figure 11) during the loading stage due to the stabilization of internal cracks and voids regardless of the moisture content of the samples. At the time of first unloading, the intensity of AE signal for fully saturated sample is greater than that for natural and dry samples, and at the time of first loading to the next level stress, and AE cumulative counts decrease with the increase of moisture contents. The intensity of AE signal of being dry state is greater than that of being natural state and saturated state when rockburst (or strength failure) occurs, and AE accumulative counts and the accumulative energy decrease with the increase of moisture content. The inner cause lies in the fact that the rock samples contain clay minerals. When saturated with water, they will soften with reduced strength. It is manifested by the relation between the bulk modulus and water-bearing content reported in Table 1. The strength and

cumulative damage decrease with increase of moisture content in the process of rockburst (or strength failure).

3.2 AE frequency spectrum

The AE signal can be transformed to frequency using Fast Fourier Transform, which allows us to extract more structural representation of effect of moisture content on rockburst because frequency spectrum reflects the internal damage during rockburst. In this paper, we use the dominant frequency spectrum at five temporal points of samples D-2, N-3 and S-1 to illustrate the difference of frequency spectrum for samples of different moisture content. The five temporal points are shown in Figure 12. At initial loading, the rock is compacted and then entered into a stable deformation stage. Capital letter A represents the compaction stage. After the initial loading, the flaws and pre-existing cracks will develop and propagate when the loading level increases; B and C indicate the key points during the deformation stages at different loading levels. When the rock sample was loaded to a sufficiently high level, i.e. the rock burst stress state ($\sigma_1 = 82$ MPa, $\sigma_2 = 29$ MPa, $\sigma_3 = 24$ MPa), the deformation will become unstable, cracks will coalesce and rock burst failure will occur. Capital letter D indicates the turning point at the onset of the bursting failure and E indicates the rock burst stress state.

In this research, we conducted nine groups rockburst experiments, three groups of each state. The average results of three different states have the laws of frequency which has been described in the paper. In order to facilitate analysis, we chose one typical group of each state, and the rule of this typical group follows the average results of all groups. As shown in Figures 13 and 14, regardless of moisture content of the samples the dominant frequency at point A is larger than that at point E (the time when rockburst (or strength failure) happened). However, the three samples differs in terms of the value of dominant frequency at point E, with 101 kHz for D-2 ("dry" sample), 98 kHz for N-3 ("natural" sample) and 80 kHz for S-1 ("fully saturated" sample). The decreasing dominant frequency value with increasing moisture content suggests that the energy releasing is more concentrated for sample with higher moisture contents over the course of rockburst. Before rockburst happens, small scale cracks are generated when the samples accumulate energy reaching a certain level, however, the larger scale cracks are generated when rockburst happens, which is the reason why the dominant frequency at point A is larger than that at point E. However, the samples can easily accumulate the energy under dry and natural state, under which more small scale cracks are generated, which is the reason why the dominant frequency under dry and natural state is larger than that under saturated state at point A. The reason why dominant frequency value is lower under the saturated state compared with the dominant frequency under dry and natural state at point E when rockburst happens is that the mineral particles are more prone to slip under the saturated state, resulting

in large scale cracks. Therefore, the samples under fully saturated state are less prone to rockburst, but strength failure.

4 Conclusions

Rockburst is one of the most devastating disasters in deep mining. Understanding the factors that affect rockburst is critical for predicting and preventing the occurrence of rockburst. In this paper, a series of rockburst experiments were conducted for samples with different moisture content, attempting to shed light on the effect of moisture content on rockburst. Experimental results are presented with photos captured by the high speed cameras and analyzed for acoustic emission energy release and frequency spectrum, which lead to the following conclusive remarks.

(1) Rockburst was observed for the samples under dry and natural moisture content conditions had the phenomenon of rockburst, whereas strength failure occurs to the samples under fully saturated condition. With the increase in moisture content, the critical stress and the damage degree of rockburst decrease.

Figure 12 AE energy rate and cumulative energy rate of the rockburst (or strength failure): (a) dry, (b) natural, and (c) fully saturated.

Table 4 AE count and cumulative energy of samples

No.	Moisture content	Cumulative count	Cumulative energy
D-2	dry	332513	1.22×10^{10}
N-3	natural	193857	8.12×10^8
S-1	saturated	191925	5.56×10^8

(2) Regardless the moisture content of the sample, the dominant frequency at initial time is larger than that at the peak time when rockburst happened. However, a comparison between dominant frequency at five point for sample with different moisture contents reveals that samples with higher moisture content have lower dominant frequency.

(3) Samples with higher moisture content show decrease in strength and the elastic energy, and subsequently reduced cumulative damage, which eventually results in decrease in the cumulative count of AE and the accumulated energy of the samples during rockburst. Because the peaking of AE counts, AE accumulative counts, AE energy and accumulative energy coincide the occurrence of rockburst, these parameters could be indicative of the occurrence of rockburst.

(4) The sandstone samples under saturated state can effectively transform the rockburst into strength failure. In actual project, watering the surrounding rock of tunnel in certain circumstances can reduce the possibility of rockburst.

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