Hindawi Publishing Corporation
Shock and Vibration
Volume 2015, Article ID 458519, 11 pages
http://dx.doi.org/10.1155/2015/458519

Research Article

Study of Acoustic Emission and Mechanical Characteristics of Coal Samples under Different Loading Rates

Huamin Li,[1,2] Huigui Li,[1,2] Baobin Gao,[1,2,3] Dongjie Jiang,[1,2] and Junfa Feng[1,2]

[1]*School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo, Henan 454000, China*
[2]*Opening Project of Key Laboratory of Deep Mine Construction, Henan Polytechnic University, Jiaozuo, Henan 454000, China*
[3]*Stage Key Laboratory Cultivation Base for Gas Geology and Gas Control, Henan Polytechnic University, Jiaozuo, Henan 454000, China*

Correspondence should be addressed to Dongjie Jiang; jiangdongjie306@126.com

Received 13 November 2014; Revised 14 April 2015; Accepted 15 April 2015

Academic Editor: Alicia Gonzalez-Buelga

To study the effect of loading rate on mechanical properties and acoustic emission characteristics of coal samples, collected from Sanjiaohe Colliery, the uniaxial compression tests are carried out under various levels of loading rates, including 0.001 mm/s, 0.002 mm/s, and 0.005 mm/s, respectively, using AE-win E1.86 acoustic emission instrument and RMT-150C rock mechanics test system. The results indicate that the loading rate has a strong impact on peak stress and peak strain of coal samples, but the effect of loading rate on elasticity modulus of coal samples is relatively small. When the loading rate increases from 0.001 mm/s to 0.002 mm/s, the peak stress increases from 22.67 MPa to 24.99 MPa, the incremental percentage is 10.23%, and under the same condition the peak strain increases from 0.006191 to 0.007411 and the incremental percentage is 19.71%. Similarly, when the loading rate increases from 0.002 mm/s to 0.005 mm/s, the peak stress increases from 24.99 MPa to 28.01 MPa, the incremental percentage is 12.08%, the peak strain increases from 0.007411 to 0.008203, and the incremental percentage is 10.69%. The relationship between acoustic emission and loading rate presents a positive correlation, and the negative correlation relation has been determined between acoustic emission cumulative counts and loading rate during the rupture process of coal samples.

1. Introduction

With a significant improvement of coal mining technology, the advancing speed of longwall face is greatly increased. However, a fast movement of longwall face may produce a certain adverse mechanical conditions around longwall face, such as the rib failure and rock bursts [1, 2]. Therefore, the loading rate, as one of the important factors, has been studied herein, being associated with mechanical properties and acoustic emission characteristics of coal samples collected from underground, to obtain some fundamental knowledge for cooperating with the current coal mining technology.

The study on the impact of loading rate on mechanics and acoustic emission characteristics in the failure process of coal and rock has never been interrupted, which has obtained some research results. Sagar et al. studied the acoustic emission of coal and rock under different loading [3–6]. Shkuratnik and Rudajev studied the characteristics of acoustic emission under uniaxial and triaxial compression [7–9]. Ma et al. studied mechanical properties of coal and rock under uniaxial and triaxial compression [10–12]. Liang et al. [13] carried out an experimental study of marble and red sandstone under uniaxial compression, and the relationship between AE parameters and loading rates was obtained. Tong et al. [14] studied AE characteristics of water cut coal samples under different loading rate, and they recognized that the loading rate has a great influence on frequency and amplitude of acoustic emission in the rupture process of coal and rock. Pan et al. [15] studied charge induction regularity of coal and rock under different loading rates using self-developed charge inductor under uniaxial compression. Wan et al. [16] studied acoustic emission characteristics in the rupture process of rock, using coal samples collected from number 3 coal of Qishan Colliery, and they obtain the positive correlation relationship between the acoustic emission activity intensity and the sizes of the loading rate are obtained.

Chen et al. [17] studied acoustic emission characteristics and Kaiser with different kinds of rock under different loading rates, focusing on sandstone, coarse sandstone, and mudstone. The acoustic emission and mechanics characteristics of sandstone, marble, and granite were analyzed under different loading rates by Xie et al. [18], and the results indicated that the loading rate has a certain influence on the acoustic emission and mechanics characteristics. Zhang and Mao [19] studied mechanics characteristics of limestone under different loading rates under the temperature condition of 200°C, and the relationship between peak strength and elastic modulus with peak strain has been obtained. Yin et al. [20] investigated the rock materials under different loading rates using numerical simulation software of PFC particles flow. Firstly, the rock samples temperature has been increased, and then an experimental work on mechanics characteristics of the high temperature processed marble under different loading rate has been conducted, and the relationship among peak stress, elasticity modulus, and peak strain with loading rate was analyzed by Xu and Liu [21]. Zhao [22] carried out an experimental research on mechanics characteristics of coal samples under different loading rates, by using MTS815 rock mechanics test system, and he obtained the relationship between mechanics characteristics and loading rate. Study on acoustic emission properties of coal samples with conventional triaxial and triaxial cyclic load and unload was carried out by He et al. [23]. Qin et al. [24] studied acoustic emission and mechanical characteristics of coal and rock with different moisture content, by using AG-250kN rigid rock testing machine, and the experiment result indicated that the moisture content had a great influence on the mechanical properties and the acoustic emission characteristics of coal and rock.

From the above discussion, it is noted that a number of works related to the mechanical and acoustic emission characteristics of rock have been conducted in recent years, but studies on acoustic emission and mechanics features of coal samples are relatively few under different loading rates. This paper is mainly study of the relationship among peak strength, elastic modulus, peak strain, acoustic emission counts, and cumulative counts with the loading rates of coal samples under the loading rate of 0.001 mm/s, 0.002 mm/s, and 0.005 mm/s, by using AE-win E1.86 acoustic emission system and the RMT-150C rock mechanics servo-controlled testing system (Figure 2).

2. Experimental Processes

2.1. Collection and Preparation of Coal Samples. In order to study mechanics and acoustic emission characteristics in the rupture process of coal samples under different loading rates, two coal samples with 300 mm in length, 300 mm in width, 200 mm in height are collected from Sanjiaohe Colliery of Huozhou coal group. Coal samples were processed into standard coal samples with diameter of 50 mm and height of 100 mm according to the regulation requirements. The photo of coal samples which had been processed is presented in Figure 1.

Figure 1: Coal samples and acoustic emission system.

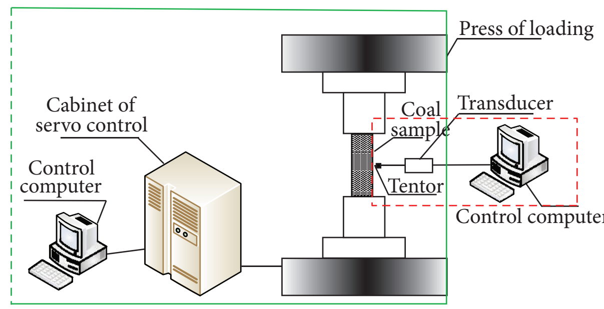


Figure 2: Test system.

2.2. Experiment System and Method. The experimental work uses the AE-win E1.86 acoustic emission experiment system and the RMT-150C rock mechanics servo-experiment system. In order to investigate the effect of loading rate on mechanics and acoustic emission characteristics in the failure process of coal samples, firstly, an experiment was carried out on the M1, M2, and M3 coal samples under the loading rate of 0.001 mm/s. Then, an experiment was carried out on the M4, M5, and M6 coal samples under the loading rate of 0.002 mm/s. Finally, an experiment was carried out on the M7, M8, and M9 coal samples under the loading rate of 0.005 mm/s. The displacement control mode had been used during all process of experimental work. A layer of coupling agent was coated between the sensor and the coal samples in the experimental process, and in order to guarantee the acoustic emission, the sensor and the coal samples were in full contact. In order to avoid the bad contact in the experimental process, they were fixed by using the elastic conductive adhesive. The threshold value was set to 55 dB, and the sampling frequency was set to 1 Msps.

3. Analysis of Mechanical Properties of Coal Samples under Different Loading Rates

An experiment was carried out to investigate mechanical properties of Sanjiaohe mine coal samples under different loading rates by using RMT-150B rock mechanics test system. The overall stress-strain curve of coal samples under different loading rates is obtained; the peak intensity, the peak strain (strain corresponding to the peak strength), and the relationship between elastic modulus and loading rate of coal

Table 1: Mechanical parameters of coal samples.

Serial number	Loading rate/mm·s^{-1}	Peak stress/MPa		Peak strain/10^{-3}		Elastic modulus/GPa	
		Experiment value	Average value	Experiment value	Average value	Experiment value	Average value
M1	0.001	20.750	22.67	5.368	6.191	4.094	4.281
M2	0.001	23.400		6.878		4.574	
M3	0.001	22.650		6.328		4.175	
M4	0.002	25.244	24.99	9.035	7.411	3.923	4.21
M5	0.002	25.990		7.978		4.373	
M6	0.002	23.740		5.219		4.334	
M7	0.005	27.578	28.01	7.309	8.203	4.030	4.196
M8	0.005	26.910		7.382		4.145	
M9	0.005	29.530		9.919		4.414	

samples under different loading rates are obtained, as shown in Table 1.

3.1. Effect of Loading Late on the Strain-Stress of Coal Sample. Figure 3 shows an overall stress-strain process curve of coal samples under different loading rates. It is note that the overall stress-strain curve of coal samples can be divided into three stages, including initial consolidation stage, linear elastic stage, and plastic damage stage. Due to the fact that coal has a lot of inside joints, cracks, and pores, three cases of coal samples inside cracks and pores were compacted in the initial consolidation stage, and the phenomenon of the curve concave appeared. Moreover, the closure degree of internal joints, cracks and pores of coal have a difference under different loading rates, so the lengths of the linear part of the emergence of coal samples were also different under different loading rates in linear elastic stage. The curves of coal samples have big difference under different loading rates in the plastic damage stage. The curves present plastic failure under the loading rates of 0.001 mm/s, and when the loading rate increased to 0.002 mm/s and 0.005 mm/s, the curves demonstrate a brittle failure of coal samples.

3.2. The Relationship of Coal Samples between Peak Stress and Loading Rate. Figure 4 shows a relationship between loading rate and peak stress in the failure process of coal samples. Broken line indicates the average value of the peak stress, scattered dots represent the peak stress of coal samples under different loading rates, and straight line is a fitting curve of the average peak stress. The correlated equation is obtained from data fitting that can be given as follows:

$$\sigma = 21.8653 + 1259.23v. \tag{1}$$

The peak stress and the loading rate are a positive correlation in the rupture process of coal samples as shown in Figure 4 and Table 1. The peak intensity is 22.67 MPa when loading rate was 0.001 mm/s. When the loading rate increased up to 0.002 mm/s, the peak intensity of 24.99 MPa has been observed, and the incremental percentage reaches 10.23%. The peak stress increased to 24.99 MPa when the loading rate increased to 0.005 mm/s. Comparing with the loading rate of

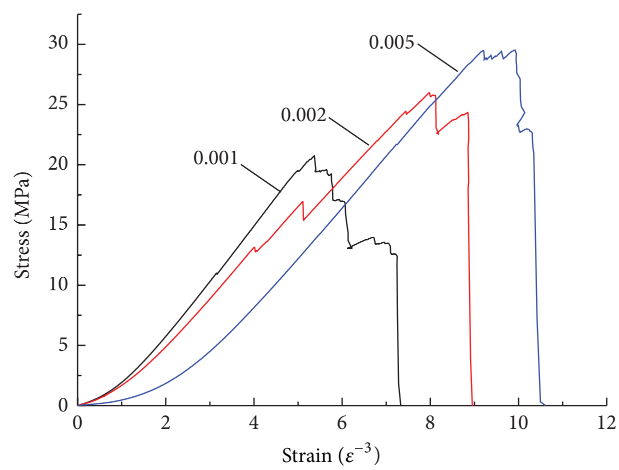


Figure 3: The overall stress-strain curves of coal samples under different loading rates.

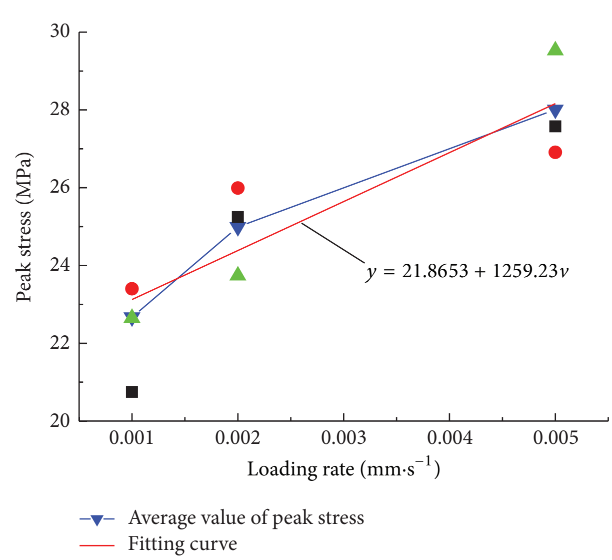


Figure 4: The relationship between peak stress and loading rate.

0.001 mm/s and 0.002 mm/s, the peak intensity increased to 23.56% and 12.08%, respectively.

3.3. The Relationship of Coal Samples between Peak Strain and Loading Rate. Figure 5 presents a relationship between loading rate and peak strain in the failure process of coal samples. Scattered dots represent the peak strain of coal samples under different loading rates, broken line indicates the average value of the peak strain, and straight line is a fitting curve of the average peak strain. The correlated equation is obtained from data fitting that can be given as follows:

$$\varepsilon = 6.674 + 447.842v. \tag{2}$$

Loading rate has an influence on the peak strain, which is a positive correlation. Compared with the loading rates of 0.001 mm/s, the peak strain increases to 0.00122 on loading rate of 0.002 mm/s, and the growth rate reached 19.71 percent. Compared with the loading rate of 0.001 mm/s, the peak strain increased to 0.002012 on loading rate of 0.005 mm/s, and the growth rate reached 32.50 percent. Comparing with the loading rate of 0.002 mm/s, the peak strain increased to 0.000792 on loading rate of 0.005 mm/s, and the growth rate reached 10.69 percent.

3.4. The Relationship of Coal Samples between Elasticity Modulus and Loading Rate. Coal is a heterogeneous material, and the stress-strain curve of coal samples is not a straight line. The selection methods of elasticity modulus have tangent modulus (Et), secant modulus (E_{50}), and average modulus (E_{av}). The average modulus (E_{av}) is used in this paper, which is shown by the slope between A point (A is a point when the stress is the peak stress of 30 percent) and B point (B is a point when the stress is the peak stress of 70 percent) based on the continuous sampling and recording data of the computer:

$$E = E_{av} = \frac{\sigma_B - \sigma_A}{\varepsilon_B - \varepsilon_A}, \tag{3}$$

where E is the elasticity modulus, E_{av} is the average modulus, A is the point when the stress is the peak stress of 30 percent, and B is the point when the stress is the peak stress of 70 percent.

Figure 6 presents a relationship between loading rate and elasticity modulus in the failure process of coal samples. Scattered dots show the elasticity modulus of coal samples under different loading rates, broken line indicates the average value of the elasticity modulus, and straight line is a fitting curve of the average elasticity modulus. The correlated equation was obtained from data fitting, which can be given as follows:

$$E = 4.2755 - 17.4231v. \tag{4}$$

From Table 1 and Figure 5, the negative correlation between the elastic modulus and loading rate of coal samples was obtained, but the correlation is not very strong. The elastic modulus of coal samples is 4.281 GPa when the loading rate is 0.001 mm/s. When the loading rate increases to 0.002 mm/s, the modulus of elastic of coal samples reduces to 4.21 GPa, and the difference is 1.66%. When the loading rate increases to 0.005 mm/s, the elastic modulus of coal samples reduces to 4.196 GPa. Comparing with the loading rate of 0.001 mm/s, the elastic modulus of coal samples reduces 0.085 GPa, and the difference is 1.99%. What is more, comparing with the loading rate of 0.002 mm/s, the elastic modulus of coal samples reduces to 0.014 GPa, and the difference is 0.33%.

From the above discussion, the loading rate has a great influence on mechanical properties in the rupture process of coal samples. The effect of loading rate on the stress-strain curve is mainly displayed in elastic and plastic damage phase. The loading rate has a strong influence on peak stress and peak strain in the rupture process of coal samples and presents a positive correlation relationship. The loading

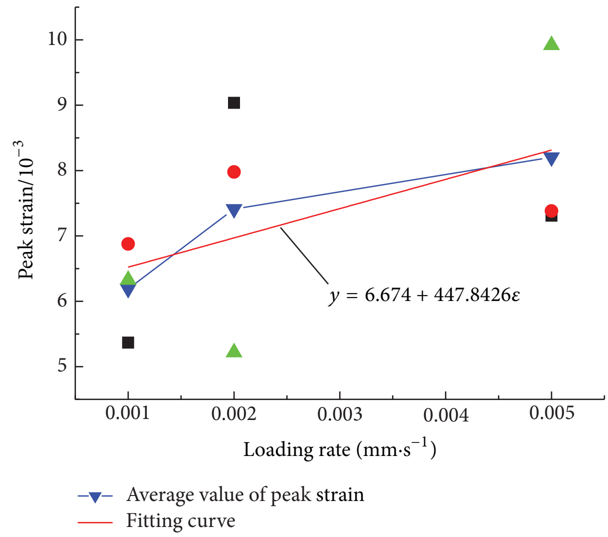


Figure 5: The relationship between peak strain and loading rate.

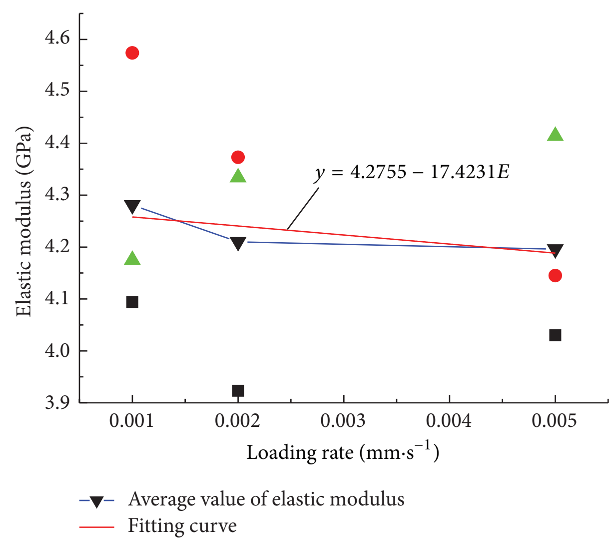


Figure 6: The relationship between elasticity modulus and loading rate.

Table 2: Acoustic emission parameters of coal samples.

Serial number	Loading rate/mm·s^{-1}	Peak count/times		Cumulative count/times	
		Experiment value	Average value	Experiment value	Average value
M1	0.001	844	871	2.66	2.76
M2	0.001	892		2.94	
M3	0.001	876		2.68	
M4	0.002	908	911	1.81	1.73
M5	0.002	926		1.46	
M6	0.002	900		1.92	
M7	0.005	980	985	1.68	1.61
M8	0.005	979		1.56	
M9	0.005	997		1.59	

rate has a slight effect on elastic modulus of coal samples. Although they demonstrate a certain negative relationship, the effect is not very big.

4. Analyzing of Acoustic Emission Characteristics with Different Types

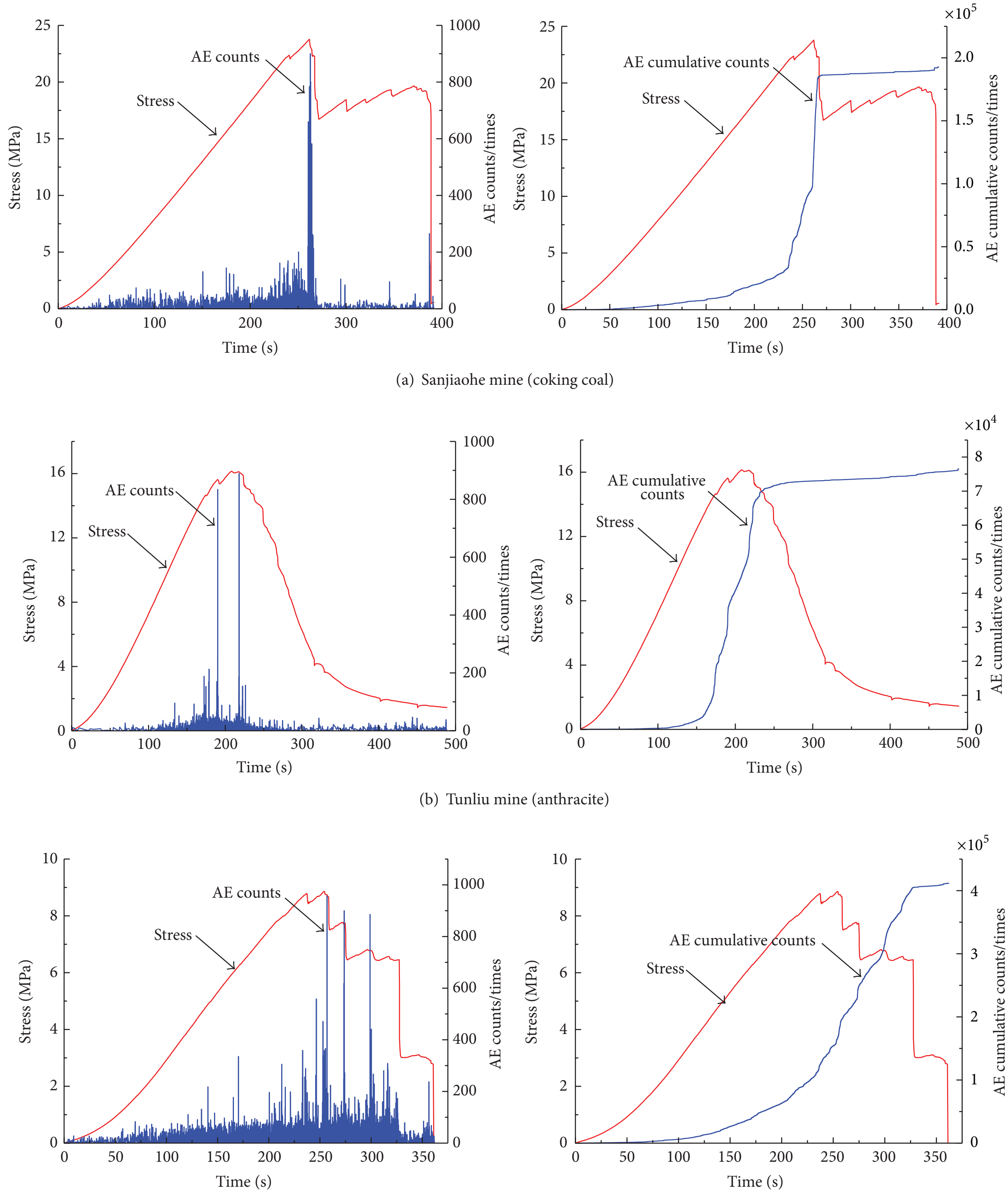
Figure 7 is the acoustic emission counts and cumulative counts with the coal samples of different types and different regions. It is noted that the characteristic of acoustic emission counts and cumulative counts have a difference, but the trend of acoustic emission counts and cumulative counts are basically similar. In the initial consolidation stage, the acoustic emission counts of three kinds of coal samples appear very litter. Moreover, the acoustic emission cumulative counts increase slowly. The appearing time of three types of coal samples are similar between peak count and peak stress. The acoustic emission cumulative counts of three species coal samples present a surge phenomenon near the peak stress. In this paper, we mainly study the acoustic emission characteristic of coal samples of Sanjiaohe mine under different loading rates. Therefore, we narrate the acoustic emission and mechanics characteristics of coal samples of Sanjiaohe mine under different loading rates.

5. Analyzing Acoustic Emission Characteristics under Different Loading Rates

Loading rate not only has a certain impact on mechanics characteristics of coal samples, but also has a certain influence on acoustic emission characteristics in the rupture process of coal samples. Study on acoustic emission characteristics of coal samples with different impact bias is carried out by Li et al. [25]. Study on acoustic emission and temperature characteristics of the prominent coal body under the mining influence is carried out by Xu et al. [26]. Su et al. [27] analyzed acoustic emission characteristics of the two dimension coal samples, focusing on coal samples of Zhangcun mine. In this paper, the acoustic emission characteristics of coal samples were studied under different loading rates. The detailed parameters of acoustic emission counts and cumulative counts are displayed on Table 2.

5.1. The Relationship of Coal Samples among AE Counts and Cumulative Counts with Loading Rate. Figure 8 indicates a relationship among AE counts and cumulative counts with times in the rupture process of coal samples under different loading rates, and it is noted that the loading rate has a certain influence on acoustic emission counts and cumulative counts. In the initial consolidation stage, acoustic emission counts and cumulative counts curve presents a concave phenomenon, and slow growth. With the gradual increase of stress, the curve enters into elastic stage. Acoustic emission counts and cumulative counts of three different coal samples increase gradually with different values. The less acoustic emission counts produced, in this stage, the slower cumulative counts grown with loading rate increasing. When the process enters plastic phase, the acoustic emission counts and the cumulative counts present a surge phenomenon. When the loading rate is 0.001 mm/s, in the peak failure stage, acoustic emission counts will continue to appear, but the frequency and intensity of appearing are weak, and AE accumulative counts also will continue to increase, but the increase intensity is reduced. When loading rate is 0.002 mm/s, the acoustic emission counts also present in this stage, but comparing with the loading rate it is 0.001 mm/s, and the degree has subsided, and the cumulative counts curve maintains a steady trend. When loading rate is 0.005 mm/s, acoustic emission counts do not occur in this stage.

5.2. The Relationship of Coal Samples among AE Energy and Cumulative Energy with Loading Rate. The relationships among AE energy and cumulative energy with times in the rupture process of coal samples are shown in Figure 9 under different loading rates, and it is noted that the loading rate has a certain influence on acoustic emission energy and cumulative energy. The relationship between acoustic emission peak energy and loading rate is positive correlation, but the negative correlation between acoustic emission cumulative energy and loading rate is presented in Figure 9. The reason is that when loading rate gradually increases, the destructive time of coal samples will reduce (when the loading rate is 0.001 mm/s, the destructive time is 535 s; when the loading rate is 0.002 mm/s, the destructive time is 262 s; when the loading rate is 0.005 mm/s, the destructive time is 151 s) and the impact also will increase, which will lead to release of

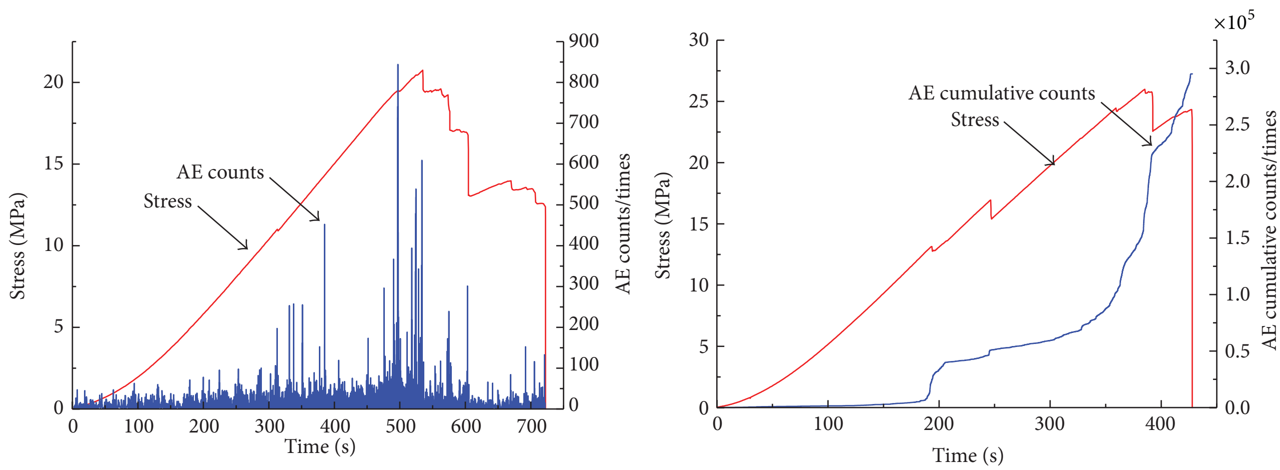


(a) Sanjiaohe mine (coking coal)

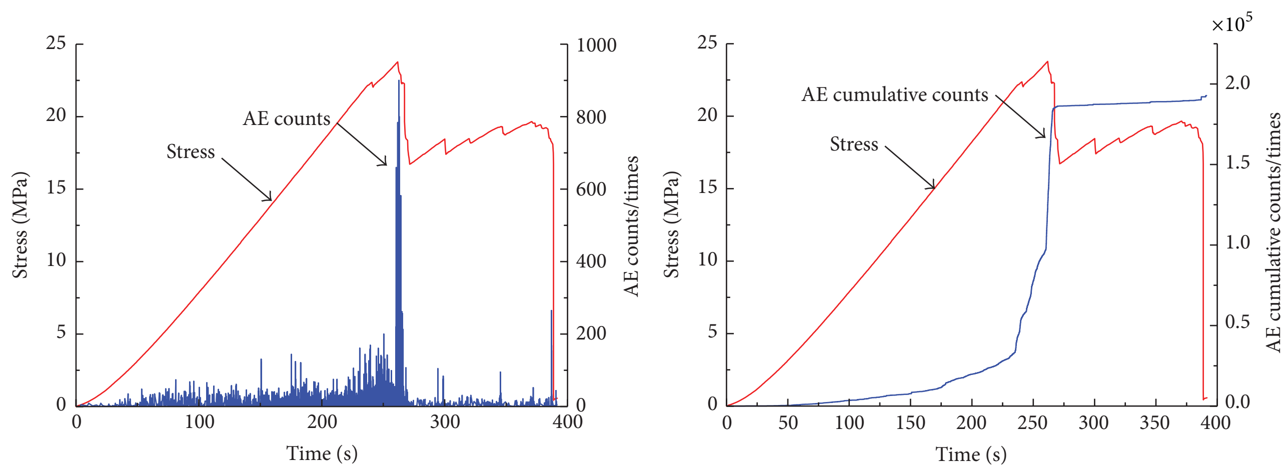
(b) Tunliu mine (anthracite)

(c) Longshan mine (gas-fat coal)

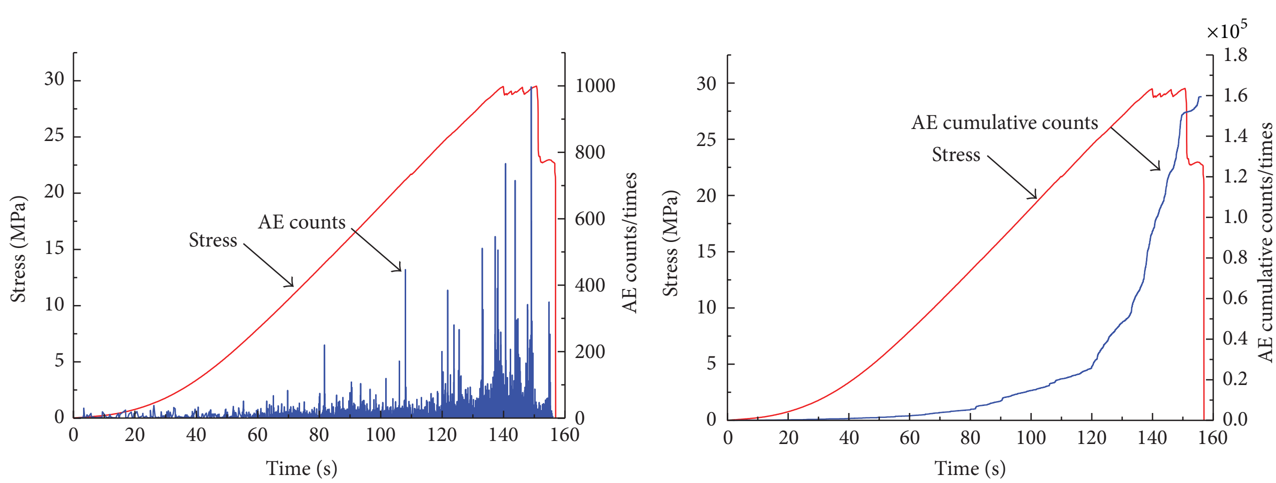
FIGURE 7: Acoustic emission characteristics with different types.



(a) AE counts and cumulative counts of coal samples M1 (0.001 mm/s)

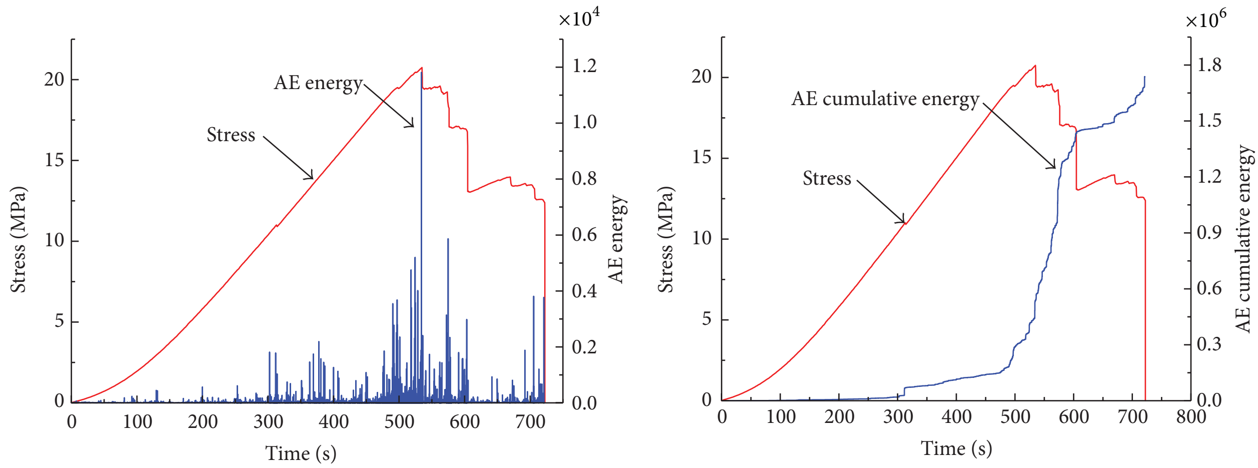


(b) AE counts and cumulative counts of coal samples M6 (0.002 mm/s)

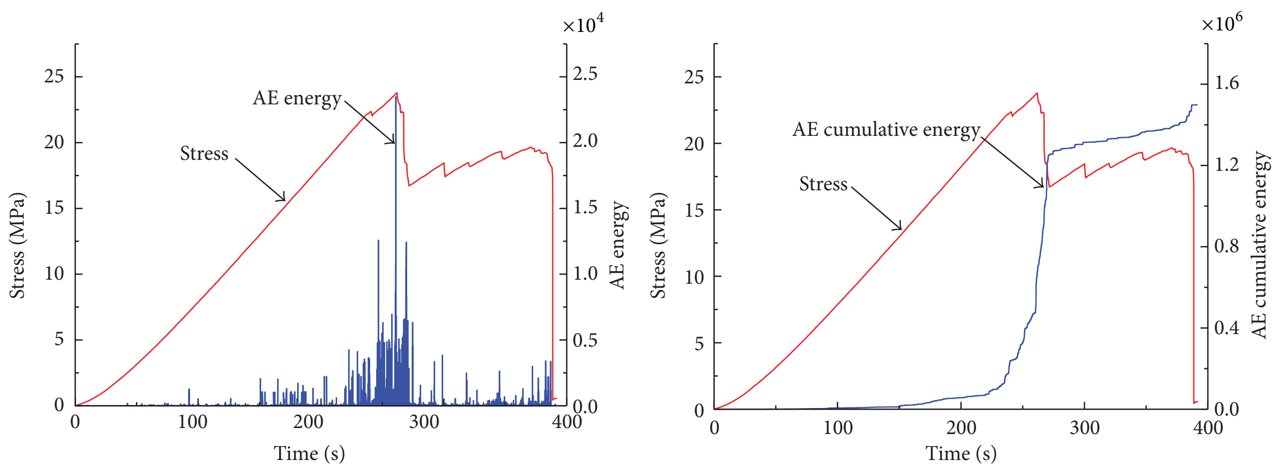


(c) AE counts and cumulative counts of coal samples M9 (0.005 mm/s)

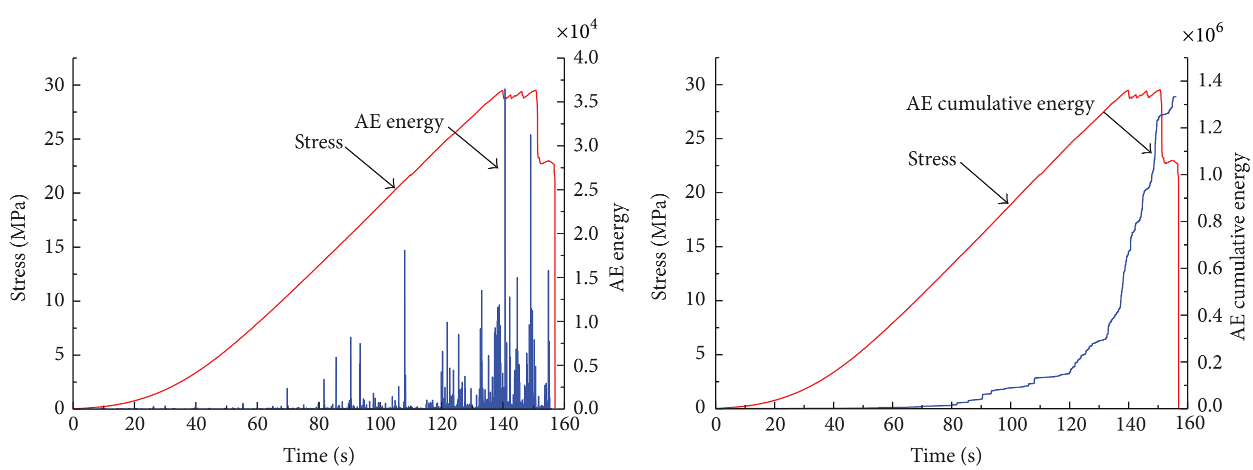
Figure 8: The relationship curve among AE counts, AE cumulative counts with times of coal samples under different loading rates.



(a) Acoustic emission energy and cumulative energy of M1 coal under loading rate of 0.001 mm/s



(b) Acoustic emission energy and cumulative energy of M6 coal under loading rate of 0.002 mm/s



(c) Acoustic emission energy and cumulative energy of M9 coal under loading rate of 0.005 mm/s

Figure 9: The relationship curve between time and AE energy, AE cumulative energy of the coal samples under different loading rates.

more energy at the moment of coal samples destructive; at the same time, coal samples will release less energy in the whole process of rupture.

5.3. The Influence of Loading Rates on AE Peak Counts. Figure 10 shows a relationship between AE peak counts and loading rate in the rupture process of coal samples under different loading rates. Scattered dots represent the peak counts of coal samples under different loading rates, and broken line indicates the average value of the peak counts. According to Figure 10 and Table 2, the positive correlation between acoustic emission peak counts and loading rate is obtained. The reason is that when loading rate gradually increased, the impact also will increase. This leads to instantaneous release of more energy from coal sample; therefore, the acoustic emission counts increase. The AE counts are 871 times at the loading rate of 0.001 mm/s. When the loading rate increases to 0.002 mm/s, AE counts increase to 911 times, and the incremental percent reaches 4.59%. Comparing with the loading rate of 0.001 mm/s, the AE counts increased to 985 times on loading rate of 0.005 mm/s, and the growth rate reached 13.09 percent. Comparing with the loading rate of 0.002 mm/s, the AE counts increased 74 times on loading rate of 0.005 mm/s, and the growth rate reached 8.12 percent.

5.4. The Influence of Loading Rates on AE Cumulative Counts. Figure 11 shows a relationship between cumulative counts and loading rate in the rupture process of coal samples under different loading rates. Scattered dots represent the cumulative counts of coal samples under different loading rates, and broken line indicates the average value of the cumulative counts. According to Figure 11, negative correlation may be defined between acoustic emission cumulative counts and loading rate. The reason is that when loading rate gradually increases, the impact also will increase, which leads to the coal samples having been broken in the process of rupture, but it does not still fully release energy. We can obtain from Figure 11 and Table 2 that the AE cumulative counts are 2.76*e*5 times at loading rate of 0.001 mm/s. When the loading rate increases to 0.002 mm/s, the AE cumulative counts are 1.73*e*5 times, which reduces to 1.03*e*5 times, and the reduction rate reaches 37.32 percent. Comparing with the loading rate of 0.001 mm/s, the AE cumulative counts reduce to 1.15*e*5 times on loading rate of 0.005 mm/s, and the reduction rate reaches 41.67 percent. Comparing with the loading rate of 0.002 mm/s, the AE cumulative counts reduce to 0.12*e*5 times on loading rate of 0.005 mm/s, and the reduction rate reaches 6.94%.

6. The Relationship among Acoustic Emission Parameters, Stress, and Strain

We obtain the damage formula of coal rock material based on the literature [28]. The damage formula is given in

$$\sigma = E\varepsilon (1 - D), \tag{5}$$

where σ is the stress, E is the elasticity modulus, ε is the strain, and D is the damage factor.

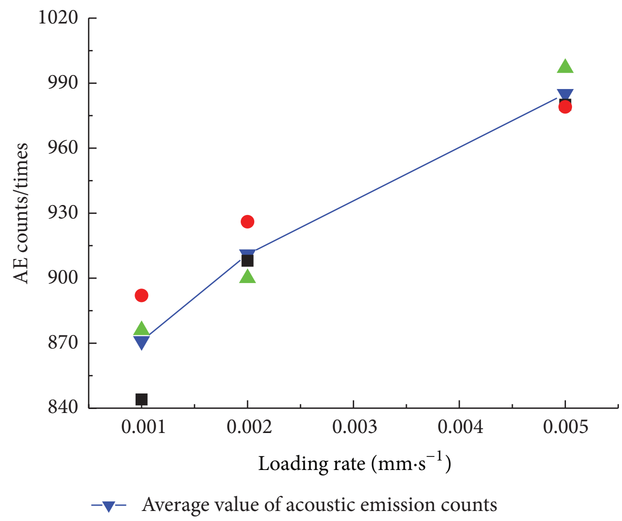


FIGURE 10: The relationship between acoustic emission counts and loading rate.

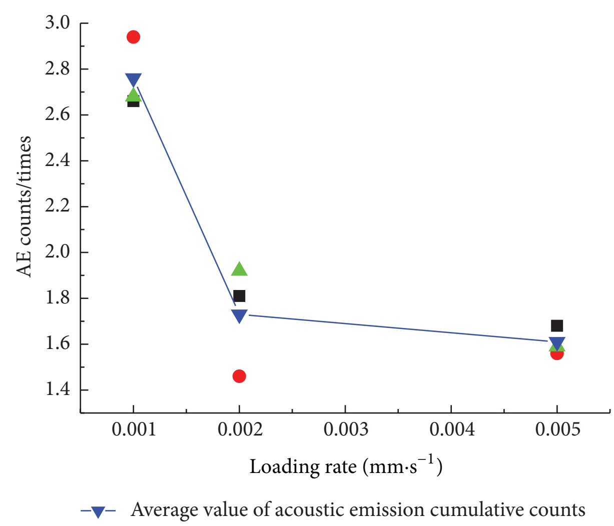


FIGURE 11: The relationship between acoustic emission cumulative counts and loading rate.

If the acoustic emission cumulative counts of the whole cross section (S_m) are Φ_0, Moreover, assumed the coal samples are completely destroyed, the acoustic emission cumulative counts of unit damage area is

$$\Phi_w = \frac{\Phi_0}{S_m}, \tag{6}$$

where Φ_0 is the acoustic emission cumulative counts when the coal samples are completely destroyed, S_m is the whole cross section, and Φ_w is the acoustic emission cumulative counts in damage area of unit element.

When the damage area of cross section is S, the acoustic cumulative emission is

$$\Phi_d = \Phi_w \cdot S = \frac{\Phi_0}{S_m} \cdot S, \tag{7}$$

where Φ_d is the acoustic emission cumulative counts when the damage area of cross section is S and S is the damage area of cross section.

Formula (8) is given by transforming (7):

$$\frac{\Phi_d}{\Phi_0} = \frac{S}{S_m}. \quad (8)$$

We obtain the damage factor formula based on the literature [29, 30]. The damage factor formula is given in

$$D = \frac{S}{S_m}. \quad (9)$$

Formula (10) is given by combining formulas (8) and (9). Moreover, the relationship among acoustic emission parameters, stress, and strain is given by

$$\sigma = E\varepsilon(1 - D) = E\varepsilon\left(1 - \frac{S}{S_m}\right) = E\varepsilon\left(1 - \frac{\Phi_d}{\Phi_0}\right). \quad (10)$$

7. Conclusions

In this paper, an experimental research of AE and mechanical characteristics of coal samples was carried out under different loading rates, and characteristics of AE and mechanics are analyzed with following conclusions as follows.

(1) Loading rate has a certain effect on the mechanical properties of coal samples, especially on the peak intensity and the peak strain. The equation related to peak stress, peak strain, and loading rate is obtained as

$$\begin{aligned} \sigma &= 21.8653 + 1259.23v, \\ \varepsilon &= 6.674 + 447.842v. \end{aligned} \quad (11)$$

(2) Loading rate has an influence on the AE properties in the rupture process of coal samples. The relationship between loading rate and AE peak counts is positive correlation, but between loading rate and AE cumulative counts it is negative correlation.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This paper was partially supported by National 973 Project under Grant no. 2012CB723103 of China, by the NNSF under Grant no. 51274086 of China, by the Ministry of Education Doctoral Foundation in Priority Areas under Grant no. 20124116130001 of China, by the basic and frontier research project in Henan Province under Grant no. 122300410115 of China, and by the State Key Laboratory Cultivation Base for Gas Geology and Gas Control under Grant no. WS2012A10 at Henan Polytechnic University, China.

References

[1] E. Unal, I. Ozkan, and G. Cakmakci, "Modeling the behavior of longwall coal mine gate roadways subjected to dynamic loading," *International Journal of Rock Mechanics and Mining Sciences*, vol. 38, no. 2, pp. 181–197, 2001.

[2] J. He, L. M. Dou, W. Cai, Z. L. Li, and Y. L. Ding, "In situ test study of characteristics of coal mining dynamic load," *Shock and Vibration*, vol. 2015, Article ID 121053, 8 pages, 2015.

[3] R. V. Sagar and M. Rao, "An experimental study on loading rate effect on acoustic emission based b-values related to reinforced concrete fracture," *Construction and Building Materials*, vol. 70, pp. 460–472, 2014.

[4] E. Aker, D. Kühn, V. Vavryčuk, M. Soldal, and V. Oye, "Experimental investigation of acoustic emissions and their moment tensors in rock during failure," *International Journal of Rock Mechanics & Mining Sciences*, vol. 70, pp. 286–295, 2014.

[5] B. Huang and J. Liu, "The effect of loading rate on the behavior of samples composed of coal and rock," *International Journal of Rock Mechanics & Mining Sciences*, vol. 61, pp. 23–30, 2013.

[6] A. Lavrov, "Kaiser effect observation in brittle rock cyclically loaded with different loading rates," *Mechanics of Materials*, vol. 33, no. 11, pp. 669–677, 2001.

[7] V. L. Shkuratnik, Y. L. Filimonov, and S. V. Kuchurin, "Experimental investigations into acoustic emission in coal samples under uniaxial loading," *Journal of Mining Science*, vol. 40, no. 5, pp. 458–464, 2004.

[8] V. L. Shkuratnik, Y. L. Filimonov, and S. V. Kuchurin, "Regularities of acoustic emission in coal samples under triaxial compression," *Journal of Mining Science*, vol. 41, no. 1, pp. 44–52, 2005.

[9] V. Rudajev, J. Vilhelm, and T. Lokajíček, "Laboratory studies of acoustic emission prior to uniaxial compressive rock failure," *International Journal of Rock Mechanics & Mining Sciences*, vol. 37, no. 4, pp. 699–704, 2000.

[10] L.-J. Ma, X.-Y. Liu, M.-Y. Wang et al., "Experimental investigation of the mechanical properties of rock salt under triaxial cyclic loading," *International Journal of Rock Mechanics & Mining Sciences*, vol. 62, pp. 34–41, 2013.

[11] J. S. Kim, K. S. Lee, W. J. Cho, H. Choi, and G. Cho, "A comparative evaluation of stress–strain and acoustic emission methods for quantitative damage assessments of brittle rock," *Rock Mechanics and Rock Engineering*, vol. 48, no. 2, pp. 495–508, 2015.

[12] Y. Zhang, D. Stead, and D. Elmo, "Characterization of strength and damage of hard rock pillars using a synthetic rock mass method," *Computers and Geotechnics*, vol. 65, pp. 56–72, 2015.

[13] Z. Y. Liang, F. Gao, X. R. Yang, S. Z. Feng, and J. T. Lin, "Experimental study of the influence of loading velocity on rock's acoustic emission signal," *Mining Research & Development*, vol. 30, no. 1, pp. 12–14, 2010.

[14] M.-M. Tong, J.-L. Hu, S.-F. Tang, and X.-L. Dai, "Study of acoustic emission signal characteristic of water-containing coal and rock under different stress rates," *Journal of Mining and Safety Engineering*, vol. 26, no. 1, pp. 97–100, 2009.

[15] Y. S. Pan, Z. Tang, Z. H. Li, L. Y. Zhu, and G. Z. Li, "Research on the charge inducing regularity of coal rock at different loading rate in uniaxial compression tests," *Chinese Journal of Geophysics*, vol. 56, no. 3, pp. 1043–1048, 2013.

[16] Z. J. Wan, X. H. Li, and C. Y. Liu, "Influence of loading velocity on the rock's acoustic emission activity," *Journal of Liaoning*

Technical University (Natural Science), vol. 20, no. 4, pp. 469–471, 2001.

[17] M. Chen, Y. Zhang, Y. Jin, and L. Li, "Experimental study of influence of loading rate on Kaiser effect of different lithological rocks," *Chinese Journal of Rock Mechanics and Engineering*, vol. 28, no. 1, pp. 2599–2604, 2009.

[18] D. Y. Xie, D. Xie, and Y. Zhang, "The influence on mechanical and AE characteristics of rock under different loading rates," in *Proceedings of the 4th Country Rock Dynamic Academic Conference*, Chengdu, China, 1994.

[19] L.-Y. Zhang and X.-B. Mao, "Experimental study of the mechanical effects of loading rates on limestone at high temperature," *Rock and Soil Mechanics*, vol. 31, no. 11, pp. 3511–3515, 2010.

[20] X. Yin, X. Ge, C. Li, and S. Wang, "Influences of loading rates on mechanical behaviors of rock materials," *Chinese Journal of Rock Mechanics and Engineering*, vol. 29, no. 1, pp. 2610–2615, 2010.

[21] J.-Y. Xu and S. Liu, "Effect of impact velocity on dynamic mechnaical behaviors of marble after high temperatures," *Chinese Journal of Geotechnical Engineering*, vol. 35, no. 5, pp. 879–883, 2013.

[22] H. B. Zhao, *Theoretical and experimental study on unstable failure and AE characteristic of coal contained gas [Ph.D. thesis]*, Chongqing University, Chongqing, China, 2009.

[23] J. He, J.-N. Pan, and A.-H. Wang, "Acoustic emission characteristics of coal specimen under triaxial cyclic loading and unloading," *Journal of the China Coal Society*, vol. 39, no. 1, pp. 84–90, 2014.

[24] H. Qin, G. Huang, and W. Z. Wang, "Experimental study of acoustic emission characteristics of coal samples with different moisture contents in process of compression deformation and failure," *Chinese Journal of Rock Mechanics and Engineering*, vol. 31, no. 6, pp. 1115–1120, 2012.

[25] H.-Y. Li, L.-J. Kang, Z.-J. Xu, Q.-X. Qi, and S.-K. Zhao, "Precursor information analysis on acoustic emission of coal with different outburst proneness," *Journal of China Coal Society*, vol. 39, no. 2, pp. 384–388, 2014.

[26] J. Xu, W.-J. Zhou, D. Liu, S.-C. Li, and H.-Y. Tan, "Temperature and acoustic emission characteristics of coal in the process of outburst under the influence of mining," *Journal of the China Coal Society*, vol. 38, no. 2, pp. 239–244, 2013.

[27] C.-D. Su, B.-H. Guo, and X. Tang, "Research on acoustic emission characteristics of Zhangcun coal samples in two sizes subject to uniaxial compression," *Journal of the China Coal Society*, vol. 38, no. 1, pp. 12–18, 2013.

[28] B. B. Gao and H. G. Li, "Research on coal samples damage model based on acoustic emission parameters," *Journal of Disaster Prevention and Mitigation Engineering*, vol. 34, no. 1, pp. 101–106, 2014.

[29] L. M. Kachanov, "On the time to failure under creep condition," *Izvestiya Akademii Nauk SSSR, Otdelenie Tekhnicheskikh Nauk*, vol. 8, no. 2, pp. 26–31, 1958.

[30] Y. N. Rabotnov, "On the equations of state for creep," *Process in Applied Mechanics*, pp. 307–315, 1963.