Experimental study on acoustic emission frequency characteristics of granite under different cyclic loading and unloading

TAN Jie¹,², SONG Zhaoyang¹,²*, WU Zaihai³, NING Fangbo¹,²
¹ Beijing Coal Mine Construction Company Ltd., Beijing 100013, China; ² National Engineering Lab of Mine Deep Shaft Construction, Beijing 100013, China; ³ Shandong Gold Group Backfilling Engineering Laboratory, Laizhou Shandong 261441, China.

*songzhaoyang@nelcsc.com
*Corresponding author’s e-mail: szhaoyang123@126.com

Abstract. In Granite acoustic emission tests were performed during three different cyclic loading and unloading processes. The relationship between the acoustic emission frequency distribution pattern and the loading and unloading mode of granite during the cyclic loading and unloading process was discussed. The distribution pattern of the peak frequency with the stress evolution is analyzed qualitatively and quantitatively. Studies have shown that: in the first cycle of loading and unloading at each stage of the three cyclic loading and unloading processes, the acoustic emission ringing count and peak frequency are significantly increased, which has a significant Kaiser effect. It proves that the Kaiser effect essentially remembers the extent of the damage inside the rock previously. In the process of loading and unloading in the fourth stage cycle, the AE ring count showed a "U"-shaped change law, showing a significant Felicity effect. Comparing the three different cyclic loading and unloading modes, with the increase of the lower limit stress, the stress amplitude decreases, and the AE ringing count corresponding to the lower limit stress value of the unloading gradually decreases, and the peak frequency distribution shows more dense or concentrated characteristics. At the beginning of the third stage cycle, the proportion of high frequency band (140~162kHz) gradually decreased, and the proportion of lower frequency band (11~18kHz) gradually increased. With the increase of the lower limit of cyclic loading and unloading, the lower frequency band (11-18kHz) in the fourth-stage cyclic loading and unloading process takes up a higher proportion, even as high as 95%. It indicates that the rock samples at this stage mainly undergo large-scale failure, and the rock samples are in a critical failure state. These provide the basis for exploring the evolution mechanism of rock mechanical behavior and the prediction method of instability and damage.

1. Introduction
At present, along with the dwindle and depletion of shallow resources, the exploration of mineral resources has been completely advanced to the deep areas of the earth, and deep rocks to be mined are in the environment full of high ground stress, high osmotic pressure, high environment temperature, high bursting liability and strong stress perturbation generated from mining. Due to the influence of exploitation methods and production processes at the deep areas, the engineering surrounding rocks often suffer from action of cyclic loading. The size and mode of action of cyclic loading will cause damage to the rock mass to varying degrees, and thus affect the long-term stability of engineering
surrounding rocks\cite{4,5}. Acoustic emission (AE), an effective means to measure the rock mass stability, can monitor the location where the cracks grow inside the rock mass and its nature in a continuous and real-time manner, and analyze the evolution laws of rock mass damage\cite{6,8}, which is the typical advantage of this monitoring method.

In terms of studying the AE characteristics during the cyclic loading and unloading of rocks, there are some literature available, including some rules on rock damage and destruction course under the cyclic loading and unloading mode. C. H. ondergeld et al.\cite{9} obtained the AE data at the early stress cycle by studying the AE characteristics of granite failure process under the cyclic loading and unloading action. M. V. M. S. Rao\cite{10} studied the influence of the magnitude of cyclic stress and intervals of cycle periods on micro-crack growth and rock failure via the AE technique.

Jiang Yu et al.\cite{11} analyzed the AE characteristics during the fatigue failure process under the rock cyclic loading action from perspectives of macroscopic irreversible deformation and microscopic damage, and then discusses the rationality of axial deformation serving as the macroscopic damage parameter. Zhang Huihui et al.\cite{12} proceeded the experiment on AE characteristics of large-scale rock failure under the triaxial stress state, and studied the surge of accelerating energy release (AER) and load-unload response ratio (LURR) --precursors of rock macroscopic failure, which can serve as the experimental evidence for earthquake prediction. Xu Jiang et al.\cite{13} conducted the experimental study on AE characteristics of fine-grained sandstone via changing the stress amplitude and loading rate under the cyclic loading action, and pointed out that the upper limit stress is the key that influence the AE during the cyclic loading process.

Li Nan\cite{14} investigated the rules that the dominant frequency and dominant frequency bandwidth of AE will change according to the variation of stresses during the process of rock damage and fracture under cyclic loading and multi-stage loading by virtue of AE frequency spectrum characteristics. Ji Hongguang et al.\cite{15} proceeded the experimental study on AE characteristics of rocks under load-unload disturbance at different stress states, and cleared up that the differences of AE signals at different stress states and relative stress level are the different constitutive characteristics of materials. Xia Dong et al.\cite{16} discussed the changes of mechanical properties, AE characteristics and load-unload response ratio of rock samples under cyclic loading and unloading action at dry state and saturation state. Song Zhaoyang et al.\cite{17} investigated the correlation between cyclic load-unload disturbance stress levels and the peak frequency density of AE. Li Shulin et al.\cite{18-20} studied the relation between the stress level of rock at the loading and unloading action and rock AE Kaiser effect as well as Felicity effect; investigated the AE fractal characteristics generated from rock uni-axial cyclic loading conditions, and gained the correlation fractal dimension of spatial distribution of AE event source via the column covering method; in addition, it conducted tests with three different kinds of loading modes, namely, uni-axial compression, incremental cycling loading and unloading and incremental constant-voltage cycling loading and unloading mode, to study the changes at the relative quiet period, Felicity ratio and load-unload response ratio of rock strength at the pre-peak.

In conclusion, this paper conducted the research on the variation rules of AE parameters, load-unload response ratio, Kaiser effect, Felicity effect and others from perspectives of the amplitude of cyclic stress, periodic intervals, loading rate, lithology, moisture conditions and others, and focused on the coupling relation between mechanical properties and AE characteristics during the rock failure process under the cyclic loading and unloading action. When the engineering surrounding rocks suffer from stress perturbation, the lower limit value of cyclic loading often fails to unload to 0MPa, and there are stress loading modes that the upper limit value and lower limit value of cyclic loading can increase at the same time. Therefore, this paper, via changing the lower limit value of stress during the cyclic loading and unloading of rocks, studies the relation between the evolution characteristics of AE parameters in rocks and loading/unloading modes during the multi-stage cyclic loading and unloading process, and investigates the rock damage, deterioration and instability mechanism under the cyclic loading and unloading action, which can serve as the effective reference for analyzing the precursor characteristics of surrounding rock instability under different stress paths.
2. Test Conditions and Schemes

2.1. Preparation of rock specimens
The granite specimens were taken from about 300m underground of Xincheng Gold Mine, Shandong Province, and have been cut into standard cylindrical rock specimens with the diameter of 50mm and height of 100mm in strict accordance with the code requirements of International Society for Rock Mechanics, as shown in Fig.1. The processed rock specimens will be divided into three groups for laboratory tests of rock mechanics under multi-stage cyclic loading and unloading action, and these rock specimens are featured with good consistency in the integrated physical parameters, thus minimizing the influence of the inhomogeneity of materials on the test of mechanical properties under different grades of cyclic loading and unloading action.

2.2. Test equipment
GAW-2000 microcomputer-controlled electro-hydraulic servo rigid pressure test machine used in this test is equipped with closed-loop control, constant-load control and load retaining function, with its hydraulic oil pumps up to the maximum load (2000 KN), and can achieve the constant-pressure control, constant-speed control and force-displacement compound control.

2.3. Test methods
In order to study the AE characteristics of granite under multi-stage cyclic loading actions, turn the different formation pressure forms of surrounding rock of underground engineering caused by underground mining to the corresponding different loading and unloading paths applicable to the laboratory test. The uni-axial loading mode has been adopted in this test, with full-process loading rate being 500 N/min, and cyclic loading and unloading for five times at each load level. Meanwhile, considering the uni-axial compressive strength value of this kind of granite, three different kinds of cyclic loading and unloading modes have been designed, as shown in Tab.1.

| Cyclic Loading and Unloading Mode | Level I | Level II | Level III | Level IV |
|---------------------------------|--------|---------|-----------|---------|
| Mode 1                          | Upper limit 40.4 | 80.8 | 121.2 | 161.6 |
| Mode 1                          | Lower limit 0 | 0 | 0 | 0 |
| Mode 2                          | Upper limit 40.4 | 80.8 | 121.2 | 161.6 |
| Mode 2                          | Lower limit 30 | 30 | 30 | 30 |
| Mode 3                          | Upper limit 40.4 | 80.8 | 121.2 | 161.6 |
| Mode 3                          | Lower limit 0 | 40.4 | 80.8 | 121.2 |
3. Test Results and Analysis

3.1. Stress-strain characteristics under multi-stage cyclic loading and unloading modes
Divide each cyclic loading and unloading mode of granite into four cyclic loading and unloading levels, and the upper limit value at each level of cyclic loading will increase with constant amplitude; while under different cyclic loading and unloading modes, the upper limit value at each level of loading remains unchanged, and the lower limit value will increase accordingly. The relationship between load and time under multi-stage cyclic loading and unloading modes is as shown in Fig.3. The full-process test duration at three cyclic loading and unloading modes is 8418.1s, 6476.6s and 3992.2s respectively. Rock failure occurs to all rock specimens when completing the Level IV cyclic loading and continuing to load, with the peak load at the rock failure being 163.95 KN, 192.91 KN and 197.68 KN. The stress-strain curve of granite under different cyclic loading and unloading modes is as shown in Fig.4.

As shown in Fig.4, when the pre-peak axial strain is the same, the axial stress value corresponding to mode 1 is the minimum, and the axial stress value corresponding to mode 3 is the maximum; there are hysteresis loops on the Stress-Strain Curve of Granite under Different Cyclic Loading and Unloading Modes, especially in mode 1, with the peak intensity at the rock failure being 83.49 MPa, lower than that in mode 2 and mode 3 (being 98.25MPa and 100.68 MPa respectively); along with the increase of times of multi-stage cyclic loading and unloading, the irreversible deformation of rocks increases in non-linear trend, which is more obvious in mode 1. According to the analysis, along with the decrease of lower limit value at each level of cyclic loading and unloading in mode 1, the stress amplitude, its disturbed effect on cracks inside of rock specimens will become more remarkable, and the damage accumulated during the cyclic loading and unloading becomes more intensive, thus leading to the obvious damage of rock specimens; since it fails to unload to 0MPa via the other two loading paths (namely mode2 and mode 3), the micro-cracks generated in the cyclic loading and unloading process have been suppressed, and the disturbance effect of cracks remains relatively low.

3.2. Ring-down count characteristics of AE
On the time-domain figure of AE waves, every pulse output by each time of oscillation of the transducer will form a AE ring-down. After analyzing figures showing the AE ring-down count over the time during the rock cyclic loading and unloading process, we can find the movement and development trend of AE activities along with the stress paths. Corresponding change curves of time, stress, ring-down count and cumulative ring-down count of rock specimens under multi-stage cyclic loading and unloading actions are as shown in Fig.5. According to the comparison and analysis of Fig. 5(a)(b)(c), we can find that:

(1) During the process of level-by-level increase of upper limit values of each level cyclic stress under three cyclic loading and unloading modes from 20.84, 41.11, 61.68 and 82.21MPa, when the loading stress value at the first cycle of each level of cyclic loading and unloading approaches or exceeds the upper limit value of the stress of the last level, AE ring-down count will significantly
increase, thus showing evident Kaiser effect. In the ideal state, when the stress imposed on the rock is no more than historical stress level, there will be no acoustic emission. In fact, due to the inhomogeneity of micro-structure of rocks, the stress imposed at the early stage will cause micro-cracks inside of rocks, and then even the stress loaded at the later stage, which is no more than the historical stress level, can also generate weak acoustic emission. Generally, scholars will take the point with surge of AE ring-down count as the Kaiser effect point of rock acoustic emission. According to the study, when the felicity ratio $\in [0.9, 1.1]$, the Kaiser effect will still remain [23]. In the cyclic loading and unloading mode 1, every time when the cyclic stress is increased, the felicity ratio is 0.92, 0.95 and 0.98 respectively; in the cyclic loading and unloading mode 2, every time when the cyclic stress is increased, the felicity ratio is 1.04, 0.96 and 0.96 respectively; in the cyclic loading and unloading mode 3, every time when the cyclic stress is increased, the felicity ratio is 1.0, 1.0 and 0.98 respectively.

(2) Among all three cyclic loading and unloading modes, the AE ring-down count corresponding to the upper limit value of stress at the first cycle of Level I, Level II and Level III cyclic loading and unloading process is the maximum, and along with the increase of cyclic loading and unloading times, the AE ring-down count corresponding to the upper limit value of cyclic stress will gradually decrease. This means that the cyclic stress of each level of cyclic loading and unloading imposes new damage to rocks based on the historical records of rocks, and the AE ring-down count corresponding to 2nd-5th cyclic loading and unloading will gradually decrease, which is mainly caused by the disturbed effect of cracks generated from the cyclic loading and unloading action on the first cyclic loading and unloading, and such disturbed effect will gradually decreases within 5 times of cyclic loading and unloading.

![Cyclic loading and unloading mode 1](image1)

![Cyclic loading and unloading mode 2](image2)

![Cyclic loading and unloading mode 3](image3)

Fig.5 Corresponding change curves of time-stress-ringing count-cumulative ringing count of rock samples under different grading cycles of loading and unloading

(3) During Level IV cyclic loading and loading process among three cyclic loading and unloading modes, the AE ring-down count corresponding to the upper limit value of cyclic stress, along with the increase of cyclic loading and unloading times, will change in the form of “U” shape, namely, along with the increase of the number of cycles, the AE ring-down count will first decrease, and then increase, and when the AE cumulative ring-down count is up to the upper limit value of cyclic loading and unloading, it will achieve step growth, which is more distinct compared to that during Level I, Level II and Level III cyclic loading and unloading process. This means the damage inside rocks has
deteriorated, and the cyclic loading and unloading action have resulted a huge amount of new cracks inside rocks. The occurrence of felicity effect during Level IV cyclic loading and unloading process reflects that rock specimens are in critical state of failure; followed by the surge of AE ring-down count when loading to exceed the historical peak stress again at the end of 5 times of Level IV cyclic loading and unloading, the brittle instability and failure of rock specimens occur soon.

(4) When the upper limit stress corresponding to each level of cyclic loading and unloading among three cyclic loading and unloading modes remains the same, along with the increase of lower limit stress, the AE ring-down count corresponding to the lower limit value of each cyclic stress will gradually decrease, with a little AE ring-down count at the point corresponding to the lower limit value of each level cyclic stress in mode 1, and almost zero AE ring-down count at the point corresponding to the lower limit value of each level cyclic stress in mode 2 and mode 3. This indicates that the lower limit value of cyclic stress in mode 1 is unloaded to 0MPa, and there are relatively more AE ring-down count of medium inside rock specimens driven by elastic recovery. The increase of lower limit stress under cyclic loading and unloading mode will suppress the cracking and sliding of cracks to a certain degree.

3.3. AE peak frequency characteristics

According to the study, there are corresponding relations between focal dimension and the frequency of seismic signals [22,23]. However, in the laboratory tests in rock mechanics, there will be different size of rock failure under different stress paths, which means that the peak frequency of AE signals will also vary. After analyzing the peak frequency distribution characteristics of AE signals under different stresses and deformation stages of granite among three cyclic loading and unloading modes, as well as the variation trend along with the increase of cyclic loading and unloading times, the corresponding change curves of time, stress and peak frequency of rock specimens under multi-stage loading and unloading action are as shown in Fig.6. In order to analyze the change of peak frequency distribution pattern over time in a quantitative way, Matlab coding program has been used to extract data among three cyclic loading and unloading modes, such as total number of peak frequencies, number of frequencies at characterized frequency band and ratio, and map the evolution curves of number of peak frequencies and proportion of frequency band under multi-stage cyclic loading and unloading action, as shown in Fig.7.

According to the analysis of Fig 6 and Fig.7, we can find that:

(1) When viewing the evolution rules of AE peak frequency of rock specimens under the cyclic loading and unloading action over time as a whole from the horizontal axis, the AE peak frequency can be divided into four main frequency bands, namely, high frequency band (140-162kHz), middle frequency band (88-110kHz), low frequency band (32-54kHz) and lower frequency band (11-18kHz), with gaps between low frequency band and middle frequency band, and no failure of rock specimens occurs in the peak frequency among 19-30kHz; along with the increase of upper limit value of cyclic stress, the total number of peak frequencies at each level of cyclic loading and unloading will increase significantly, namely, the increase of density of AE peak frequencies, which indicates the gradual worsen of damage and failure inside rocks.

![Fig.6](image-url)  
(a) Mode 1  
(b) Mode 2  
(c) Mode 3

Fig.6 Corresponding curves of time-stress-peak frequency of rock samples under different grading cyclic loading and unloading
(2) When viewing the evolution rules of AE peak frequency of rock specimens under the cyclic loading and unloading action over time as a whole from the vertical axis, during the first cyclic loading and unloading process of each level of cycles among three cyclic loading and unloading modes, the bandwidth of AE peak frequency will increase, the distribution range will get wider, namely cross frequency (connecting peak frequencies among main frequency band) will get more evident; meanwhile, the total number of peak frequencies during the first cyclic loading and unloading process of each level of cycles is the maximum, and along with the increase of cyclic loading and unloading times, the total number of peak frequencies gradually declines, which is similar to the AE kaiser effect. The increase of upper limit value of peak stress at the first cycle lead to form new cracks and growth of existing cracks, which proves that AE Kaiser effect, in fact, memorizes the degree of damage previously existing inside rocks \[24\]; along with the increase of number of cycles, the fatigue failure of cracks will lead to the growth and connection of internal cracks.

![Graphs showing distribution and percentage of peak frequencies](image)

Fig. 7 Distribution curve of peak frequency of acoustic emission of rock and its proportion under different graded cyclic loading and unloading

(3) Comparing the three cyclic loading and unloading modes, when their upper limit stress under the cyclic loading and unloading action is the same, the upper limit value generating from cyclic loading and unloading will increase, the amplitude of cyclic stress will decrease, the peak frequency...
distribution of specific peak frequencies at the characterized timeline will be more intensive or more aggregated.

(4) Along with the increase of stress under cyclic loading and unloading action, the distribution proportion of AE peak frequencies also constantly varies; as a whole, during Level I and Level II cyclic loading and unloading, the proportion of high frequency band and lower frequency band is much high, and the proportion of high frequency band is higher that of lower frequency band; the proportion of high frequency band gradually decreases and the proportion of lower frequency band gradually increases from Level III cycles among three cyclic loading and unloading modes; along with the increase of lower limit value during cyclic loading and unloading process, the proportion of lower frequency band during Level IV cyclic loading and unloading process gets higher, even more than 95%. The peak frequency obtained from uni-axial compressive deformation and failure is less than 100 kHz, with its theoretical size of rock failure being more than 10mm\[^{25}\]. As a result, the size of failure of rock specimens during Level IV cyclic loading and unloading process is calculated in centimeter, mainly large-scale rock failure, which means that cracks of rock specimens grow quickly or become connected, thus making the rock specimens in critical failure stage.

4. Conclusion

(1) The AE ring-down count and peak frequency corresponding to the first cycle under three cyclic loading and unloading modes increase significantly, thus proving evident KAISER effect; AE ring-down count presents “U-shaped” rules during Level IV loading and unloading process, which is obvious Felicity effect, reflecting the critical failure state of rock specimens; AE Kaiser effect and Felicity effect, in fact, memorize the degree of damage previously existing inside the rocks.

(2) Along with the increase of upper limit stress, the AE ring-down count corresponding to the lower limit value of every cyclic stress gradually decreases; the decrease of stress amplitude can suppress the cracking and sliding of cracks to a certain degree.

(3) The distribution of AE peak frequency can be divided into four main frequency bands, namely, high frequency band (140-162kHz), middle frequency band (88-110kHz), low frequency band (32-54kHz) and lower frequency band (11-18kHz), with gaps between low frequency band and lower frequency band, and no failure of rock specimens occurs in the peak frequency among 19-30kHz.

(4) Along with the increase of stress under cyclic loading and unloading action, the distribution proportion of AE peak frequencies also constantly varies; as a whole, during Level I and Level II cyclic loading and unloading process, the proportion of high frequency band and lower frequency band is much high; the proportion of high frequency band gradually decreases and the proportion of lower frequency band gradually increases from Level III cycles among three cyclic loading and unloading modes; along with the increase of lower limit value during cyclic loading and unloading process, the proportion of lower frequency band during Level IV cyclic loading and unloading process gets higher, even more than 95%. It indicates that rock specimens mainly suffer from large-scale rock failure, and make the rock specimens in critical failure stage, which can serve as the basis for predicating the rock buckling and failure

Acknowledgments

This paper is supported by the State Key Research Development Program of China (Grant No. 2016YFC0600801) and the Special Funds for Technological Innovation and Entrepreneurship of China Coal Science and Engineering Group Co. Ltd.(2018-TD-MS011). The authors thank the anonymous reviewers for their valuable and instructive comments that greatly help improve the quality and completeness of this paper.

References

[1] XIE Heiping,JU Yang,GAO Mingzhong,et al. Theories and technologies for in-situ fluidized mining of deep underground coal resources[J]. Journal of China Coal Society,2018,43(5):1210-1219.
[2] KANG Hongpu, WANG Guofa, JIANG Pengfei, et al. Conception for strata control and intelligent mining technology in deep coal mines with depth more than 1 000 m[J]. Journal of China Coal Society, 2018, 43(7): 1789-1800.

[3] YANG Xiaobin, HAN Xinling, LIU Enlai, et al. Experimental study on the evolution of non-uniform deformation of rock under constant amplitude cyclic loading[J]. Journal of Mining & Safety Engineering, 2019, 36(2): 388-395.

[4] WANG Ruihong, JIANG Yuzhou, LIU Jie, et al. Experimental study of deformation Characteristics of Sandstone under cyclic loading and unloading conditions[J]. Journal of Mining & Safety Engineering, 2011, 28(2): 231-235.

[5] LI Ziyun, WU Guang, HUANG Tianzhu, et al. Variation of energy and criteria for strength failure of shale under triaxial cyclic loading[J]. Chinese Journal of Rock Mechanics and Engineering, 2018, 37(3): 662-670.

[6] MENG Qingbin, ZHANG Mingwei, HAN Lijun, et al. Acoustic emission characteristics of red sandstone specimens under uniaxial cyclic loading and unloading compression[J]. Rock Mechanics and Rock Engineering, 2018, 51(4): 969-988.

[7] LI Huamin, WANG Kailin, LI Huigui, et al. Study on mechanical and acoustic emission characteristics of weakly cementation sandstone in Shendong coal field[J]. Journal of Mining & Safety Engineering, 2018, 33(04): 843-851.

[8] SONG Zhaoyang, JI Hongguang, LIU Zhiqiang, et al. Experimental study on acoustic emission characteristics of weakly cemented granular rocks affected by dry-wet cycling process[J]. Journal of Mining & Safety Engineering, 2019, 36(04): 812-819.

[9] SONDERGELD C H, ESTEY L H. Acoustic emission study of microfracturing during the cyclic loading of Westerly granite[J]. Journal of Geophysical Research, 1981, 86(B4): 2915-2924.

[10] RAO M V M S, RAMANA Y V. A study of progressive failure of rock under cyclic loading by ultrasonic and AE monitoring techniques[J]. Rock Mechanics and Rock Engineering, 1992, 25(4): 237-251.

[11] JIANG Yu, GE Xiurun, REN Jianxi. Deformation rules and acoustic emission characteristics of rocks in process of fatigue failure[J]. Chinese Journal of Rock Mechanics and Engineering, 2004, 23(11): 1810-1814.

[12] ZHANG Huihui, YAN Yuding, YU Huaizhong, et al. Acoustic emission experimental research on large-scaled rock failure under cycling load—fracture precursor of rock[J]. Chinese Journal of Rock Mechanics and Engineering, 2004, 23(21): 3621-3628.

[13] XU Jiang, TANG Xiaojun, LI Shuchun, et al. Experimental research on acoustic emission rules of rock under cyclic loading[J]. Rock and Soil Mechanics, 2009, 30(5): 1241-1246.

[14] LI Nan, WANG Enyuan, ZHAO Enlai, et al. Experiment on acoustic emission of rock damage and fracture under cyclic loading and multi-stage loading[J]. Journal of China Coal Society, 2010, 35(7): 1099-1103.

[15] JI Hongguang, HOU Zhaofei, ZHANG Lei, et al. Acoustic emission character of loaded rock under load-unload disturbance[J]. Journal of University of Science and Technology Beijing, 2011, 33(1): 1-5.

[16] XIA Dong, YANG Tianhong, WANG Peitao, et al. Experimental study of acoustic emission characteristics of dry saturated rocks during cyclic loading and unloading process[J]. Journal of China Coal Society, 2014, 39(7): 1243-1247.

[17] SONG Zhaoyang, DING Zhenyu, TAN Jie, et al. Experiment study on acoustic emission characteristics of weak cementation sandstone under effect of periodical disturbance stress[J]. Mine construction technology, 2019, 40(4): 25-30.

[18] LI Shulin, YIN Xiangang, WANG Yongjia, et al. Studies on acoustic emission characteristics of uniaxial compressive rock failure[J]. Chinese Journal of Rock Mechanics and Engineering, 2004, 23(15): 2499-2503.
[19] LI Shulin, TANG Haiyan. Acoustic emission characteristics in failure process of rock under different uniaxial compressive loads[J]. Chinese Journal of Geotechnical Engineering, 2010, 32(1): 147–152.

[20] LI Shulin, ZHOU Mengjing, GAO Zhenping, et al. Experimental study on acoustic emission characteristics before the peak strength of rocks under incrementally cyclic loading-unloading methods[J]. Chinese Journal of Rock Mechanics and Engineering, 2019, 38(4): 724-735.

[21] WANG Xiaoqiong, GE Hongkui, SONG Lili, et al. Experimental study of two types of rock sample acoustic emission events and Kaiser effect point recognition approach[J]. Chinese Journal of Rock Mechanics and Engineering, 2011, 30(3): 580-588.

[22] Benson P. M, Vinciguerra S., Meredith P. G, et al. Laboratory simulation of volcano seismicity[J]. Science, 2008, 322(5899): 249-252.

[23] Burlini Luigi, Vinciguerra Sergio, Di Toro Giulio D, et al. Seismicity preceding volcanic eruptions: New experimental insights[J]. Geology, 2007, 35(2), 183-186.

[24] LI Yuanhui, YUN Ruifu, ZHAO Xingdong. Effect of different stress paths on Kaiser effect of rock acoustic emission [J]. Journal of Northeastern University (Natural Science), 2007, 28(4): 576-579.

[25] LIU Xiling, WANG Jinpeng, LI Xibing, et al. Frequency Characteristics of Acoustic Emission Signals from Rocks under Compression and Fracture Conditions [J]. Journal of experimental mechanics, 2018, 33(2): 201-208.