Mining Science, vol. 27, 2020, 209–225

www.miningscience.pwr.edu.pl

Mining Science

(Previously Prace Naukowe Instytutu Gornictwa Politechniki Wroclawskiej, ISSN 0370-0798)

ISSN 2300-9586 (print)
ISSN 2353-5423 (online)

Received December 23, 2019; Reviewed; Accepted September 24, 2020

ACOUSTIC EMISSION CHARACTERISTICS OF DEEP GRANITE UNDER TRIAXIAL CYLIC LOADING AND UNLOADING

Feng PEI[1, 2]*, Yue-Zheng ZHANG[1, 2],
Ji-Wei ZHAO[1, 2], Jing-Ming GENG[1, 2]

1 School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing 100083, China

2 Beijing Key Laboratory of Urban Underground Space Engineering, University of Science and Technology Beijing, Beijing 100083, China

Abstract: In order to obtain the damage and AE characteristics of deep granite, TAW-2000 electro-hydraulic servo rigid testing equipment and PCI-2 acoustic emission acquisition system were used to clarify the relationship between AE characteristics and stress level under conventional triaxial and cyclic loading and unloading. The results show that: AE characteristic parameters such as counts and energy under different confining pressures have good consistency in reflecting cracks growth process, which correspond to the stress level of rock sample; Before the critical failure, the AE amplitude increases significantly and extremely high peak frequency and extremely low peak frequency began to appear; The phenomenon that peak frequency band number increases significantly can be used as the precursor of rock failure; The change trend of characteristic parameters, amplitude and peak frequency band were related to the stress level of rock, and the loading path has little influence on it, which verified the effectiveness of AE precursory feature recognition; FR value decreases continuously with the increase of cyclic stress level and overall trend is downward, which indicated that AE memory gradually decreases as the stress level increases; From the perspective of damage mechanics, the AE characteristics of rock before failure are explained reasonably by the development of damage rate.

Keywords: *deep granite, acoustic emission, frequency spectrum, precursory feature recognition*

* Corresponding author: Feng Pei, 1078938768@qq.com

doi: 10.37190/msc202715

1. INTRODUCTION

With the rapid development of mining technology and rapid increase of economic needs, deep mining has become an important way to solve the resource shortage in the future. The deep rock is in the complex geological environment (high geo-stress, high temperature, high water pressure and strong disturbance). Owing to high geo-stress, the deep hard brittle rock shows obvious mechanical difference from the shallow rock. However, under the action of underground engineering excavation, rock often suffers from cyclic loading and unloading (Zhou et al. 2017). In order to better characterize the crack development behavior of deep hard brittle rock under high stress, it is necessary to use AE monitoring method to study the AE characteristics of deep hard brittle granite under triaxial conventional loading and cyclic loading and unloading. The AE characteristic study on the failure process of deep hard brittle granite under high stress is helpful to reveal the failure mechanism of hard brittle rock and reveal the AE precursor information of dynamic disasters such as rock burst, and play an important role in the prediction dynamic disasters of deep excavation.

Acoustic emission (AE) is an advanced nondestructive testing method, which releases strain energy in the form of elastic stress wave in material fracture process (Ji 2004; Peng et al. 2017). Since AE technology was introduced into rock mechanics, experts and scholars at home and abroad have done a lot of field and laboratory research on it, and obtained rich research results (Li et al. 2015; Zhang et al. 2004; Gao et al. 2009; Ai et al. 2012). At present, the research mainly includes parameter analysis and spectrum analysis. AE parameters mainly include counting rate, cumulative counting, energy rate, cumulative energy, event rate, cumulative event and other characteristic parameters (Yang et al. 2006; Ji et al. 2012). These parameters can directly reflect the severity of internal damage of rock (Shkuratnik et al. 2004; 2005; He et al. 2014), and establish corresponding damage evolution equation (Liu et al.2009). Some scholars have improved the prediction effect of rock damage by comprehensive multi-parameters method (Cao et al. 2007; Farhidzadeh et al. 2014; Behnia et al. 2014; Shahidan et al. 2013). The analysis of AE spectrum is mainly to get AE spectrum characteristics after processing AE waveform signals. The AE waveform contains all the information of stress level, structure, physical and mechanical properties, etc., analyzing the waveform information can better understand the failure mechanism and precursor information. Waves with different frequency components correspond to different types of AE sources, and also correspond to different types of micro crack forms of rock (Wang et al. 2004; Zhang et al. 2015; Ji et al. 2015, Zeng et al. 2017; Li Nan et al. 2010).

The mechanical properties of deep rock and shallow rock are obviously different due to the geo-stress and long-term geological process. It is obvious that most of the previous studies mainly focus on the shallow rock with a depth of lower than 800 m, while the research on the crack evolution of deep rock (more than 1500m) is relatively rare. In order to explore the crack development characteristics of deep hard brittle granite under high stress environment, the conventional triaxial and cyclic loading and unloading tests are carried out with TAW-2000 electro-hydraulic servo rigid testing equipment, and the AE characteristics under different confining pressures and stress paths are obtained. It provides theoretical support for further study of rock damage mechanism and prediction of dynamic disasters such as deep rock burst.

2. EXPERIMENTAL DESIGN

Granites were all collected from Shaling Gold Mine, Laizhou, Shandong Province. According to the ISRM suggestion, the specimen was processed into a standard cylinder sample of ∅ 50 × 100 mm. The ultrasonic detector is used to detect the wave velocity of specimens, and the rock samples with approximate wave velocity are selected for experiment. The mineral composition and micro-morphology characteristics of samples are obtained by combining powder X-ray diffraction (XRD) and binocular transmission polarization microscopy. Comprehensive analysis shows that the deep granite has a porphyry-like structure with obvious schistosomiasis. The porphyry is feldspar (60%) with a grain size of about 0.5mm. The matrix is mainly quartz (30%). The dark minerals are mainly biotite (5%) with directional arrangement. Other minerals include chlorite (about 3%) and pyrite (about 2%). The equivalent radius is mainly distributed in the range of 0.2–0.75 mm.

The loading system used in the experiments is TAW-2000 servo rock mechanics test system, and the acoustic emission adopts PCI-2 multichannel monitoring system produced by American physical acoustics company, shown in Fig. 1.

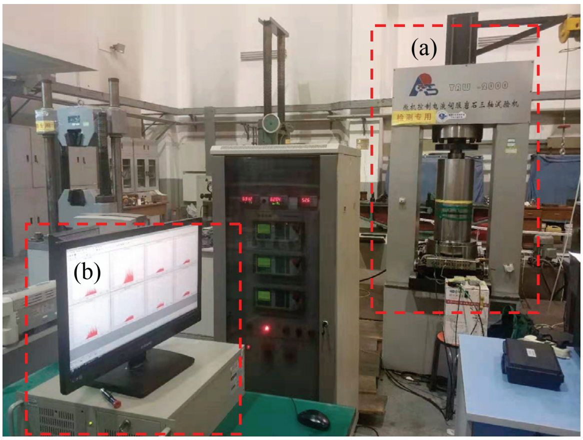


Fig. 1. Measurement system for experiment:
(a) loading system, (b)AE acquisition system

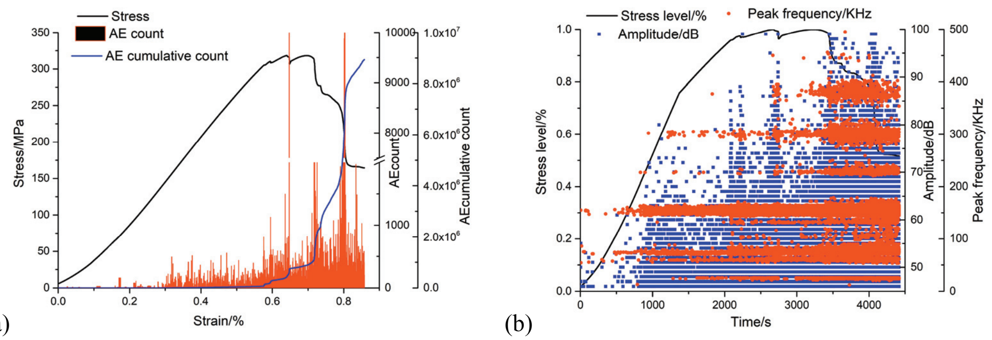
First, routine loading experiments under confining pressure of 10, 20, and 30 MPa were performed to ascertain peak stress and strain, which provide data support for cyclic loading/unloading tests. Subsequently, cyclic loading/unloading tests were conducted at three confining pressures. After sample installation, the confining pressure was applied at 0.2 MPa/s up to a predetermined value, and then a 5 KN axial force was added to bring the rock sample into contact with the testing machine. After the confining pressure stabilized, the axial force was applied up to a predetermined value according to deformation control. The loading rate was 0.02 mm/min and the unloading rate was 0.04 mm/min. In order to ensure the cycles number, the loading gradient is 30–60 KN until peak stress was reached. The annular strain after peak stress increased by 0.1 to 0.2 mm as a cyclic unloading point until the residual strength of rock sample is reached.

In order to eliminate the impact of external environment, the machine and the AE host are grounded to eliminate the noise caused by electric current. The Pre-amplifier threshold is set to 40 dB, and the acoustic emission sampling threshold is set to 45 dB. People are not allowed to walk or talk during testing. The sampling rate of transmitting waveform is 1 MSPS, the pre trigger is 256, and the length is 2 K. Vaseline was coated between sensors and rock sample to enhance the coupling between them and reduce the attenuation of AE signals before testing. In order to ensure that the data of each system corresponds to each other strictly in time, timing synchronization shall be carried out for each test data acquisition system before the test.

3. RESULTS

3.1. AE CHARACTERISTICS OF CONVENTIONAL TRIAXIAL COMPRESSION

AE signals can reflect the evolution process of cracks initiation, propagation and penetration, and it is a powerful tool for monitoring rock damage development.



(a) (b)

Fig. 2. 10 MPa confining pressure:
(a) count and cumulative count, (b) amplitude and peak frequency

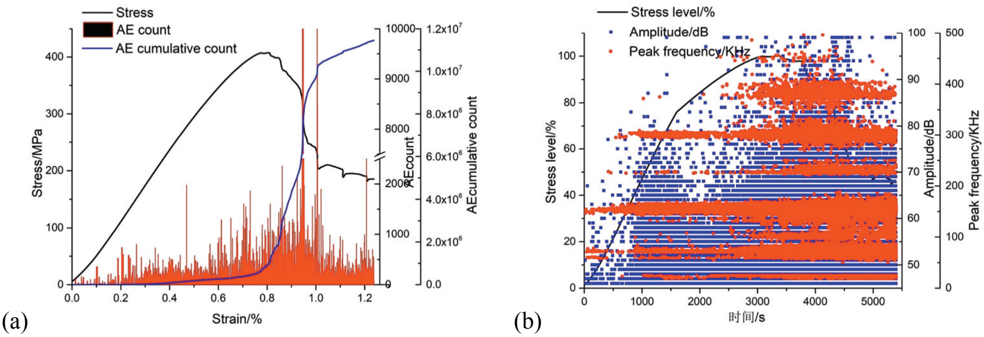


Fig. 3. 20 MPa confining pressure:
(a) count and cumulative count, (b) amplitude and peak frequency

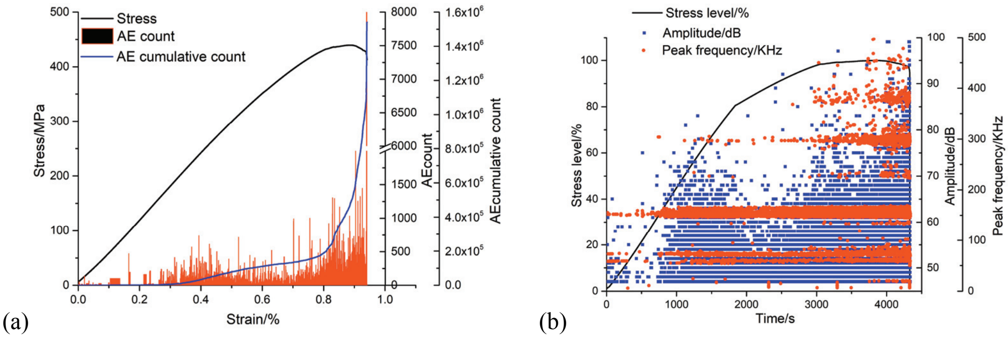


Fig. 4. 30 MPa confining pressure:
(a) count and cumulative count, (b) amplitude and peak frequency

For the application of AE monitoring technology in deep granite, it is mainly based on the change process of AE parameters on time to evaluate the stability of granite. Based on this, the AE characteristics of deep granite under different stress levels were analyzed by using AE count (*n*), cumulative counts (Σn), amplitude (a), peak frequency and time variation. Figures 2–4 show the AE detection results in conventional triaxial compression process. It can be seen that the AE characteristics under different confining pressures are highly similar, so taking sample under 10 MPa confining pressure as an example for analysis:

1) Initial loading stage, the rock sample is in consolidation stage ($0 < \sigma_1 - \sigma_3 < 42.5$ MPa), which produces a small number of low counts and low amplitude AE signals, and the cumulative ringing counts increase slowly. The internal structure of granite is consolidated, and some defects have been closed after confining pressure applied, and the micro defects in rock with axial stress applied are further closed, so there are less AE signals, and the compaction stage is gradually not obvious.

2) Elastic deformation stage (42.5 MPa < $\sigma_1 - \sigma_3$ < 276.2 MPa), the stress–strain curve develops linearly, the inputted energy is stored in the form of elastic deformation energy, the applied stress is not enough to produce a large number of new cracks, so the AE signals are not active (quiet period). The ringing count and amplitude are low, and the cumulative ringing counts increase horizontally slowly.
3) The stress–strain curve gradually deviates from the linearity in cracks growth stage (276.2 MPa < $\sigma_1 - \sigma_3$ < 318.322 MPa), and the overall performance is that the stiffness is weakened, and the pre-peak stress–strain curve rises in a fluctuating way. AE signals are active and the closer to peak stress, the stronger the AE signals are. The damage inside rock gradually accumulates with the stress level increase, the ringing count, energy and so on increase obviously, and the high amplitude signals (80 dB) appear locally. The cumulative ringing count becomes steeper obviously, which indicates that the cracks expansion scale gradually increases.
4) After failure, a large number of cracks expand and penetrate to form a macro fracture surface, but rock still has a certain bearing capacity on account of confining pressure effect. In the process of macro cracks sliding, the phenomenon of climbing and gnawing teeth produces obvious AE signals with high amplitude (95dB). The cumulative count slope gradually increases, and the loud noise is heard at the place where the rapid stress drops after the peak. The transmitted signals strength reach the peak value.

In brief, AE signals generated by triaxial compression tests of deep granite under different confining pressures show obvious similarity characteristics, and the overall performance is that high ring count and high amplitude AE signals are gradually appeared with the stress level increase of, and the slope of cumulative count curve is gradually improved. AE signal is the external manifestation of internal damage, which can better reflect the internal cracks development process during loading. The slope of cumulative count curve reflects the degree of internal damage, so it could be used as the precursor point of failure stress according to the obvious deviation of cumulative count curve from the linearity. Under the confining pressure of 10, 20 and 30 MPa, the failure precursory points correspond to 89.1, 86.3 and 87.9% of the peak strength, respectively. In addition, the AE quiet period appears before the peak stress under 10 MPa confining pressure, and the count and amplitude are relatively low. However, the quiet period gradually disappears or is no longer obvious under the 20 MPa and 30 MPa confining pressure, which indicates that the phenomenon of AE quiet period gradually disappears with the confining pressure increase. So it should be cautious to use AE quiet period as the precursory feature of rock failure.

3.2. AE SPECTRUM CHARACTERISTICS

Combined with the characteristics of AE signals frequency distribution, the three frequency bands of 0–128, 128–256 and 256–512 kHz are called low frequency, medium frequency and high frequency respectively. In actual statistics, according to the results of spectrum transformation, it is found that the AE frequency of mechanical vibration in the loading process is basically the low frequency component less than 30 kHz, so the low frequency (mechanical vibration) and low amplitude (electromagnetic signal collected by the instrument) are deleted.

Under 10 MPa confining pressure, the peak frequency of consolidation and elastic development stage (0–78% stress level) is mainly concentrated in two frequency bands, 65–80 and 150–170 kHz, respectively. When sample enters the unstable cracks development stage (78–100% stress level), the frequency bands of 380–400 kHz, nearby 300 kHz and 240–250 kHz are appeared, and the frequency bands of 65–80 kHz and 150–170 kHz are gradually dense. The frequency bands increase from 2 to 5, indicating that internal cracks mode of rock changes from single to complex, and the joint development of multiple cracks modes leads to the sharp increase of rock damage. In the post peak stage, there is a nearby 225 kHz band, and the AE signals intensity increase and shows an intensive growth trend.

The peak frequency of consolidation and elastic development stage (0–81% stress level) is mainly concentrated in two frequency bands of 85 kHz and 150–160 kHz under 20 MPa confining pressure. Against the stress level increase, sporadic peak frequency of 300 kHz is generated in 65% stress level, and the peak frequency bands of 290–305 and 390–400 kHz are appeared and increased in 81–100% stress level, increasing the number of peak frequency bands from 2 to 4. In the post peak stage, the signals in peak frequency band are gradually intensive, and the 220 kHz band appears at the same time. According to the comprehensive analysis, this band is closely related to the friction between the internal structural surfaces of the fractured rock.

Peak frequency band is mainly concentrated in nearby 55 kHz caused by cracks compaction under 30 MPa confining pressure, while in the elastic development stage (15–84% stress level), the stable cracks development is mainly in 150–165 and 60–70 kHz frequency bands, but the signals in 150–165 kHz frequency band are significantly stronger than those in the 60–70 kHz frequency band. Peak frequency bands of 300 and 370–400 kHz caused by cracks connecting and expansion appeared.

Based on the above analysis, it could be concluded that in consolidation and elastic development stage, the peak frequency is mainly concentrated in two frequency bands, namely 60–80 and 150–170 kHz. When the rock enters unstable cracks growth stage (approximately 85–100% stress level), the AE signals increase significantly and the peak frequency develops intensively, increasing the frequency range of 370–400, 290–305, and 240–250 kHz. The number of AE peak frequency range increased from 2 to 4 or 5. After failure, 220-230 kHz frequency band is observed. The damage is mainly caused by the continuous development and penetration of cracks and the crack surface friction. The correlation friction between crack surfaces produces a new peak frequency range. With the stress level increase, high peak frequency band is produced, which shows that high peak frequency is caused by cracks interpenetration. The increase of peak frequency band is related to lithology and confining pressure level.

Therefore, the increase number of peak frequency band before peak strength can be regarded as a sign of unstable crack growth, which is of great significance to predict peak strength and failure of rock.

The stress level with a significant increase in frequency band is defined as the precursory point of rock failure. The corresponding precursory points of granite failure under 10, 20 and 30 MPa confining pressure are 78, 81 and 84% of peak strength respectively. It can be concluded that the precursory point of rock failure predicted increases gradually with the confining pressure increase.

3.3. AE CHARACTERISTICS OF TRIAXIAL CYCLIC LOADING AND UNLOADING

According to cyclic loading/unloading experiment method as mentioned above, the typical stress-strain curves under different confining pressures are obtained in Fig. 5. Outer envelopes of cyclic loading/unloading are obviously similar to conventional triaxial loading curves. During different stages of full stress–strain loading curve, even proximate original loading path. When the loading stress exceeds last unloading stress level, a significant hysteresis loop caused by damage is formed.

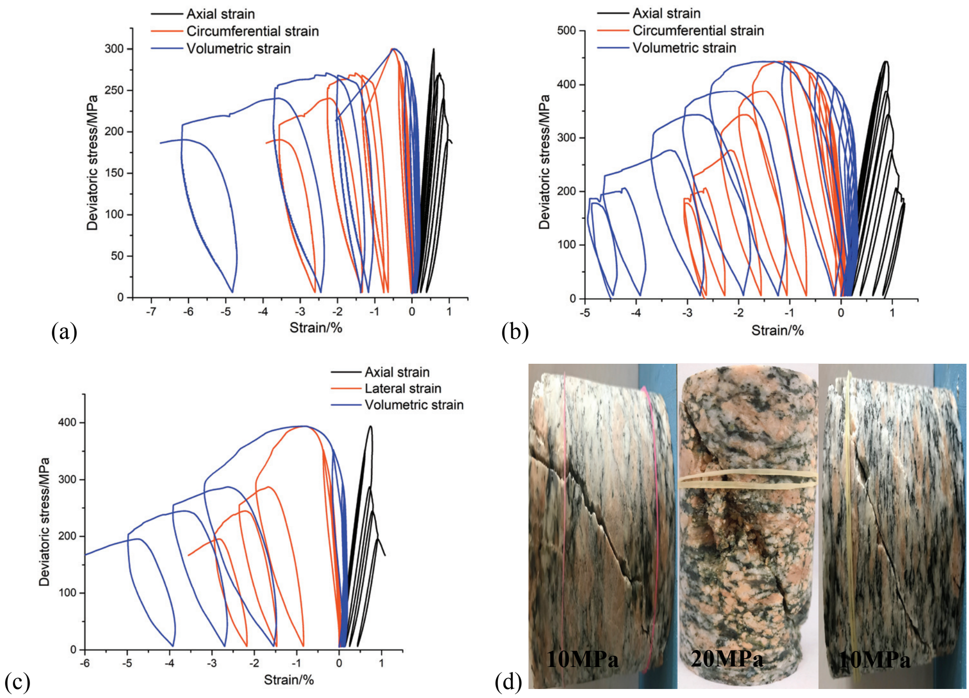


Fig. 5. Confining pressure and failure patterns:
(a) 10 MPa, (b) 20 MPa, (c) 30 MPa, (d) failure patterns

Taking the AE signals characteristics of cyclic loading/unloading under 10 MP confining pressure as an example, AE characteristic parameters and peak frequency are depicted in Figs. 5a and 5b. According to AE cumulative count curve generated by a single cycle loading/unloading, the whole loading process is divided into four stages as shown in Figs. 5c and 5d.

1) Before first five cycles (stage I), AE signals are not active and low intensity AE signals appeared sporadically, with the 20–45 kHz peak frequency. The cumulative count curve was at a low level and the increase rate was slow. Elastic deformation is main dominated. With the loading and unloading stress, the elastic deformation energy is stored and released continuously.

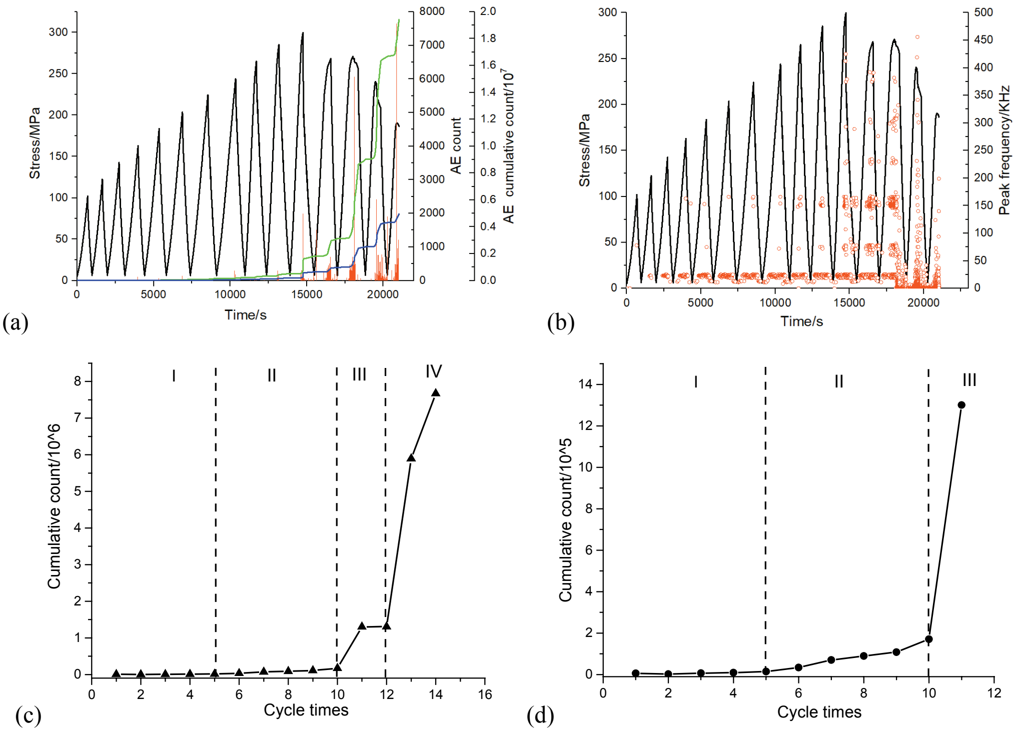


Fig. 6. Cumulative count with cycle times:
(a) count and cumulative count, (b) peak frequency, (c) cumulative count by a single cycle,
(d) cumulative count by a single cycle before failure

2) From the fifth cycle to the tenth cycle (stage II), AE signals are gradually active along with the stress level increase, but the intensity are low. When specimen is loaded to current maximum stress level, it will generate obvious AE signals. In the unloading stage, there are still some AE signals, but the intensity and quantity at loading stage are significantly reduced, and the cumulative ringing count

curve increases slowly, and peak frequency signals near 175 kHz began to appear. Elastic deformation always dominates, but with the increase of cycle times, the damage gradually increases and more AE signals will be generated. However, micro cracks are mainly developed inside the sample. In the stable crack development stage, the AE signals weakens rapidly, and the cumulative count curve develops horizontally, indicating that there is no new crack in the unloading stage. The inactive AE signals are mainly the result of the internal structural adjustment of original crack.

3) From the tenth to the eleventh cycles (stage III), the samples enter yield development stage. Small-scale cracks appear continuously and connect with each other under high stress, resulting in the increase of the number of large-scale cracks and ultimately producing the macro crack surface. The cumulative count curve increases rapidly. AE signals are abnormally active, and increases significantly in the number and strength. The AE peak frequency near 175 kHz increased significantly, and the peak frequency signals near 75 kHz start to appear. Due to cumulative damage, even in unloading stage, the AE signals increase significantly, and the unloading stress which produces obvious AE signals decreases gradually. In unstable cracks development stage, micro cracks in rock will not stop developing immediately even if the loading suddenly decreases, it will continue to expand and may be connected with the adjacent cracks. This is obviously different from the crack propagation behavior before unstable crack propagation.
4) From the 12th to the 15th cycles (after destruction), the rock has generated macro crack surface, signals strength will gradually be strengthened with the stress level increase, but the most active AE signals will still be generated at the loading maximum stress level. At the same time, there are 0–25, 200–250, 300–350 and 375–450 kHz multi-band AE signals. The obvious increase of AE signals peak frequency band indicates the diversity of internal failure forms of samples.

In conclusion, the AE activity in the pre-peak stage is far less than that in the post-peak stage, and the AE cumulative ring count curve develops in a “ladder” shape with the strain increase. The rock has obvious memory characteristics, and less AE signals are generated in the unloading stage. The AE characteristics and axial strain curves of rock were not changed obviously during loading/unloading process. The number of peak frequency band before critical failure increases significantly, and the number of post peak frequency band increases more significantly.

3.4. AE SIGNALS CHARACTERISTICS RESPONSE TO ADDING THE SAME STRESS

The overall shape of the curve between cumulative AE counts and axial strain is not affected by cyclic loading/unloading. It is very important to study AE response characteristics of rock under different damage conditions for a comprehensive understanding of rock fracture behavior.

During the three cycles of loading/unloading in unstable cracks development stage, the AE counts present a significant growth trend, and the axial strain difference ($\Delta\varepsilon_1$) under the same load increment presents the same development trend, showing that the number of AE events increases sharply, and the slope of cumulative AE events increases abruptly.

In order to quantitatively characterize the damage degree with the same load increment under different stress levels, each unloading is followed by loading. When the load approaches the corresponding stress level at unloading point, the plastic hysteresis loop is completely closed, resulting in a cumulative AE count called γ, which can reflect that the impact of cyclic loading/unloading on the micro crack behavior is gradually strengthened. For all cycles of loading/unloading in this experiment, the maximum value of γ appears in the stage of strain softening (the first cycle after peak). Rock has generated macro cracks after failure, compared with unstable cracks development before peak stress, the development of macro crack surface after peak stress is more unstable in the early stage of unloading, which inevitably leads to more AE signals.

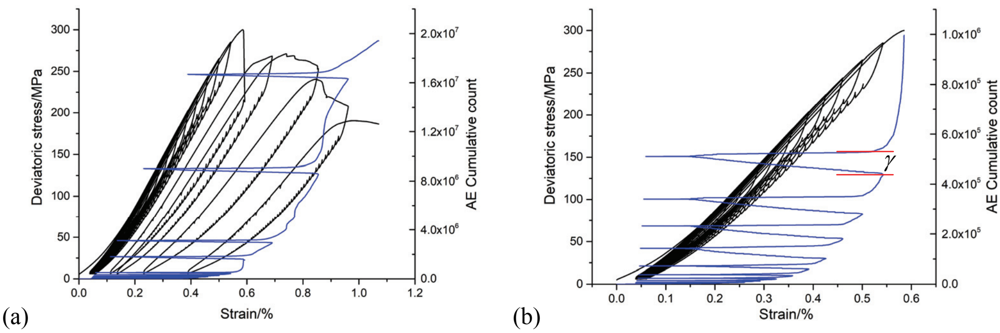


Fig. 7. 10 MPa confining pressure:
(a) cumulative count and strain, (b) cumulative count and strain before failure

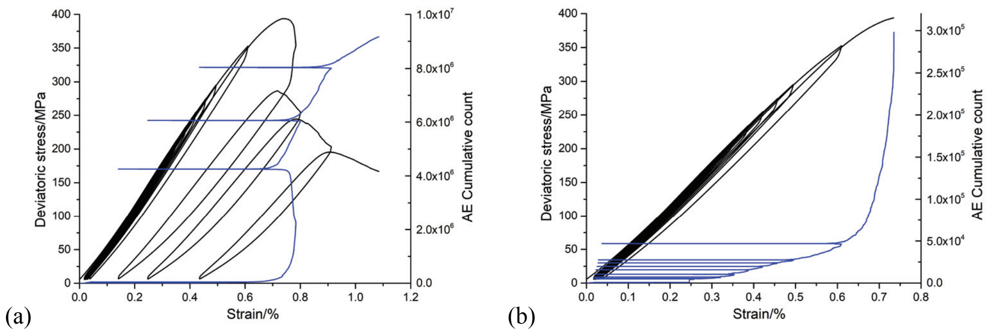


Fig. 8. 20 MPa confining pressure:
(a) cumulative count and strain, (b) cumulative count and strain before failure

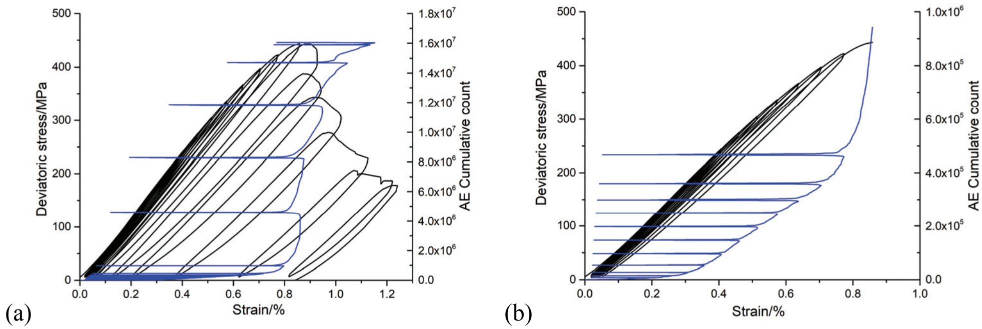


Fig. 9. 30 MPa confining pressure:
(a) cumulative count and strain, (b) cumulative count and strain before failure

The AE signals generated at peak strength is the strongest, and the AE signals from the peak strength to the residual strength of rock has a decreasing trend, which is the result of the crack surface development after the peak is more unstable, and the crack surface is connected and rubbed with each other. When the rocks are recombined to form a new stable structure and enter the residual stage, the rock no longer produce a new through structural plane, mainly the mutual friction between the structural planes and the development of microcracks.

3.5. DAMAGE RATE BASED ON DISSIPATION ENERGY

Rock is a heterogeneous material with natural cracks and defects. Due to the geological history, sampling process and the difference of its own structure, obvious initial damage is caused. Micro cracks inside rock are closed tightly under loading. As part of the cracks are reopened after forced unloading, the second loading will cause the original defects and the first cracks to be compacted together, so the area of hysteresis loop is the energy represented by the crack is accumulated in the second hysteresis loop. It can be concluded that in cyclic loading and unloading process, the area of former hysteresis loop is subtracted from the area of the latter hysteresis loop, i.e., the damage caused by the difference between the two loads. Through the damage difference, the damage rate and the degree of crack development are expressed.

The damage is low under the low stress level action. Rock is in elastic development stage, and the internal heterogeneous dissipation energy increment fluctuates, but the whole tends to be stable. The increment of dissipated energy in the middle stress level is nearly linear, which is the result of stable expansion of internal cracks. Under high stress level, the increment of dissipative energy increases rapidly, and the closer it is to the peak strength, the greater the damage rate is until the rock sample is destroyed. The relationship between damage rate of rock sample and AE count is obvious.

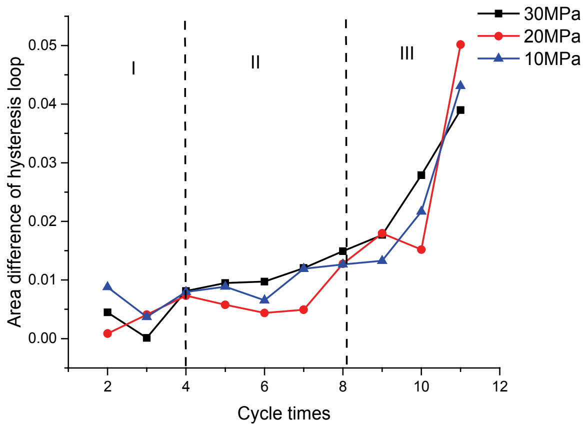


Fig. 10. Area difference of hysteresis loop with cycle times

3.6. AE KAISER EFFECT

Researchers at home and abroad have carried out extensive theoretical and experimental research on rock memory characteristics and achieved fruitful results, establishing the relationship between stress–strain and AE characteristics. However, the research results are mainly focused on the use of Felicity ratio to characterize the damage degree of rock before peak strength, and the research on Felicity ratio after peak strength is still in a blank stage. It is of great theoretical and practical significance to study the post peak failure mechanical characteristics of rock for guiding practical engineering application. In this paper, the evolution of Felicity ratio with loading and unloading cycle is studied, and the Felicity ratio is used to further characterize the damage degree of rock.

In the process of repeated loading and unloading, Kaiser effect of materials will weaken with the stress level increase, and this phenomenon will become more obvious with the increase of damage degree of materials, and this characteristic is called Felicity effect. The accuracy of Kaiser effect can be measured by Felicity ratio, which is inversely proportional to the internal damage of rock. The specific expression is as follows:

$$FR_i = \frac{P_{i+1}}{P_{i\,\max}}, \tag{1}$$

where, FR_i is the Felicity ratio of material in i-th cycle; P_{i+1} is the stress level when the effective AE is restored in the $i + 1$ loading process; $P_{i\,\max}$ is the maximum stress level reached in the i-th loading process. $FR_i \geq 1$ indicates that rock has obvious memory effect, and when $FR_i \leq 1$, indicates that the increase of internal damage causes the memory weakening. The smaller the FR_i is, the more serious the internal damage is.

Therefore, Felicity ratio evolution trend can be used to characterize the severity of rock damage. The Felicity ratio changes with the number of loading and unloading cycles as shown in Fig. 11.

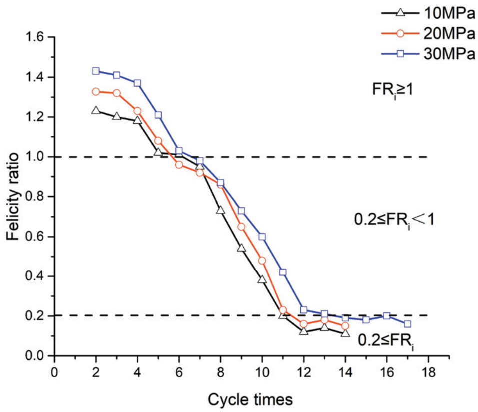


Fig. 11. Felicity ratio with cycle times

It can be seen from Fig. 11 that Felicity ratio decreases gradually with the increase of cycles times, and the variation trend of Felicity ratio under different confining pressures has obvious similarity characteristics. The FR_i of 10 and 20 MPa in the first five cycles (corresponding to 61 and 54% stress levels, respectively) and 30 MPa confining pressure in the first six cycles (62% stress levels) are all greater than 1, indicating that samples have obvious Kaiser effect and obvious memory characteristics. Specimens are mainly in the elastic deformation stage, and the work of external load on rock is mainly dissipated in the form of elastic strain energy. AE events are mainly due to internal original cracks expansion. The Felicity ratio decreases obviously with the stress level increase, which indicates that AE events are gradually active. A large number of AE signals are generated even if the maximum stress of last loading is not exceeded, and obvious Felicity ratio effect appears, and the stress memory becomes poor. When rock gradually enters the unstable cracks growth stage, and new cracks continue to be generated, and original cracks expand and run through. The irreversible plastic deformation increases significantly, resulting in the cumulative damage increase. However, the Felicity ratio does not decrease continually with the cycles increase, but it is stable in the range of 0.15–0.2.

In post peak stage, Felicity ratio effect is significant with the increase of loading and unloading times, which shows a downward trend as a whole, but the downward decrease is small. The author believes that the strength of sample after failure is not completely disappeared due to the drastic adjustment of internal structure of rock under confining pressure, and there is still a certain bearing capacity, i.e. residual strength. The residual strength of rock is in a sub-stable state, the crack structure reaches a new balance under the confining pressure, the rock generates a new memory again, and Felicity ratio shows a relatively stable development trend. As the number of loading/unloading cycles continues to increase, active AE signals appear due to the friction between crack surfaces and the generation of new cracks. Only when the internal structure of rock is adjusted in a large scale Felicity ratio present a significant downward trend.

The change trend of Felicity ratio has obvious confining pressure effect. Under the same stress level, the Felicity ratio of high confining pressure is significantly higher than that of low confining pressure. The effect of high confining pressure limits the development of internal crack and plastic deformation, and the densification of internal structure of rock increases, which leads to the improvement of memory of rock sample.

4. CONCLUSION

Through the study of AE phenomenon in loading stage, AE characteristics under different confining pressures and cyclic loading and unloading were revealed and the following conclusions are obtained:

1) In conventional triaxial compression experiments, there are obvious corresponding relationships between AE count, cumulative counts and amplitude with stress level, which can better reflect the internal failure process of deep granite. The slope of cumulative count curve can be used as a precursor point of failure.
2) The AE peak frequency characteristics of deep granite during the whole loading process are obtained. The unstable cracks growth result in peak frequency band increase, followed by extremely high frequency band and extremely low frequency band.
3) The calculation of rock damage based on dissipative energy method reflects the damage characteristics of rock in different stages. Felicity ratio has obvious confining pressure effect, Felicity ratio has three stage characteristics in cyclic loading process, and the overall trend is decreasing. Felicity ratio shows a relatively stable development trend after failure.
4) Both dissipated energy and AE count under cyclic loading/unloading can better reflect the progressive damage of rock failure. From point of view of stress level and energy damage, *FR* can more truly reflect the Kaiser effect of rock. The larger the confining pressure is, the larger the *FR* is, and the higher the confining pressure is, the damage of rock is restrained.

ACKNOWLEDGEMENTS

This paper was supported by the National Key Research and Development Plan (No. 2016YFC0600801) and Key Program of National Natural Science Foundation of China (51534002) and Major Scientific and Technological Innovation Project of Shandong Province (No. 2019SDZY05).

REFERENCES

LIU B.X., HUANG J.L., WANG Z.Y. et al., 2009, *Study on damage evolution and acoustic emission character of coal rock under uniaxial compression*, Chinese Journal of Rock Mechanics and Engineering, 28 (S1), 3233–3238.

CAO S.G., LIU Y.B., ZHANG L.Q., 2007, *Study on characteristics of acoustic emission in outburst coal*, Chinese Journal of Rock Mechanics and Engineering, 26 (Suppl. 1), 2794–2799 (in Chinese).

FARHIDZADEH A., MPALASKAS A.C., MATIKAS T.E. et al., 2014, *Fracture mode identification in cementitious materials using supervised pattern recognition of acoustic emission features*, Construction and Building Materials, 67 (2), 129–138.

BEHNIA A., CHAI H.K., SHIOTANI T., 2014, *Advanced structural health monitoring of concrete structures with the aid of acoustic emission*, Construction and Building Materials, 65, 282–302.

SHAHIDAN S., PULIN R., BUNNORI N.M. et al., 2013, *Damage classification in reinforced concrete beam by acoustic emission signal analysis*, Construction and Building Materials, 45 (13), 78–86.

WANG E.Y., HE X., LIU Z.T. et al., 2004, *Study on frequency spectrum characteristics of acoustic emission in coal or rock deformation and fracture*, Journal of China Coal Society, 29 (3), 289–292.

ZHANG L.M., MA S.Q., REN M.Y. et al., 2015, *Acoustic emission frequency and b value characteristics in rock failure process under various confining pressures*, Rock and Soil Mechanics, 34 (10), 2057–2063.

JI H.G., LU X., 2015, *Characteristics of acoustic emission and rock fracture precursors of granite under conventional triaxial compression*, Chinese Journal of Rock Mechanics and Engineering, 34 (4), 694–702.

ZENG P., LIU Y.J., JI H.G. et al., 2017, *Coupling criteria and precursor identification characteristics of multi-band acoustic emission of gritstone fracture under uniaxial compression*, Chinese Journal of Geotechnical Engineering, 39 (3), 509–517.

LI N., WANG E.Y., ZHAO E.L. et al., 2010, *Experiment on acoustic emission of rock damage and fracture under cyclic loading and multistage loading*, Journal of China Coal Society, 35 (7), 1099–1103.

JI H.G., 2004, *Research and application on acoustic emission performance of concrete material*, China Coal Industry Publishing House, Beijing, 13–14.

PENG R.D., LIU H.B., WANG J.Q. et al., 2007, *Developments in rock damage detection techniques*, Rock and Mineral Analysis, 26 (1), 61–66.

ZHOU Y., JI H.G., ZHANG Y.Z. et al., 2017, *Analysis on acoustic emission characteristics of monzonitic granite during triaxial loading-unloading process*, Chinese Journal of Underground Space and Engineering, 13 (2), 314–321.

LI H.G., GAO B.B., LI H.M., 2015, *Study on macroscopic fracture structure and acoustic emission character of coal rock under uniaxial compression*, Chinese Journal of Underground Spaceand Engineering, 11 (3), 612–618.

ZHANG H.H., YAN Y.D., YU H.Z. et al., 2004, *Acoustic emission experimental research on large--scaled rock failure under cycling load-fracture precursor of rock*, Chinese Journal of Rock Mechanics and Engineering, 23 (21), 3621–3628.

CAO S.G., LIU Y.B., LI Y. et al., 2009, *Experimental study on acoustic emission characteristics of coal rock at different confining pressure*, Journal of Chongqing University, 32 (11), 1322–1327.

AI T., ZHANG R., LIU J.F. et al., 2012, *Space-time evolution rules of acoustic emission locations under triaxial compression*, Journal of China Coal Society, 36 (12), 2048–2057.

YANG Y.J., CHEN S.J., HAN G.D., 2006, *Experimental on acoustic emission during compression rupture procedure of coal sample*, Journal of China Coal Society, 31 (5), 362–365.

JI H.G., ZHANG Y.Z., JIN Y. et al., 2012, *Experimental study of confining pressure effect on acoustic emission characteristics of monzonite granite under triaxial compression*, Chinese Journal of Rock Mechanics and Engineering, 31 (6), 1162–1168.

SHKURATNIK V.L., YU L.F., KUCHURIN S.V., 2004, *Experimental investigations into acoustic emission in coal samples under uniaxial loading*, Min. Sci., 40 (5), 458–464.

SHKURATNIK V.L., YU L.F., KUCHURIN S.V., 2005, *Experimental regularities of acoustic emission in coal samples under triaxial compression*, Min. Sci. 41 (1), 44–53.

HE J., PAN J.N., WANG A.H., 2014, *Acoustic emission characteristics of coal specimen under triaxial cyclic loading and unloading*, Journal of China Coal Society, 39 (1), 84–90.