Study on Failure Characteristics and Acoustic Emission Characteristics of Sandstone Under Variable Angle Shear

Feng Luo  
Hebei University of Engineering

Peidong Xu  
Hebei University of Engineering

Yijun Guo  
Hebei University of Engineering

Yanglong Diao  
Hebei University of Engineering

Meng Li (lmlm0520@126.com)  
Hebei University of Engineering  https://orcid.org/0000-0001-7725-0241

Research Article

Keywords: variable angle shear, failure characteristics, acoustic emission characteristics, shear stress

DOI: https://doi.org/10.21203/rs.3.rs-355612/v1

License: © This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License
Abstract

To study the shear damage and failure characteristics of red sandstone under different normal stress conditions, the failure process of sandstone under three different shear angles (50°, 55°, 60°) were studied by using variable angle shear test device. The shear stress-deformation curves and failure characteristics of sandstone were obtained, and the relationships between shear cracks and acoustic emission impact times, amplitude, peak frequency were established. With the increase of shear angle, the normal stress, shear stress and peak shear stress decrease gradually. The development of micro-cracks in the shear plane appear more earlier. The high frequency signal decreases significantly, which may have a significant corresponding relationship with the rock friction and shear effect. The failure mode of rock changes from plasticity to brittleness. The amplitude changes are concave, and more acoustic emission energy is released at compaction stage and plastic(failure) stage. The rock spalling mainly occur in the penetrating area of main and secondary cracks surrounding the two ends of specimen. The spalling degree was obviously weakened with the increase of shear angle. The results have important guiding value for judging and predicting the instability mechanism of rock engineering.

Introduction

Shear failure is the most common failure form in rock engineering. Usually, the shear failure in rock engineering is not the pure shear mode but the shear stress related to normal stress exceeds the limit equilibrium (Jia 2011). In the stability control engineering of rock mass, it is of great significance to study the shear failure characteristics of engineering rock mass under different normal stress conditions. Acoustic emission is a important physical phenomenon with a large number of internal cracks propagation in the failure process of rock mass, and the transient elastic waves are generated by the rapid release of local energy in materials (Shen 2015). As a negative monitoring method, acoustic emission monitoring technology could be used to monitor the micro-fractures in rock mass, and give an effective early warning for rock mass failure (Xiao et al 2016; Feng et al 2019). In this paper, the shear failure process of sandstone was studied by using variable angle shear test device, the failure and acoustic emission characteristics of sandstone under different normal stress conditions were obtained by using PCI-II acoustic emission system.

Domestic and foreign scholars have done lots of work on rock failure and acoustic emission characteristics, and achieved some achievements. Chen et al. (2011) studied the acoustic emission characteristics of sandstone in the whole process of stress-strain under uniaxial compression and the influence of loading rate on it. Li et al. (2014) carried out the tensile and shear tests of sandstone in laboratory, and obtained the characteristics of tensile and shear fracture surface of rock by SEM and numerical simulation method. Liu. (2014) carried out the simultaneous detection of acoustic emission (AE) and infrared radiation (IR) in sandstone shear test, and studied the time-frequency characteristics of AE and IR in the process of rock loading. Zhang et al. (2017) found that the crack evolution stage of rock can be accurately divided according to the change law of AE events. Li et al. (2017) analyzed the damage evolution process of brittle rocks under shear stress. Eberhardt et al. (1998) defined the slope of volume
strain-axial stress curve as volume strain stiffness, and found that the AE parameters increased significantly near crack initiation stress point. Yuan et al. (2020) studied the response law of force chain and acoustic emission. The macro and micro damage characteristics and evolution law of force chain and AE of rock specimens were studied. Li et al. (2021) studied the acoustic emission characteristics of roof rock under uniaxial compression by using similar simulation test, and analyzed the acoustic emission characteristics, failure mode and energy damage mechanism in the progressive failure process. Wu et al. (2015) analyzed the relationship between AE characteristics and stress, strain, damage variables under different failure modes of rocks. Liu et al. (2018) adopted strain analysis and AE monitoring methods to study the crack evolution characteristics of two groups of hard sandstone specimens under uniaxial and triaxial compression, and the crack initiation strength and damage strength values of sandstone specimens were obtained. Wang et al. (2012) conducted the acoustic emission test on marble under uniaxial compression, and found that the wave velocity, elastic modulus and strength of the rock increase before the loading stress exceed the damage stress, and decreased significantly then. Xu et al. (2012) studied the acoustic emission characteristics of sandstone fatigue failure process, and revealed the fatigue damage evolution law. Zhao et al. (2021) studied the evolution law of acoustic emission time series model under different water content conditions, and constructed the damage evolution model of red sandstone.

According to the analysis of the above literature, although domestic and foreign scholars have done amount of work on rock failure characteristics under shear conditions and AE events under different mechanical conditions, the study on rock failure and AE characteristics under different normal stress conditions is few. In view of this, the shear failure process and acoustic emission characteristics of sandstone under different shear angles were studied in this paper. The characteristic parameters such as AE event count, cumulative count, amplitude and peak frequency were used to analyze the mechanical behaviors, and the evolution laws of rock damage were discussed. The achievements of this paper can provide theoretical support for the establishment of shear instability theory and site monitoring of sandstone engineering.

Specimen Preparation And Testing Methods

2.1 Specimen preparation

The experimental material is red sandstone from Zigong, Sichuan Province. Firstly, the ZS-200B rock coring machine were used to drill a core with a diameter of 50mm in the rock block. Secondly, the SHM-200B end face grinding machine was used for grinding, the end face flatness of the specimen were ensured. Finally, the specimens(diameter is 50mm and height is 50mm) were well appeared, which meet the national standard. The specimens were stored in a dry environment and room temperature before being tested. The preparation process were shown in Figure 1.

Table 1 Physical geometry parameters and test conditions of specimen
| Number | Diameter /mm | Height/mm | Shear angle $\alpha/^\circ$ | Loading rate /kN·s$^{-1}$ |
|--------|--------------|-----------|-----------------------------|-----------------------------|
| 1      | 50           | 50.15     | 50                          | 0.2                         |
| 2      | 50           | 50.25     |                             |                             |
| 3      | 50           | 50.18     | 55                          |                             |
| 4      | 50           | 50.20     |                             |                             |
| 5      | 50           | 50.10     | 60                          |                             |
| 6      | 50           | 50.20     |                             |                             |

2.2 Testing methods and equipment

The YA-600 electro-hydraulic servo mechanical test machine were used to provide the loading force. The loading mode was stress control, and the loading rate is 0.2kN/s. To ensure the steady stress of the specimen during the loading process, a preload of 0.3kN was applied at the beginning of the test. The PCI-II AE instrument produced by PAC company was used to collect the characteristic parameters such as acoustic emission waveform, counting and peak frequency during the whole process. According to the experimental conditions, the acoustic emission probe is Nano 30, which was attached to the center (the back) of the specimen. To reduce the influence of laboratory noise on signal acquisition, the threshold value was set to 40 dB, and the sampling frequency was set to 1 M/s. High-definition camera was used to get the experimental image. The test system is shown in Figure 2.

### Analysis Of Mechanical Properties Of Rock Under Different Shear Angles

3.1 Shear strength

Accounding to Coulomb criterion, the mainly failure pattern of rock is shear failure, which is not only related to shear stress on shear plane, but also related to the normal stress. Based on a large number of experiments and mathematical analysis, the shear strength criterion was obtained, as shown Equation 1.

See equation 1 in the supplementary files.

In Equation (1), $\tau$ is the shear stress (shear strength) on shear plane; $\sigma$ is the normal stress on shear plane; $C$ is the cohesion; $\varphi$ is the internal friction angle.

Variable-angle shear test is a common method to conduct the limited shear strength test. The vertical load is applied by a mechanical testing machine, the rock specimen is fractured along a shear plane by adjusting the test clamp, and then obtains the mechanical parameters such as normal stress, tangential shear force, internal friction angle and cohesion of the shear plane by statics and statistics (Zhu et al.,
2001). The shear stress and normal stress of the specimens can be calculated according to the following Equation.

**See equations 2 and 3 in the supplementary files.**

In Equations (2) and (3), \( \sigma \) is the normal stress on the shear plane, MPa; \( \tau \) is the shear stress on the shear plane, MPa; \( P \) is the maximum load when the specimen is damaged, kN; \( A \) is the shear surface area, cm\(^2\); \( \alpha \) is the included angle between shear plane and horizontal plane (°); \( f \) is the friction coefficient of contact surface, \( f = \frac{1}{nd} \); \( n \) is the number of rollers \((n=7)\); \( d \) is the roller diameter \((d=8)\), mm.

Three sets of variable angle shearing devices with angles of 50°, 55° and 60° were used in the experiment. In this experiment, two groups of contrast experiments under the same conditions were carried out for each angle. Specimens 1, 3 and 5 were the first group, and specimens 2, 4 and 6 were the second group. The peak loadings of sandstone specimens under three groups of shear angles can be obtained by three variable angle shear tests. The corresponding normal stress \( \sigma \) and shear stress \( \tau \) can be obtained by Equations (2) and (3). The cohesion and internal friction angle of sandstone can be obtained by linear fitting \( \sigma \) and \( \tau \), and the strength curve can be drawn.

**Table 2 Results of sandstone shear experiment**

| Group     | Number | Shear angle \( \alpha/° \) | Peak load \(/kN\) | Shearing stress \(/MPa\) | Direct stress \(/MPa\) | Cohesive forces \(c/MPa\) | Internal friction angle \(\varphi/°\) |
|-----------|--------|-----------------------------|-------------------|---------------------------|------------------------|---------------------------|-----------------------------------|
| Group 1   |        |                             |                   |                           |                        |                           |                                   |
| 1         | 50     | 62.55                       | 19.16             | 16.09                     |                        |                           |                                   |
| 3         | 55     | 50.93                       | 16.68             | 11.69                     |                        |                           |                                   |
| 5         | 60     | 38.42                       | 13.31             | 7.68                      |                        |                           |                                   |
| Group 2   |        |                             |                   |                           |                        |                           |                                   |
| 2         | 50     | 64.15                       | 19.65             | 16.50                     |                        |                           |                                   |
| 4         | 55     | 52.84                       | 17.31             | 12.13                     |                        |                           |                                   |
| 6         | 60     | 40.96                       | 14.19             | 8.19                      |                        |                           |                                   |
| Linear fitting |    |                             |                   |                           |                        |                           |                                   |
|           | 50     | 63.35                       | 19.41             | 16.30                     | 8.59                   | 34                        |                                   |
|           | 55     | 51.89                       | 17.00             | 11.91                     |                        |                           |                                   |
|           | 60     | 39.69                       | 13.75             | 7.94                      |                        |                           |                                   |

Note: round off and keep two decimal places.

According to Figure 3, the normal stress of sandstone specimen is approximately linearly related to the shear stress. The shear stress increases monotonously with the normal stress. With the increase of shear angle, the peak load, normal stress and shear stress decrease monotonously. The peak load, normal stress and shear stress of 55° group specimens are reduced by 18.1%, 26.9% and 12.4% compared with
those of 50° group specimens respectively. Compared with 55° group specimens, the peak load, normal stress and shear stress of 60° group specimens decreased by 23.5%, 33.3% and 19.1% respectively. The change rate of peak load, normal stress and shear stress of 55° to 60° group specimens is significantly higher than that of 50° to 55° group specimens. The difference of change rate indicates that the larger of the shear angle, the more obvious the stress variation.

See equation 4 in the supplementary files.

3.2 Analysis of deformation and failure characteristics of sandstone

According to Figure 4, it can be found that two or more cracks appear in sandstone specimen during the process of shearing, which are main cracks and secondary cracks respectively. The main cracks propagate along the shear stress direction. This kind of crack penetrates through the rock specimen and eventually leads to the failure of the rock mass. The secondary cracks developed along the local stress concentration area of the rock specimen, but do not appear on the main shear plane. By observing the development of secondary cracks in the loading process, it was found that the rock spalling mainly occur in the penetrating area of main and secondary cracks surrounding the two ends of the specimen. The spalling degree is obviously weakened with the increase of loading angle. However, the relationship between spalling degree and shear angle needs to be further investigated.

During the loading process, with the increase of normal stress on the shear plane, the friction on the shear plane increases correspondingly. The phenomenon leads to different scratch scope and degree on the shear plane with the shear angle changes. Through the comparative analysis of scratches, it can be clearly observed that the scratch area of shear plane of 50° specimens is the largest, and the scratch area of shear plane of 60° specimens is the smallest. With the increase of shear angle, the peak load of the specimen and the normal stress on the shear plane decreases gradually and synchronously. The friction force is determined by the normal stress linearly on the shear plane, and the normal stress is proportional to the friction force and the amount of scratches on the shear plane.

The analysis shows that the normal stress and the friction force on the shear plane decrease gradually with the increase of shear angle. When the shear angle approaches 90°, the normal stress on the shear plane is close to zero, and the failure pattern of the specimen changes from compression-shear failure to pure-shear failure.

Acoustic Emission Characteristic Parameters Analysis Of Sandstone Under Variableangle Shear Test

During the loading process of the specimen, a large number of microcracks will appear. At the same time, it will be accompanied by the release of elastic wave and energy. Monitoring and analyzing the AE signal during the loading process, is helpful to understand the micro-fracturing process in the rock specimen. Acoustic emission can capture the elastic wave released by crack propagation in the specimen. Conversely, crack propagation location and the damage degree of the rock mass can be expressed by the
acoustic emission characteristic parameters such as the event counts and so on. According to these characteristic parameters, the acoustic law of fracturing and damage in the sandstone under different shear angles can be revealed. The results will provide theoretical basis for the analysis of rock failure precursors.

4.1 Analysis of acoustic emission counting characteristics of sandstone under different shear angles

Acoustic emission counts refers to the times that the ringing pulse crosses the threshold in a unit time. This parameter is a very important and basic for AE signal, and its change law can reflect the real-time state of rock in the whole failure process (Ji et al., 2012). The AE count during the failure process of the specimen was recorded, and the distribution curve of AE count and cumulative count are drawn according to the recorded results, as shown in Figure 5.

It can be obtained from Figure 5 that the evolution of shear force, AE ringing count and cumulative count with time in the process of variable angle shear. The evolution law of characteristic parameters of AE ringing count can well reflect the failure process of sandstone specimens. The loading process of specimens can be divided into four stages: compaction stage, elastic stage, plastic stage and failure stage. Compaction stage: at this stage, some micro-cracks inside the specimen will be compacted to produce lots of intense AE signals. Elastic stage: at this stage, the AE activity gets into the "quiet period", and the stress begins to increase linearly with the loading time, which lasts for a long time. Plastic stage: at this stage, the AE activity gets into the "active period", and the stress reaches about 85% of the peak load. At this time, some tiny cracks can be observed on the surface of the specimen, which appear and continue to propagate. Failure stage: at this stage, the AE activity is extremely intense, and the stress reaches the peak value. The specimen is instantly fracturing along the shear plane, and then the AE ringing count and the stress decreases rapidly until the end of the experiment.

With the increase of the angle, the required loading time decreases in the compaction stage, elastic stage, plastic stage and fracturing stage. Under the same experimental conditions, the normal stress on the shear plane changes with the change of loading angles, and the friction of rock particles on the shear plane also changes, which makes the peak load, shear stress and normal stress at different shear angles inconsistent.

The AE parameters of failure process have different evolution characteristics under different shear angles:

1) 50° shear angle

The peak shear force of two groups specimen are about 50 kN, and the loading time is about 330 s. At the compaction stage, the intense activity time of AE lasts about 10 s, and the shear force is about 10% of the peak load. The active time of AE in plastic stage lasts for 15-20 s. When the shear force reaches about 85% of the peak load, the AE activity of the specimen gets into the "active period" and continues until failure completely.
2) 55° shear angle

Compared with 50° specimens, the peak shear stress and loading time of this group of specimens are reduced by about 20% and 18% respectively. The duration of acoustic emission "active period" began to increase.

3) 60° shear angle

The acoustic emission "active period" of 60° specimen lasts for the longest time, reaching about 20s. It is also found that this group of specimens will have strong acoustic emission activity for 3-5 seconds in the elastic stage of loading process.

The comparison shows that there are differences between deformation characteristics and AE characteristic parameters evolution with the increase of shear angle. At the same stage, the AE activity of different angle specimen is basically the same. With the increasing of the shear angle, the intense activity time of AE in the compression stage and the "active period" of AE activity in the plastic stage gradually increase. This shows that the development of micro-cracks in the shear plane appear more earlier with the decrease of normal stress. In addition, it is observed that the rock failure is more sudden and more violent with the increase of shear angle. This phenomenon indicates that the rock gradually transforms from plasticity to brittleness. Therefore, the AE ringing count characteristics can better predict the instability of sandstone engineering.

4.2 Analysis of acoustic emission amplitude characteristics of sandstone under different shear angles

Amplitude in the AE characteristic parameter is the maximum amplitude of AE waveform, which is one of the most important characteristic parameters for measuring signal size. Its unit is dB, which has a direct relationship with the signal strength. It is usually used to identify the type of wave source, the measurement of strength and attenuation. During the test, the threshold value of AE instrument was set to 40 dB, and the amplitude of AE only changes in the range of 40-100 dB. The relationship between AE signal amplitude and loading time of sandstone failure process under different shear angels are shown in Figure 6.

It can be seen from Figure 6 that with the increase of normal stress on the shear plane of the specimen, the variation of AE amplitude presents a law of "increase-decrease-increase" during the loading process. Under different shear angles, the AE amplitude signal points present concave distribution, and the amplitude signals are high at both ends and low in the middle. The AE amplitude signals are relatively strong during the compaction stage and the failure stage during the loading process, and most of the amplitude signals are in the range of 70 dB-90 dB. However, the amplitude signal in the elastic stage is relatively weak, and most of the amplitude signals are in the range of 40 dB-70 dB.

The high decibel AE signals of 50° group specimens are mainly distributed in the compression stage and failure stage, the duration of high decibel signals in the compression stage are about 30 s, and about 20 s at failure stage, the rest signals are about 50 dB for 50°-1 specimen and about 70 dB for 50°-2 specimen,
and the overall signal changes smoothly. The high decibel AE signals of 55° group specimens are mainly distributed in the compression stage and failure stage, the duration of high decibel signals in the compression stage is about 40 s, and about 25 s at failure stage, and the overall amplitude signals are distributed smoothly during the loading process. The high decibel AE signals of 60° group specimens are mainly distributed in the compression stage and failure stage, the duration of high decibel signals in the compression stage is about 50 s, and about 35 s at failure stage.

It can be seen that with the increase of shear angle, the duration of high decibel signal in the compression stage and failure stage increases continuously during the loading process, which indicates that the micro-crack propagation in the specimen becomes more seriously with the normal stress on the shear plane of the specimen decreasing. As shown in Figure 6, the high decibel amplitude signal generation interval is the internal micro-crack compression stage and the plastic-failure stage, while the low decibel amplitude signal generation interval is the elastic stage. At the compression stage and plastic-failure stage, the crack closure and crack growth will be more intense.. However, at the elastic stage, the crack closure and crack growth are stable and slight. Therefore, the generating the high decibel amplitude signals has obvious difference between these two stages. It can be concluded from the relationship between the amplitude and the fracturing law of the specimen that the magnitude of the signal can predict the fracturing of the specimen to a certain extent.

4.3 Analysis of peak frequency characteristics of sandstone under different shear angles

Waves with different frequencies correspond to different types of AE sources and microscopic crack pattern of rocks. With the failure process of rock, the frequency of AE signal will changes with the loading level and deformation degree. Therefore, the development process of AE peak frequency can reflect the fracturing information and the loading state of rock (Ji et al., 2012). Under different shear angles, the relationship between peak frequency of AE signal and loading time are shown in Figure 7.

It can be seen from Figure 7 that the peak-frequency signals of AE under different shear angles are basically concentrated in the intermediate frequency signal region and the ultra-high frequency signal region, while the signal distribution in section I is generally less.

The acoustic emission peak frequencies of the three groups of specimens are mainly distributed in the intermediate frequency signal area of about 100 kHz and the ultra-high frequency signal area of about 300 kHz during loading. Under different shear angles, there are obvious differences of signal distribution in section I. Among them, the signal distribution in section I of 50° group specimens is more and evenly distributed. the signals in section I of 55° group specimens are less and concentrated the range of the intermediate frequency and ultra-high frequency. The number of signals in section I of 60°-1 specimen are the least. With increase of the shear angle, the signal distribution in section I of the high-frequency signal area shows a decreasing trend.

Based on the above analysis and the fracturing process of the specimen, it can be seen that during the test loading process, the AE peak frequency signal is mainly the intermediate frequency signal. The peak
frequency signal of AE in elastic stage is also dominated by IF frequency signal. As an important AE parameter, the peak frequency signal may be of great significance to determine the fracturing type of rock failure. The different peak frequency of sound wave may be related to the failure mechanism of the fracturing location. With the increasing of shear angle, the normal stress of shear plane and the confining pressure effect decreases gradually, which leads to the weakening of friction shear effect. Compared with the peak frequency signal distribution, it is found that high frequency signal decreases significantly with the increase of shear angle, which may have a significant corresponding relationship with the rock friction and shear effect. Therefore, further investigation on the relationship between the peak frequency signal of acoustic emission and the fracturing type of rock failure has important guiding value for judging and predicting the instability mechanism of rock engineering.

Conclusions

1) With the increase of shear angle, the peak load, peak normal stress and peak shear stress of sandstone specimens are decrease gradually; the scratch area of the shear surface also decreases gradually, the loading time required for the test also shows a decreasing trend.

2) During the loading process, with the increase of normal stress on the shear plane, the friction on the shear plane increases correspondingly. The phenomenon leads to different scratch scope and degree on the shear plane with the shear angle changes. By observing the development of secondary cracks in the loading process, it was found that the rock spalling mainly occur in the penetrating area of main and secondary cracks surrounding the two ends of the specimen. The spalling degree was obviously weakened with the increase of loading angle.

3) With the increase of angle, The "active period" of acoustic emission increased gradually before the failure of the specimen, the duration of acoustic emission signal and the time required for specimen destruction are gradually shortened. The failure mode of specimen changes from plastic failure to brittle failure, the damage energy increase significantly.

4) The amplitude changes are concave, and more acoustic emission energy was accumulated at both ends of loading. However, with the increase of angle, the high-frequency signals in peak frequency gradually decrease, which shows that high-frequency signals are related to plastic failure and brittle failure of rock, and the relationship between high-frequency signals and rock failure forms can be further studied. The active degree of AE can directly reflect the micro-fracture degree in rocks. By analyzing the distribution of AE characteristic parameters, amplitude and peak frequency characteristics of sandstone under different shear angles, the internal relationship between failure damage law of sandstone and acoustic emission under variable shear was revealed.

Declarations
Funding: This research is financially supported by the National Natural Science Foundation of China (51804093, 52074100), Natural Science Foundation of Hebei Province (E2020402048, E2020402041), Science and technology projects for colleges and universities in Hebei Province (BJ2019021), Handan science and technology research and development program (19422091008-32).

Conflicts of interest/Competing interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and material: The data that support the finding of this study are available from the corresponding author upon reasonable request.

Code availability: The code that support the finding of this study are available from the corresponding author upon reasonable request.

Authors' contributions: Conceptualization, writing-original draft preparation, experiment design, physical experiment, methodology, software, Feng Luo and Peidong Xu; supervision, writing-review and editing, funding acquisition, Feng Luo; methodology, validation, conceptualization, writing-review and editing, Meng Li; visualization, investigation, Yijun Guo and Yanglong Diao. All authors have read and agreed to the published version of the manuscript.

Ethics approval: Not applicable.

Consent to participate: Not applicable.

Consent for publication: Not applicable.

References

Chen J, Yang R, Kang Y (2020) Influence of the Rock Length-to-Diameter Ratio and Fracture Modes on Uniaxial Compression Strength [J]. Geotech Geol Eng 38: 2551-2557

Chen YL, Wei ZA, Xu J, et al (2011) Experimental study on acoustic emission characteristics of rock under uniaxial compression [J]. Acta Sinica de Coalmine 36(S2): 237-240

Eberhardt E, Stimpson B, Read RS et al (1998) Identifying crack initiation and propagation thresholds in brittle rock [J]. Canadian Geotechnical Journal 35(2) : 222-233

Feng X, Young RP, Reyes-Montes JM et al (2019) ISRM Suggested Method for In Situ Acoustic Emission Monitoring of the Fracturing Process in RockMasses [J]. Rock Mechanics and Rock Engineering 52: 1395-1414
Ji HG, Wang HW, Cao SZ et al (2012) Experimental study on acoustic emission signal frequency characteristics of granite under uniaxial compression [J]. Chinese Journal of Rock Mechanics and Engineering 31(S1): 2900-2905

Jia XR, Rock Mechanics [M]. China University of Mining and Technology Press, 2011: 1-195

Jiang Y, Luan H, Wang D et al (2019) Fracture Mechanism and Acoustic Emission Characteristics of Rock Specimen with Edge Crack Under Uniaxial Compression [J]. Geotech Geol Eng 37: 2135-2145

Li SD, Li X, Guo JY et al (2014) Experimental study on tensile shear fracture of rock [J]. Chinese Journal of Engineering Geology 22(4): 655-666

Li X, Zhang D, Yu G et al (2021) Research on Damage and Acoustic Emission Properties of Rock Under Uniaxial Compression [J]. Geotech Geol Eng. https://doi.org/10.1007/s10706-021-01710-5

Li Z, Li L, Li M et al (2017) A numerical investigation on the effects of rock brittleness on the hydraulic fractures in the shale reservoir [J]. Journal of Natural Gas Science & Engineering S1875510017304481

Liu JW (2014) Acoustic emission-infrared characteristics and damage evolution law of rock under variable angle shear [D]. Jiangxi University of Science and Technology, Jiangxi

Liu QS, Wei L, Lei GF et al (2018) Experimental study on damage strength and brittleness parameter evolution of sandstone crack initiation [J]. Chinese Journal of Geotechnical Engineering 40(10): 1782-1789

Pei F, Ji H, Zhang T (2019) Detection of Cracking Levels in Granite by AE Signals Under Uniaxial Compression [J]. Geotech Geol Eng 37: 2565-2576

Shen GT (2015) Acoustic emission detection technology and application [M]. Science Press, Beijing

Wang B, Zhu JB, Yan P et al (2012) Identification of marble damage intensity and evolution rule of parameters based on damage control [J]. Chinese Journal of Rock Mechanics and Engineering 31(S2): 3967-3973

Wu XZ, Liu JW, Liu XX et al (2015) Study on the coupling relationship between cumulative acoustic emission ringing count and damage constitutive model of rock [J]. Journal of Mining and Safety Engineering 32(01): 28-34+41

Xiao Y, Feng X, Hudson JA et al (2016) ISRM Suggested Method for In Situ Microseismic Monitoring of the Fracturing Process in Rock Masses [J]. RockMechanics & Rock Engineering 49(1): 343-369

Xu J, Wu H, Lu LF et al (2012) Study on acoustic emission characteristics of sandstone shear process under different water cut conditions [J]. Chinese Journal of Rock Mechanics and Engineering 31(5): 914-920
Yuan A, Hou J, Yin Z (2020) The Force Chain and Acoustic Emission Response Law for the Uniaxial Compression of Rock [J]. Geotech Geol Eng 38: 4479-4499

Zhang D, Liu C, Zhou Y et al (2020) Characteristics of Fracture Mechanism and Acoustic Emission of Rock-Coal Combined Body with Prefabricated Fissure [J]. Geotech Geol Eng 38: 6245-6254

Zhang GK, Li HB, Xia X et al (2017) Study on acoustic emission and wave propagation characteristics of granite under uniaxial loading [J]. Chinese Journal of Rock Mechanics and Engineering 36(05): 1133-1144

Zhao K, Ran SH, Ceng P et al (2021) Influence of water content on characteristic stress and acoustic emission characteristics of red sandstone [J]. Rock and soil mechanics 04: 1-10

Zhu DH, Hu QX, Liu JH (2001) Development of rock variable angle shear apparatus [J]. research and exploration in laboratory 01: 66-67

Zhu X, Li Y, Wang C et al (2019) Deformation Fracture Characteristics and Loading Rate Effect of Sandstone Under Uniaxial Cyclic Loading and Unloading [J]. Geotech Geol Eng 37: 1147-1154

Figures

Figure 1

Processing and preparation of specimen

Figure 2

Test system
Figure 3

Strength curve of sandstone

Figure 4

The failure characteristics of shear plane of sandstone specimen
Figure 5

Distribution of acoustic emission count and cumulative count in sandstone under different angles
Figure 6

Sandstone shear force-acoustic emission amplitude distribution curves
Figure 7

Distribution curve of shear force-acoustic emission peak frequency in sandstone