

Study on Acoustic Emission Characteristics and Crack Evolution Characteristics of Conglomerate Under Uniaxial Compression

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Abstract: Taking the giant thick conglomerate in Yima mining area as the research background, this paper investigates the acoustic emission characteristics and crack evolution law of conglomerate with different grain sizes under loading conditions through uniaxial compression test and acoustic emission (AE) technology, and discusses the influence of grain size on its damage mechanism and damage evolution. The results show that : the AE energy and ringing counts of conglomerate specimens increase significantly with the increase of grain size, and large-grained conglomerates show stronger shear damage characteristics during the damage process; Specimens with larger grain sizes have a higher rate of AE events during the damage process, whereas those with smaller grain sizes show a lower damage variable D and higher load-bearing capacity after the damage intensity; During the whole process of rock damage, the AF value shows the evolution law of first fluctuation, then decrease, and a small increase near the damage, while the RA value is overall lower, and rises sharply near the damage, indicating that the change of AF and RA values can be used as a precursor indicator of rock destabilization damage; The crack extension form evolves significantly with the loading process, with tensile and shear cracks predominating before the initiation of the fracture strength, and shear cracks predominating near the destabilization damage. Shear cracks dominate near the destabilizing damage. The shear crack surge stage of medium and coarse grain specimens with larger grain size appeared after the crack initiation strength, while the shear crack surge stage of fine grain specimens with smaller grain size appeared after the damage strength. The results reveal the acoustic emission characteristics and crack evolution laws of conglomerates with different grain sizes during the damage process, deepen the understanding of the mechanical behavior and damage mechanism of conglomerates, and provide theoretical basis and technical support for the stability evaluation of the giant conglomerate strata in the Yima Mining Area and the prediction of engineering disasters.

Keywords: Different gravel grain sizes; Uniaxial compression; Crack evolution; Acoustic emission technology; Damage evolution.

1. Introduction

In the process of mining, rock damage often induces serious dynamic disasters, especially impact ground pressure, which occurs along with the rupture of the rock layer and the rapid release of energy, posing a major threat to mine safety. Take a mining area as an example, due to the complex conditions of the deep coal seams in the thick conglomerate, impact ground pressure disasters occur frequently, and the intensity and scale of the disaster far exceeds the shallow mining area, which not only seriously threatens the safety of miners' lives, but also causes great damage to the mining equipment and mining efficiency. The occurrence of impact ground pressure is usually closely related to the accumulation and release of energy triggered by rock damage^{[1],[2]} and it is of great significance to capture the precursor information of rock damage for the effective prediction of impact ground pressure.

Conglomerate is a typical sedimentary rock, due to the non-homogeneity of the grains in its internal conglomerate, conglomerate with different grain sizes will show different fracture patterns and different mechanical properties. Liu et al^[3] studied the whole process of destruction of fine-grained sandstone and coarse-grained sandstone by high-speed photographic observation test under uniaxial compression load, and found that the grain size significantly affects the

crack extension characteristics and destruction mode. Kang et al^[4] conducted high-temperature treatment on granites with different grain sizes, and found that the weakening of the heated granite is more serious with the increase of the grain size; Sabi et al^[5] Brazilian splitting experiments, indicating that coarse-grained granite produces more cracks, and with the increase in grain size to induce the production of tensile cracks, the number of shear cracks also increased; Deng et al^[6] three-point bending experiments on four different grain sizes of granite, found that with the increase in grain size, the peak load, fracture toughness value, the ratio of yield limit and peak load are reduced, the amount of deformation occurred in the damage increases. The non-homogeneity of the specimens is more obvious; Zhao et al^[7] investigated the role of particle size in controlling the permeability of sedimentary rocks through core size analysis and extraction of logging geologic parameters, and established a model for calculating the particle size and permeability, which revealed its non-homogeneity characteristics. Wang et al^[8] investigated the crack evolution characteristics of granite with different grain sizes by uniaxial compression acoustic emission test, and found that the grain size affects the crack sprouting ability, damage brittleness and acoustic emission signal characteristics. Song et al^[9] investigated the damage process of weakly cemented sandstone with different grain sizes by uniaxial compression acoustic emission tests, and found that the rock specimens showed more obvious brittle damage and

stronger AE signal characteristics as the grain size decreased. Wang et al^[10] found that the acoustic emission ringing counts of sandstone have fractal characteristics, and the sudden drop of fractal dimension can be used as a precursor of damage, and the larger the grain size, the more intense the damage. Zhang et al^[11] investigated the damage mode and crack evolution characteristics of Longmaxi shale with different inclination angles by uniaxial compression experiments and acoustic emission techniques. Wang et al^[12] investigated the effect of different laminar dip angles on crack extension and acoustic emission characteristics of soft and hard interbedded rocks. Zhao et al^[13] based on the three-point bending test showed that the cumulative number of acoustic emission events and high-energy acoustic emission events at the peak load of the rock specimens increased with the decrease of grain size, and the change of correlation dimension decreased; Wang et al^[14] found that the statistical information of the acoustic emission source type information of different grain sizes found that the percentage of crack type shifted from tensile to shear with the increase of the grain size of the rock specimens.

The rock specimens used in the above acoustic emission studies are mainly from granite, sandstone and other rocks, and there are fewer acoustic emission studies for conglomerates, and there are fewer studies on the damage characteristics and damage evolution laws of conglomerates

during stress based on acoustic emission localization. Therefore, in order to investigate the damage and injury law of conglomerate with different grain sizes, the acoustic emission uniaxial compression experiments carried out on conglomerate were analyzed to analyze the damage characteristics, the acoustic emission characteristics of the compression process, and the rupture form of conglomerate was quantified and analyzed by RA-AF.

2. Test Overview

2.1. Specimens preparation

The nine conglomerate specimens used in the test were all taken from a certain borehole, and after sampling, they were firstly cut and polished on both sides, and then prepared into a standard cylindrical specimens of 50 mm×100 mm(As shown in Fig.1), with the roughness error of both ends of the specimens within 0.05mm, and the surface of the specimens was polished to ensure that it was smooth, which could satisfy the precision requirements of the test. The specimens were numbered as fine-grained conglomerate (S-1, S-2, S-3), medium-grained conglomerate (Z-1, Z-2, Z3), and coarse-grained conglomerate (M-1, M-2, M-3), and the distribution of the grain sizes of each group was in the ranges of 2-25 mm, 2-45 mm, and 2-60 mm, and the specimens were relatively intact.



Figure 1. Standard specimens

2.2. Test equipment and methods

The test system is mainly composed of two parts: loading system and acoustic emission monitoring system, as shown in Fig.2 and Fig.3 RMT-150B rock mechanics test system developed by Wuhan Institute of Geotechnics, Chinese Academy of Sciences is used for loading, the maximum output force of the vertical hydraulic cylinder of the test machine is 1000kN, and the maximum compression deformation is 50mm; the range of loading rate in displacement loading mode is 0.001~1mm/s, and the set loading rate of the test is 0.005mm/s. PCIE type 8-channel acoustic emission monitoring system is adopted to collect the acoustic emission signals, which is mainly composed of acoustic emission probe and signal amplifier as well as acquisition host. PCIE type 8-channel acoustic emission

monitoring system is used to collect acoustic emission signals, which is mainly composed of acoustic emission probes, signal amplifier and acquisition host. Two acoustic emission probes are symmetrically arranged on both sides of the geometric center of the soft and hard interlayered rock specimens, when the specimens is damaged and cracked to produce acoustic emission signals, the acoustic emission signals are collected by the acoustic emission probes, amplified by the signal amplifiers and transported to the acquisition host for storage and processing, so that real-time acoustic emission parameters and other real-time data can be obtained. The sampling frequency is set to 5 MHz and the threshold is set to 40 dB to filter the background noise. During the test, the loading system is synchronized with the acoustic emission detection system to ensure that the loading information corresponds to the time of acoustic emission signal generation.

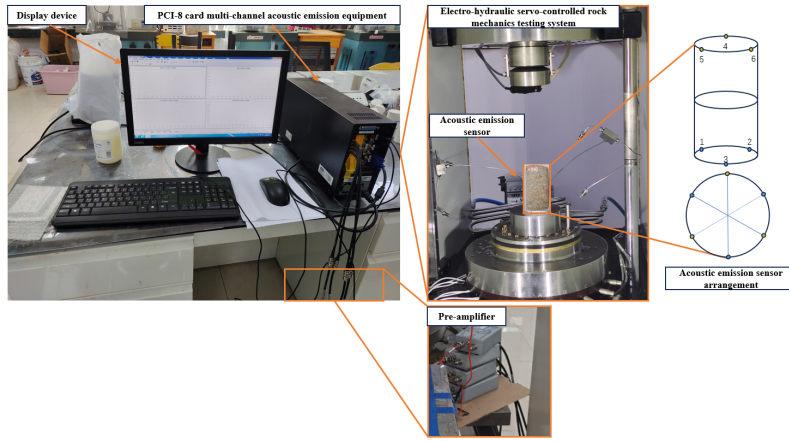


Figure 2. Site layout of acoustic emission

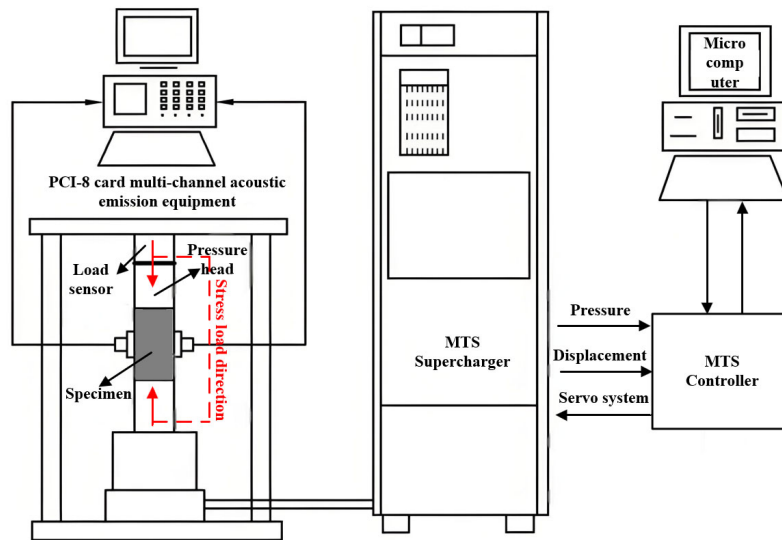


Figure 3. Uniaxial compression and acoustic emission monitoring schematic diagram

2.3. Principle of acoustic emission monitoring

The phenomenon in which strain energy is released in the form of elastic waves from deformations or damages that occur within a specimens or structure under the action of external forces, internal forces or temperature is called Acoustic Emission (AE). Acoustic emission signals are usually weak and need to be detected by means of an acoustic emission sensor. The sensor converts the mechanical vibrations inside the specimens into electrical signals, which are amplified by a signal amplifier and transmitted to the AE hardware system (shown in Fig. 4). After processing, these

signals are converted into recognizable waveform data. Under the external load, the primary cracks inside the rock will close or open with the change of load, accompanied by the generation and expansion of new cracks and fissures. The cracks at both ends of the rock gradually derive and form a crack zone, which gradually expands with the increasing load, and eventually triggers the macro-damage of the rock and leads to its rupture instability. Before the microscopic cracks evolve into macroscopic cracks, the cracks undergo a stable expansion stage. The crack expansion is intermittent, and each expansion is accompanied by the generation of a large number of acoustic emission signals.

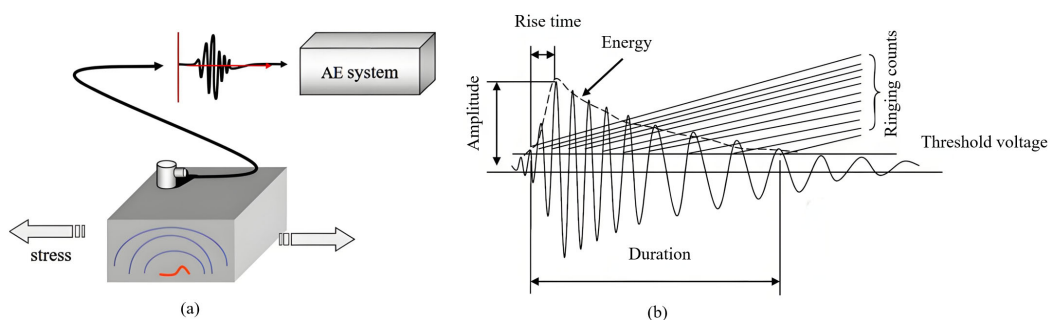


Figure 4. Acoustic emission monitoring schematic diagram (a) and acoustic emission signal simplified waveform parameter diagram (b)

3. Acoustic Emission Characteristics and Damage Evolution

3.1. Acoustic emission energy characteristics

During specimens loading, crack initiation and extension are the key stages of damage evolution, and both micro and macro cracks generate acoustic emission signals. Figure 5

shows the coupling relationship curve between the time-load relationship and the acoustic emission energy signal. The acoustic emission energy curve can clearly reflect the energy change characteristics of conglomerate during damage evolution: the low flat period indicates the slow release or accumulation of energy, while the energy peak corresponds to the instantaneous elastic energy release during the formation of the main crack at the interface.

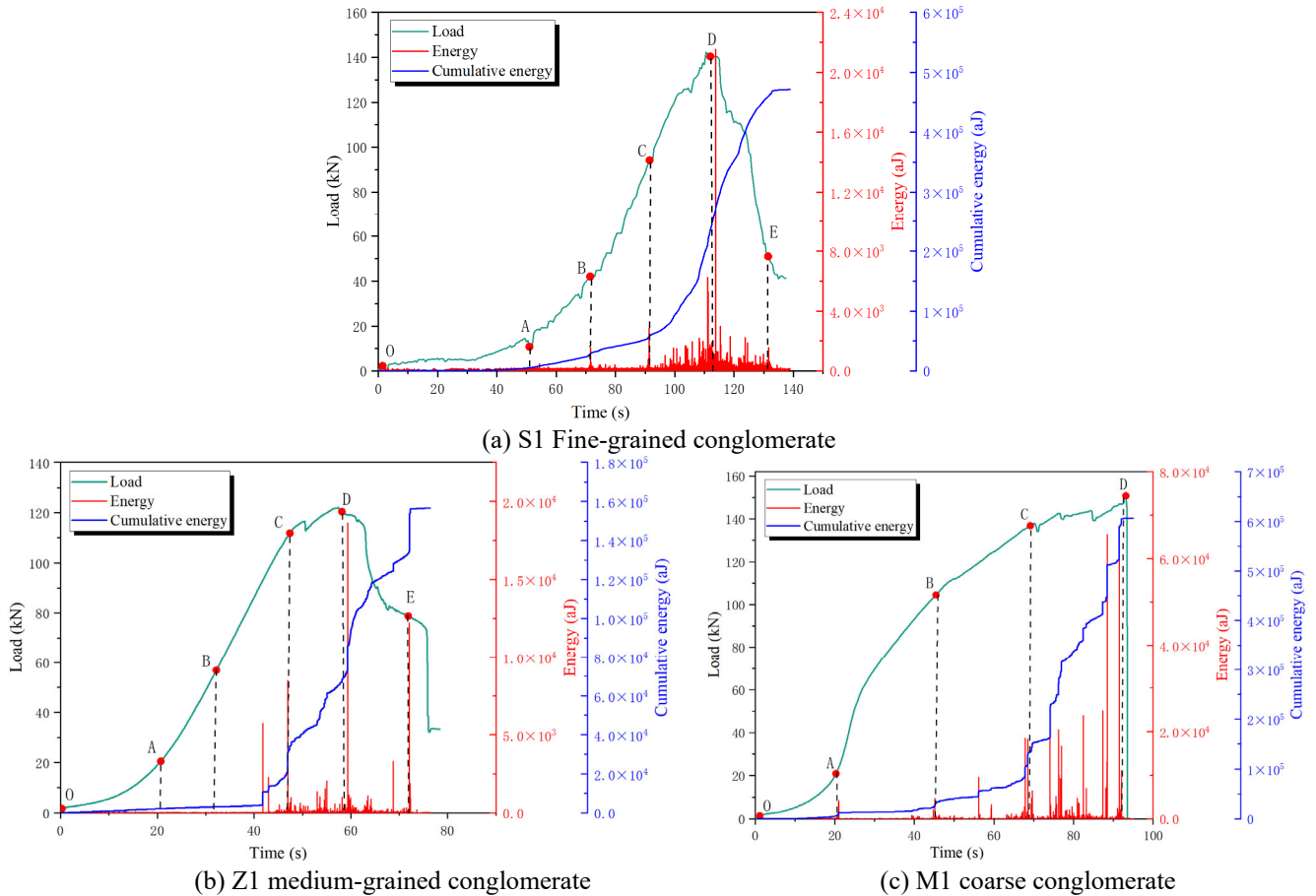


Figure 5. Acoustic emission energy characteristics of different particle sizes

As can be seen from Fig. 5, the acoustic emission (AE) energy evolution characteristics of conglomerate specimens with different grain sizes have a good correspondence with the shear path, which can effectively reflect the damage process of conglomerate. In the uniaxial loading experiment, the loading process was synchronized with the real-time monitoring of the acoustic emission signals. Taking conglomerate specimens S1, Z1 and M1 as examples, their peak loads were 120.4 kN, 140.68 kN and 151.32 kN, respectively, and from the analysis of the load-ringer counts-energy time curves, it can be seen that the S1 specimens showed a transient decrease in the load, accompanied by a decrease in the acoustic emission energy, when it reached the point C. This phenomenon is consistent with the micro-emissions in the conglomerate. This phenomenon is closely related to the closing process of microcracks inside the conglomerate. When the microcracks are closed, part of the energy is consumed to overcome the friction between the particles, resulting in a short-term decrease in the load and a subsequent decrease in the acoustic emission energy. Overall, the load-time curve can be divided into five stages: initial compaction stage, linear-elastic stage, elastic-plastic stage,

unstable development of cracks and residual load stage.

In the initial compaction stage (OA), the acoustic emission energies of the S1, Z1 and M1 specimens were low and grew slowly, but the M1 specimens showed a sudden increase in energy at point A. The acoustic emission energy of the S1, Z1 and M1 specimens was low and increased slowly. This phenomenon is mainly related to the load-concentration effect of large-grained conglomerates, which triggers a surge in acoustic emission energy by rapid expansion of microcracks or nucleation of new cracks when the load exceeds the grain strength. The energy fluctuation of M1 specimens is large, and the cumulative energy reaches an order of magnitude of 10^4 . In contrast, Group S specimens exhibit more acoustic emission events in the localized load concentration region, whereas Group M specimens show less energy fluctuation due to the larger interparticle space and the weakened load concentration effect.

In the elastic-plastic phase (AB), the acoustic emission energies of the S1 and Z1 specimens were maintained at a low level, while the M1 specimens exhibited significant energy fluctuations. In this stage, the localized damage in Group S

and Z specimens releases larger energy near point B due to the more dense internal structure and uniform load transfer. In contrast, the specimens of group M have an inhomogeneous internal structure due to the presence of large-sized particles, and the local load concentration effect is significant, and the damage releases energy frequently, triggering multiple energy fluctuations, with the maximum value reaching 702.

In the online elastic phase (BC), the fluctuation of the acoustic emission energy of the S1 specimens is relatively small, the acoustic emission energy of the Z1 specimens grows slowly, and the energy fluctuation range of the M1 specimens is larger. the S1 specimens has less overall energy release due to the uniform load distribution, but due to the effect of structural inhomogeneity, the local region is the first one to experience damage and release energy. the Z1 specimens has a slower development of damage due to the uniform load distribution. Z1 specimens has slower damage development due to uniform load distribution and limited strain energy release, so the acoustic emission energy grows more slowly. In contrast, the structural inhomogeneity of the M specimens is significant, resulting in the concentration of the load in the local region, frequent local damage and release

of energy, thus the acoustic emission energy fluctuation is larger, but the overall trend of growth.

In the stage of unstable crack development (CD), the acoustic emission energy of S1, Z1 and M1 specimens all showed a rapid growth trend. With the rapid crack extension, the sprouting of new cracks and the concentration of load at the crack tip resulted in a rapid increase in the acoustic emission energy. Crack extension and load redistribution lead to successive damage and release of strain energy in various regions within the specimens, driving the rapid growth of the acoustic emission energy.

During the residual load stage (DE), the loads on the S1 and Z1 specimens gradually decrease, but the acoustic emission energy remains active, indicating that the internal damage process continues. On the contrary, the acoustic emission energy of the M1 specimens decayed rapidly to disappear after the load dropped abruptly, indicating that the damage process was basically completed. After the E point, the acoustic emission signals of the S1 and Z1 specimens gradually disappeared, indicating that the specimens had been completely destroyed.

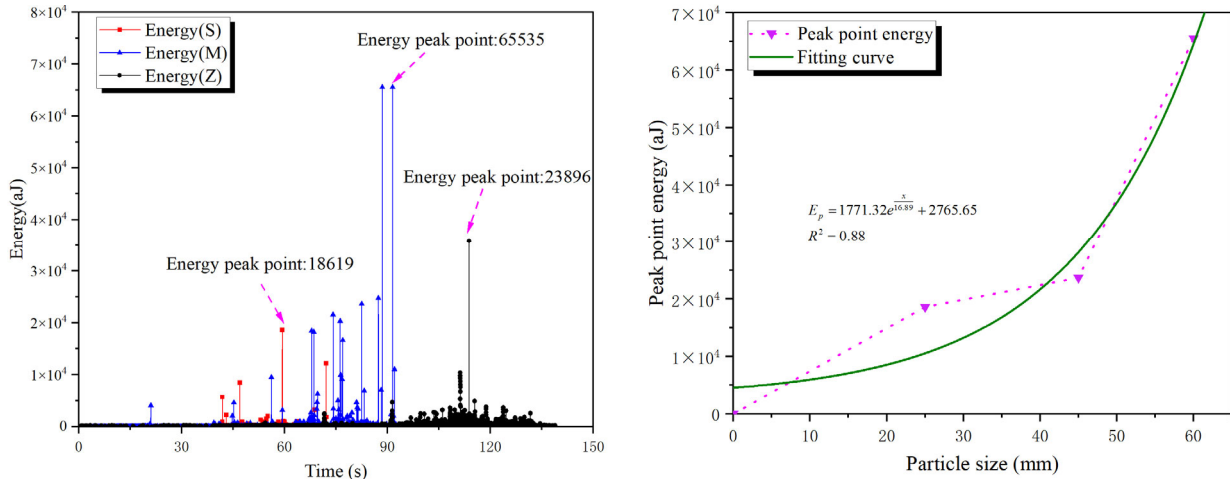


Figure 6. Comparison of cumulative AE energy curves of conglomerate (a) and relationship between cumulative AE energy and particle size (b)

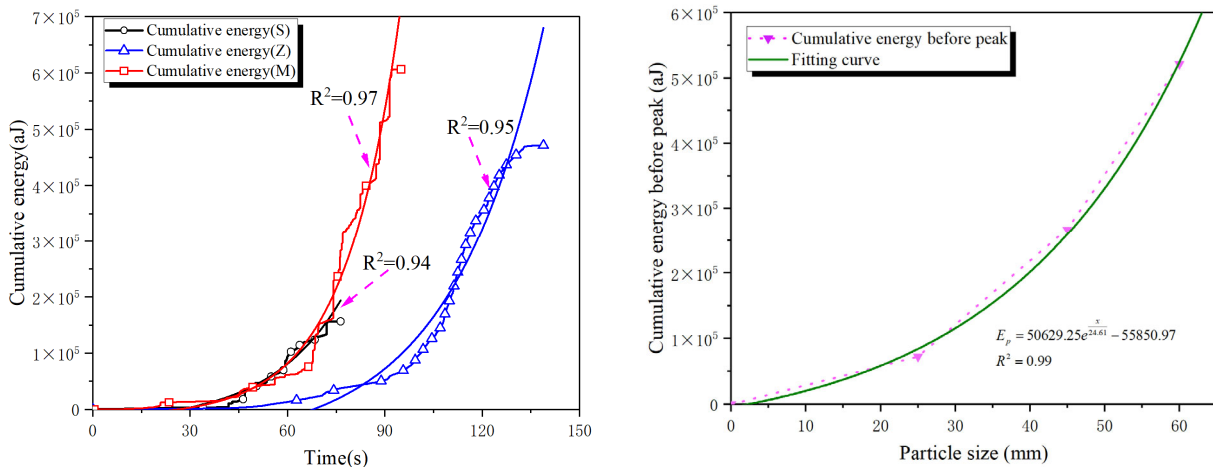


Figure 7. Comparison of cumulative AE energy curves (a) and relationship between pre-peak cumulative AE energy and particle size (b)

As shown in Fig. 6(a), the comparison curves of acoustic emission (AE) energy with displacement for conglomerate specimens of different grain sizes, the variation of AE energy has a good correspondence with the shear parameters such as peak load and peak normal displacement. Although the trends

of AE energy with time are basically the same for specimens of different grain sizes, they all increase sharply near the peak load. Fig. 6(b) further shows that, similar to the variation rule of peak load, the peak AE energy of the specimens shows a slow growth trend with the increase of grain size. The peak

elastic strain energies of the specimens of each grain size at the time of damage were 18619, 23696 and 65535, whose increases were 27.28% and 251.98%, respectively. Among them, the Z specimens showed the largest increase in peak energy. The accumulated acoustic emission (AE) energy reflects the damage strength of the rock under external or internal forces. Fig. 7(b) shows that the cumulative AE energy before the peak is consistent with the OD segment of the cumulative curve in Fig. 5. As seen in Fig. 7(b), the accumulated AE energy of the specimens before the peak load shows a growing trend as the grain size increases, which is different from the change rule of the peak AE energy. At the peak load, the cumulative AE energy shows an exponential growth, and the growth is more significant with the increase of particle size. This is mainly due to the fact that the energy transfer is simple and direct in the smaller particle size specimens, and part of the energy is rapidly dissipated or transformed through fewer paths. In contrast, the energy transfer process within and between particles is more complex in larger specimens due to the larger size of the particles, with more branching paths, reflections and scattering phenomena. The complex energy transfer process results in more energy being converted into AE energy, and at the same time, the AE energy shows an exponential increase due to the delayed energy transfer and accumulation effects.

The evolution curves of peak point AE energy, pre-peak cumulative AE energy and cumulative AE energy with particle size can all be expressed as exponential functions:

$$E = A_1 e^{B_1 t} + C \quad (1)$$

Where: parameters A_1 , B_2 , C were determined when fitting the curves. From Fig. 6(a), Fig. 7(b) and Fig. 8, it can be seen that the fit of the experimental results is high, which can represent the change rule of AE energy, and the correlation coefficients are 0.88, 0.99, and 0.97, respectively, with high correlation.

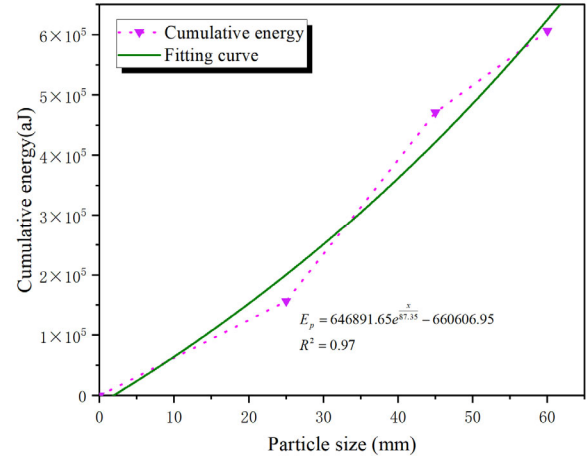
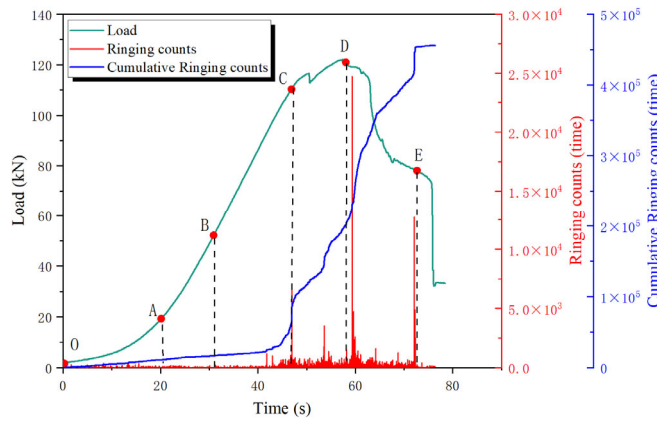


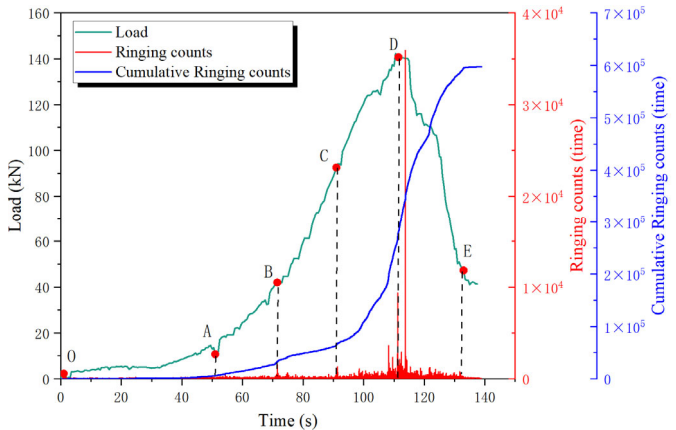
Figure 8. Relationship between particle size and cumulative energy of acoustic emission

3.2. Acoustic emission ringing counts

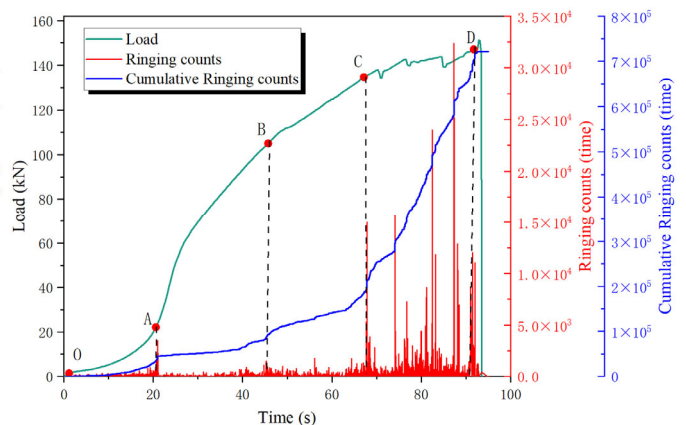
AE ringing counts characteristics are similar to AE energies and can be substituted for each other to some extent. The ringer counts can effectively reflect the activity of rupture events within the assemblage as well as the accumulated damage. Fig. 9 shows the acoustic emission ringing count characteristics for different grain sizes.



(a) S1 Fine-grained conglomerate



(b) Z1 medium-grained conglomerate



(c) M1 coarse conglomerate

Figure 9. Acoustic Emission Ringing Counts Characteristic Diagram of Different Particle Size

Through comparative analysis, it can be seen that the change rule of AE ringing counts is basically consistent with the AE energy characteristics. In the pre-peak load period, the AE ringing counts are small, and the AE cumulative ringing counts curve rises gently, indicating that the AE events rarely occur at this stage, and the AE ringing counts show a surge when the load reaches the peak, which indicates that the

cracks inside the specimens at this stage are rapidly penetrated to form the main crack surface under the action of the force. Afterwards, the AE ringing counts return to calm with the load reduction, but the cumulative AE ringing counts still keep increasing, but there are few more prominent ringing signals.

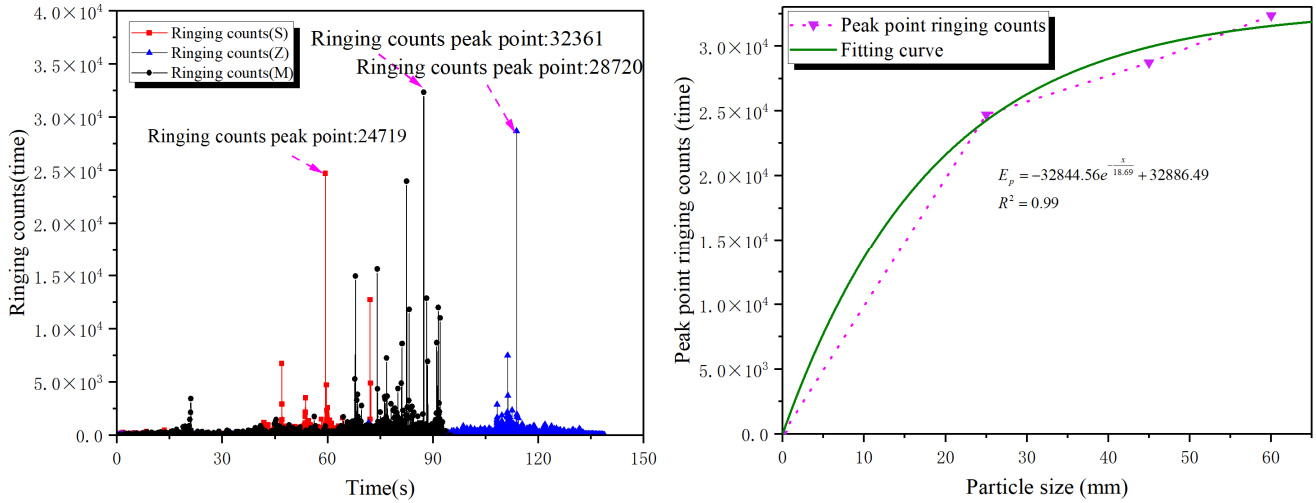


Figure 10. AE ringing count curves of different particle sizes (a) and the relationship between peak AE ringing count and particle size (b)

The change curves of AE ringing counts with displacement for different grain sizes and the relationship between peak AE ringing counts and grain sizes are shown in Fig. 10, and it can be found that the change rule is similar to the acoustic emission energy characteristics. The peak point ringing counts at the destruction of different grain sizes are 24717,

28720, 32361, and their growth rate is 16.20%, 30.93%, respectively. It can be seen that with the increase of particle size, the peak point ringing counts of the specimens also increased gradually, and the growth trend of AE peak ringing counts is preserved consistently.

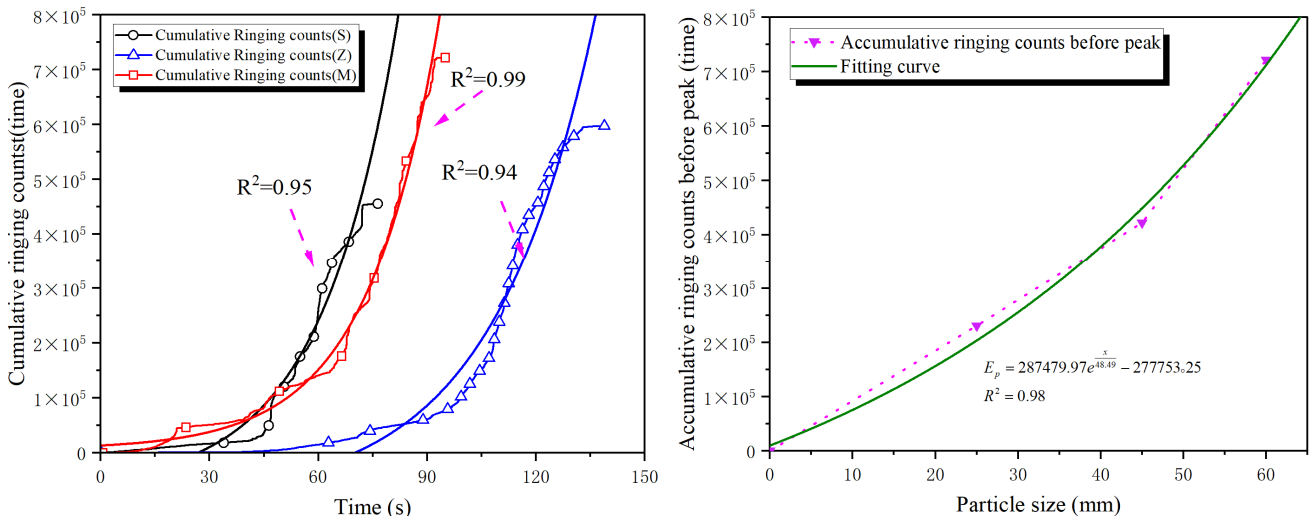


Figure 11. Comparison of cumulative AE ringing count curves (a) and relationship between pre-peak cumulative AE ringing count and particle size (b)

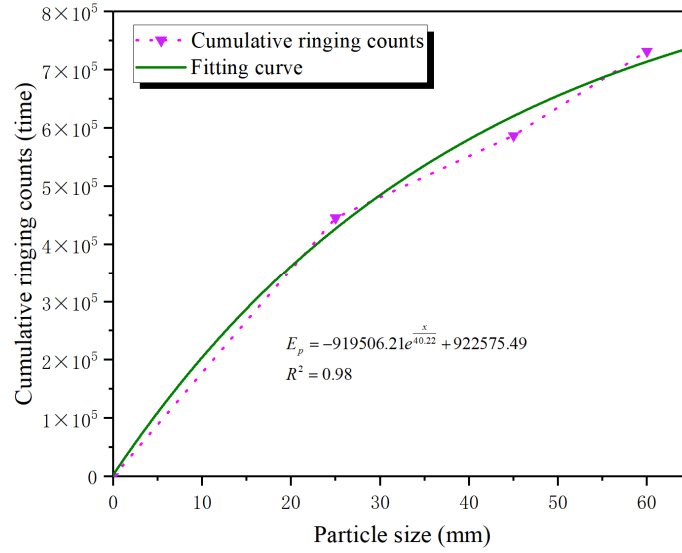


Figure 12. Relationship between particle size and cumulative ringing count of acoustic emission

Fig. 10(b), Fig. 11(b) and Fig. 12 illustrate that the acoustic emission ringing counts of conglomerate specimens increase exponentially with the increase of grain size, and the peak ringing counts, the cumulative ringing counts before the peak, and the total cumulative ringing counts are all positively correlated with the grain size. This is mainly due to the increase in the interstitial space of particles with larger particle size, which leads to a more complex energy transfer process, more intense local load concentration and crack extension, thus releasing more energy and generating more acoustic emission events.

3.3. Evolution analysis of damage variable D based on AE events

The AE phenomenon of rock materials is the generation and development of its internal microfractures and pores, and it is closely related to the damage state of the rock, therefore, scholars have carried out a lot of research work combining the relationship between AE parameters and rock crack evolution [15]-[17], and the damage state of the rock is described by AE parameters. For the deterioration damage state of rock materials, the damage variable D is usually used to describe, Kachanov defines the damage variable D as the ratio of the defect area on the loaded cross section of the material to the total area when it is not damaged, and the expression of the damage variable D for rocks is as follows:

$$D = \frac{A_d}{A} \quad (1)$$

Where: A_d denotes the cumulative projected area of existing damage in a cross-section orthogonal to the direction of the principal stresses, and A denotes the area in the undamaged state.

The generation of AE events mainly originates from the generation of microcracks within the material, with a certain degree of being able to approximate the characterization of

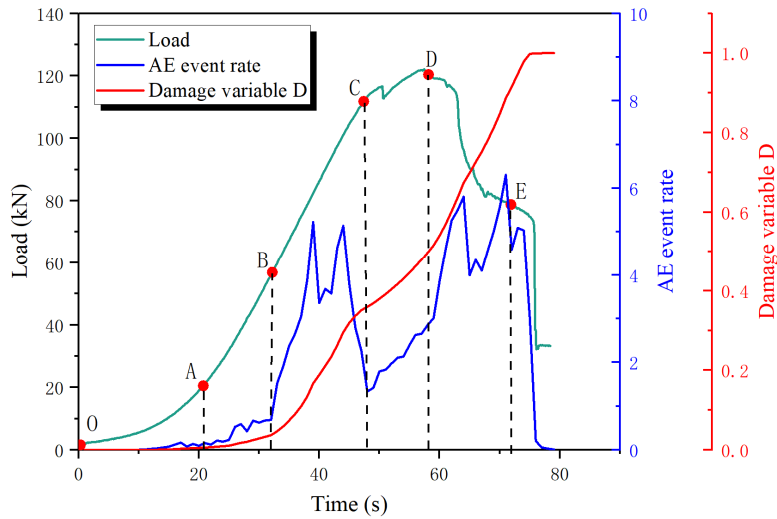
the damage variable D [18], assuming that there is no obvious initial damage within the material, and that the cumulative number of AE events at the time of complete destruction of the cross-section is N_m , then the rate of AE events per unit area is η_v , which can be expressed as follows:

$$\eta_v = \frac{N_m}{A} \quad (2)$$

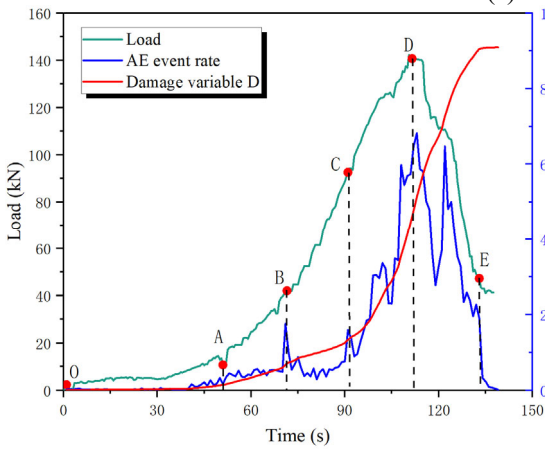
Therefore, the relationship between the number of AE events and the damage variable D can be described as follows :

$$D = \frac{N}{N_m} \quad (3)$$

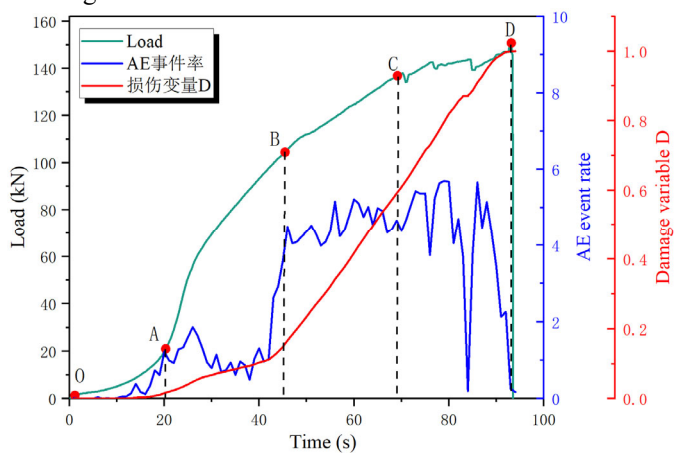
Equation (3) is an ideal model to characterize the relationship between AE events and damage variables, which requires the initial state of the material to be damage-free, i.e., Equation (2) requires that the AE events all come from the generation and expansion of cracks, while in the actual test process, due to the existence of a small number of primary microfracture defects within the rock, there are still a small number of AE events generated during the crack closure process. The specimens are conglomerate materials with different grain sizes, the porosity is generally at a lower level, and only a small number of AE events are generated before the closure strength, which has no obvious effect on the overall regularity of the calculation results. In order to simplify the solution process, the focus is on discussing the damage law of the various stages before the peak strength, and no discussion is made about the part of the post-peak residual strength during the solving process. According to the equation (3) for different grain size conglomerate damage variable D to calculate the solution, each group of grain size conglomerate selected AE signal acquisition is more stable in two cases to draw the damage variable D and AE event rate curve shown in Fig. 12.



(a) S1 Fine-grained conglomerate



(b) Z1 medium-grained conglomerate



(c) M1 coarse conglomerate

Figure 12. Damage variable D and AE event rate of conglomerate specimens with different particle sizes.

In Fig. 12, the AE event rate reflects the number of AE events per unit of time in the rock damage process, which can better indicate the rate of crack generation and expansion; the damage variable D based on the characterization of the number of AE events is able to qualitatively analyze the degree of rock damage, the damage rate, and the main stages of damage. Based on the research of existing scholars on rock damage and damage variable D, the damage behaviors of conglomerate specimens with different grain sizes were analyzed by combining the change rules of AE event rate and damage variable D.

(1) Evolution of AE event rate and damage variable D

In the initial loading stage, the rock is in the crack closure state, the AE event rate is low, and the damage variable D does not change significantly, indicating that the rock is not obviously damaged at this time. When the loading exceeds the crack closure strength, the rock enters the elastic deformation stage, and the AE event rate and damage variable D start to rise gradually, which is characterized by the dominant elastic deformation and accompanied by a small amount of plastic damage. Close to the crack initiation strength, the damage variable D curve shows an obvious inflection point, the AE event rate and damage variable D increase sharply, the crack expansion rate inside the rock accelerates, and the deformation gradually turns into plastic crack deformation. As the load approaches or exceeds the damage intensity, the AE event rate decreases sharply, the damage variable D reaches a high level, and the rock enters a stage of unstable development with fewer large-scale cracks, and ultimately

loses its load-bearing capacity until it reaches peak damage.

(2) The effect of grain size on AE event rate

The AE event rates of conglomerate specimens with different grain sizes differed significantly from each other, with relatively low AE event rates for conglomerate specimens of group S, and high AE event rates for conglomerate specimens of groups Z and M during the whole damage process, indicating that larger grain sizes are accompanied by more microcracks and expansion during the damage process. Specifically, in the initial compaction stage, the AE event rates of all grain sizes are low, and the rocks are in the state of crack closure. When entering the elastic deformation stage, the AE event rate starts to increase, in which the inflection point of the AE event rate growth of the conglomerate specimens of group S is close to the crack initiation intensity, while the inflection point of the conglomerate specimens of group Z and group M is earlier. Especially, the coarse-grained conglomerates are accompanied by larger fluctuations of AE event rates in the elastic phase, indicating that the phenomena of crack initiation and closure are more significant in rocks with larger grain sizes. After exceeding the crack initiation intensity, the AE event rate decreases and rapidly drops to a very low level between the damage intensity and the peak intensity, at which time the cracks enter the unstable expansion stage, and the AE events mainly come from large-scale crack extension penetration, which eventually manifests as macroscopic crack damage.

(3) Effect of grain size on the evolution pattern of damage

variable D

In the crack closure stage, the damage variable D of conglomerate specimens with three grain sizes did not change significantly, indicating that no significant damage occurred in the rock at this time. After entering the elastic deformation stage, the damage variable D shows an obvious growth inflection point and is consistent with the growth inflection point of the AE event rate. The inflection point of the growth of the damage variable D for fine-grained conglomerate is close to the crack initiation strength, while the inflection point for medium- and coarse-grained conglomerate is earlier, indicating that the rocks with larger grain sizes are more prone to incipient damages during the loading process. When the load exceeded the crack initiation strength, the damage variable D increased rapidly for the three grain sizes. As the load reaches the damage intensity, the rock approaches damage. At this time, the D value of coarse-grained conglomerate is close to the maximum level, the medium-grained conglomerate is slightly lower, and the D value of fine-grained conglomerate is significantly lower. It can be seen that for the same type of rock, the fine-grained conglomerate still maintains a strong bearing capacity after reaching the damage strength, while the rock with larger grain size is close to the peak damage state after the load exceeds the damage strength, and the bearing capacity is poor.

In summary, the grain size has a significant effect on the

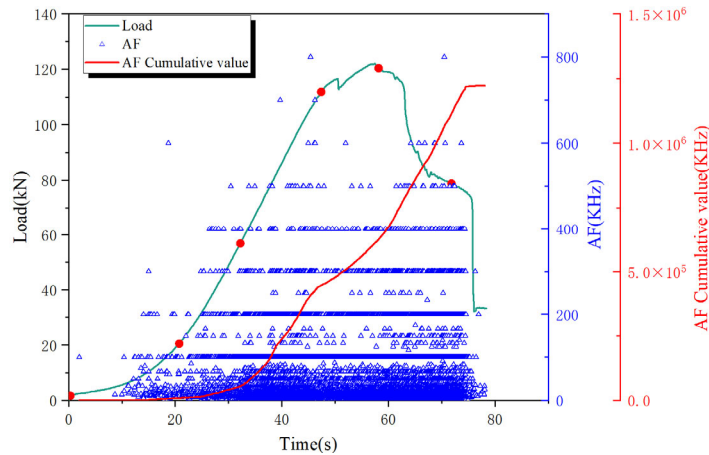
evolution pattern of AE event rate and damage variable D. Conglomerates with larger grain sizes showed more microcrack generation and expansion during the damage process, faster growth rates of AE event rate and damage variable D, and greater volatility in the damage process. In contrast, the damage process of fine-grained conglomerates is smoother, the growth of AE event rate and damage variable D is slower, and the bearing capacity still maintains a high level before damage.

4. Analysis of Crack Evolution Types of Conglomerate with Different Particle Sizes

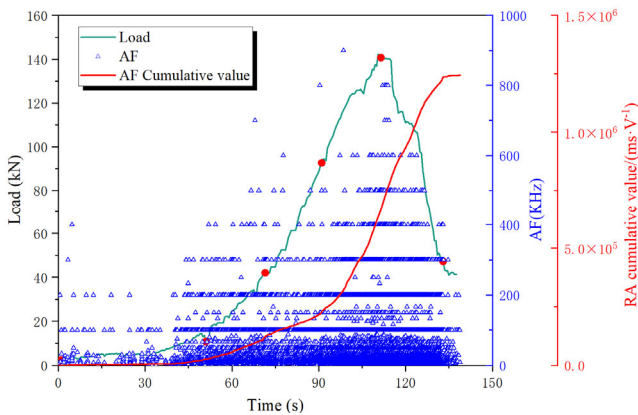
4.1. AF Value Characteristic Analysis

The AF values and AF statistical values of conglomerate specimens with different grain sizes were calculated, and one specimens with more stable AE signal acquisition was selected from each group to plot its AF values and AF statistical curves, and the results are shown in Fig. 13.

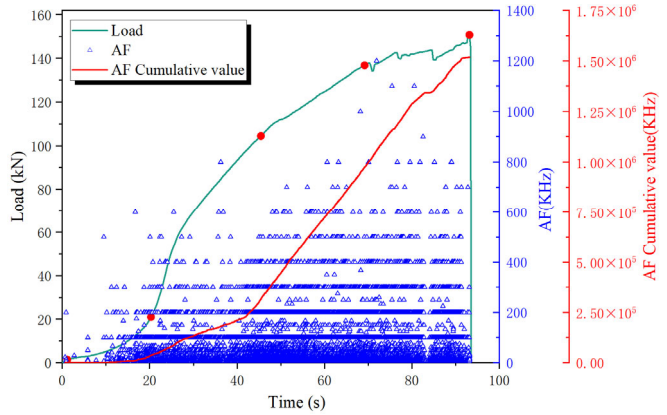
According to the AF value, AF statistical value, and the change rule of the load curve of different characteristic strength intervals in Fig. 13, the AF evolution law of the damage process of conglomerate specimens with different grain sizes is discussed.



(a) S1 Fine-grained conglomerate



(b) Z1 medium-grained conglomerate



(c) M1 coarse conglomerate

Figure 13. AF and AF cumulative values of conglomerate specimens with different particle sizes

(1) Characterization of AF values at different damage stages

In the initial compression stage, the AE events mainly come from the closure of primary cracks, at this time, the AF

value of the specimens have large fluctuations, indicating that the form of primary crack structure is different, and the closure process is accompanied by a large variability in the average frequency of the AE signal.

After the elastic-plastic stage, the specimens is dominated by elastic deformation, and the AE events mainly come from the emergence of a small number of microcracks, and the fluctuation of the AF value at this stage gradually decreases and the overall performance is a slow downward trend, which indicates that the internal microcracks in the rock at this time tend to converge in the form of generation.

When the load exceeds the crack initiation strength, the rock enters the linear elasticity stage, and most of the AE events come from the expansion of microcracks. The AF values at this stage are more stable compared with the previous stage, indicating that the internal cracks of the rock enter a stable state at this stage, and the crack expansion forms are basically consistent.

When the load exceeds the damage strength, the crack enters the unstable propagation stage, and the bearing capacity of the specimens decreases rapidly and tends to be unstable. At this time, the AF value shows a slight upward trend with a small amount of fluctuation.

(2) Influence of grain size on the evolution of AF values

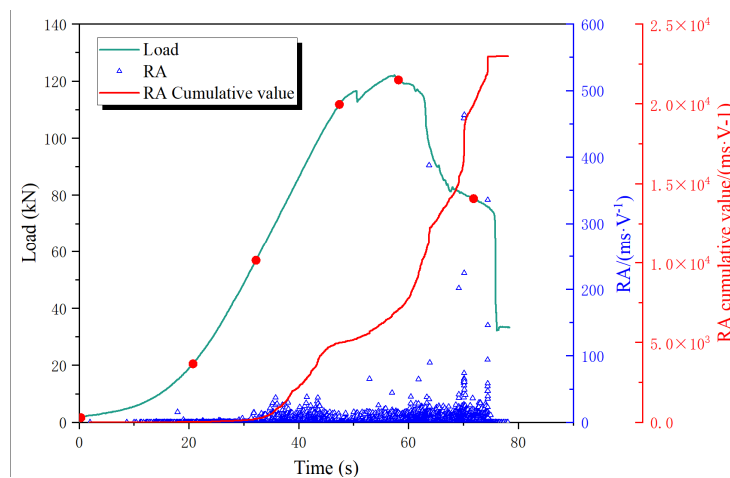
The overall trend of AF value in the rock damage process is basically the same, but there are still some differences in the evolution law of AF value corresponding to different grain sizes, which is mainly reflected in the fact that when the load exceeds the damage strength, the crack enters into the stage of unstable expansion, and the AF value of different grain sizes shows a rising trend, and the overall trend is the same, but the AF value of the fine-grained conglomerate specimens

is relatively stable without significant fluctuations, indicating that the crack expansion form is relatively stable, while the medium- and coarse-grained conglomerate specimens with larger grain size show more substantial fluctuations, indicating that at this time, the crack expansion is relatively stable. However, the AF values of fine-grained conglomerate specimens are relatively stable without significant fluctuations, indicating that the crack extension is relatively stable, while those of medium- and coarse-grained conglomerate specimens with larger grain sizes show larger fluctuations, indicating that the crack extension is more complicated at this time.

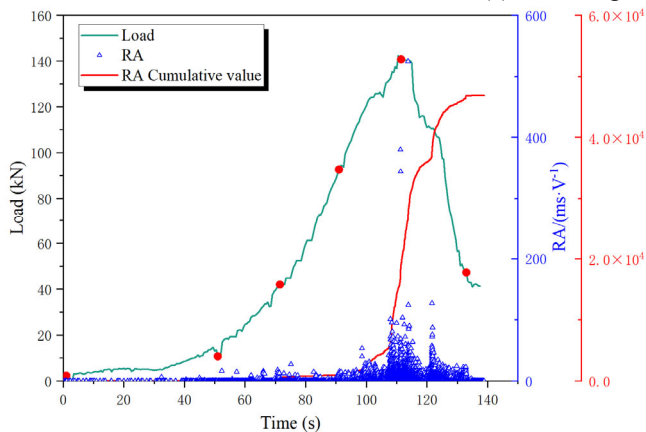
Therefore, the expansion of internal cracks in rocks with larger grain sizes is more complicated when they are close to destruction.

4.2. RA Value Characteristic Analysis

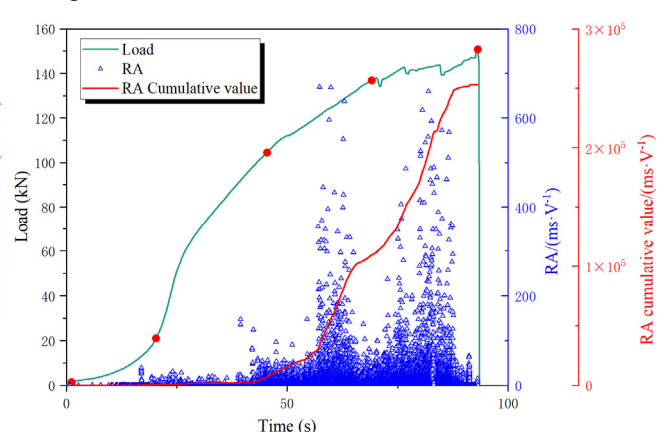
The RA values and RA statistics of conglomerate specimens with different grain sizes were calculated, and two specimens with more stable AE signal acquisition were selected from each group to plot their RA values and statistics curves, and the results are shown in Fig. 13. According to the RA value, RA statistical value, and the change rule of the stress curve in different characteristic intensity intervals in the figure, the RA evolution law of the damage process of conglomerate specimens with different grain sizes is discussed.



(a) S1 Fine-grained conglomerate



(b) Z1 medium-grained conglomerate



(c) M1 coarse conglomerate

Figure 13. RA and RA cumulative values of conglomerate specimens with different particle sizes

(1) Analysis of the evolution law of RA value
In the crack closure stage and elastic deformation stage, the

overall distribution of RA value is at a very low level and the fluctuation amplitude is small, i.e., the rise time of the AE

signal is more stable than the amplitude, which indicates that the shear crack in the crack form of this process accounts for a relatively small number of cracks; when the load exceeds the fracture initiation strength, the crack enters into the stage of stable expansion, and the RA value begins to show a slow rising trend; when the load is close to the damage strength, the RA value shows a surge state, rapidly increasing to a very high level, at which time the rock bearing capacity rapidly decreases, approaching the state of destabilization and damage. Therefore, it is considered that the surge state of RA value can be used as one of the reference factors for the precursor of rock rupture.

(2) Influence of grain size on the evolution of RA values

The overall trend of RA value in the whole process of rock damage is basically the same, but there are still some differences in the evolution of RA value of different grain sizes corresponding to different stages of damage, which are mainly reflected in the starting point of RA value and the form of surge as a precursor of damage.

For the starting point of RA value, the fine-grained conglomerate specimens with smaller grain sizes were roughly distributed after the damage intensity, while the starting point of RA value of medium and coarse-grained conglomerate specimens with larger grain sizes were basically distributed between the crack initiation intensity and the damage intensity, which indicated that the emergence of large-scale cracks during the loading process of the specimens with smaller grain sizes was more lagged than that of the specimens with larger grain sizes.

For the RA value surge as a precursor of damage, the growth trend of fine-grained conglomerate specimens with smaller grain sizes is more stable without obvious fluctuations,

while for medium and coarse-grained conglomerate specimens with larger grain sizes, there are larger fluctuations in the surge process, which indicates that the internal cracking morphology of the specimens with larger grain sizes is more complex in the proximity to the instability damage, which is in line with the conclusions obtained from the analysis of the AF value.

4.3. Analysis of crack failure form of conglomerate

The principle of using the RA value and AF value during rock damage to determine the fracture mechanism of rock is shown in Fig.14. JCMS-III b5706 (2003) (Japan Concrete Materials Association) [19] considers $y=x$ as the straight line distinguishing between tensile and shear cracks, and the data points located on the upper side of the straight line represent the tensile crack damage, while the data points on the lower side of the line represent the shear crack damage. At present, there are more methods to distinguish the boundaries of tension damage and shear damage, but most scholars and researchers believe that the straight line $y=x$ is a more reasonable boundary. Therefore, generally using the straight line $y=x$ as the boundary, the acoustic emission RA value as the horizontal coordinate and the AF value as the vertical coordinate, after normalizing the acoustic emission data, the rupture mechanism of the rock at a certain moment can be judged as a whole by the position of the acoustic emission feature points during the rock damage. The acoustic emission events corresponding to tensile rupture are located on the upper side of the line $y=x$, while the acoustic emission events corresponding to shear rupture are located on the lower side of the line $y=x$.

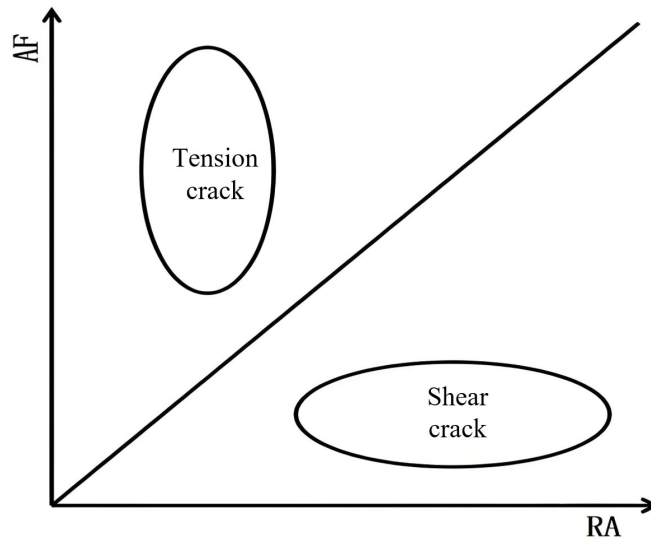
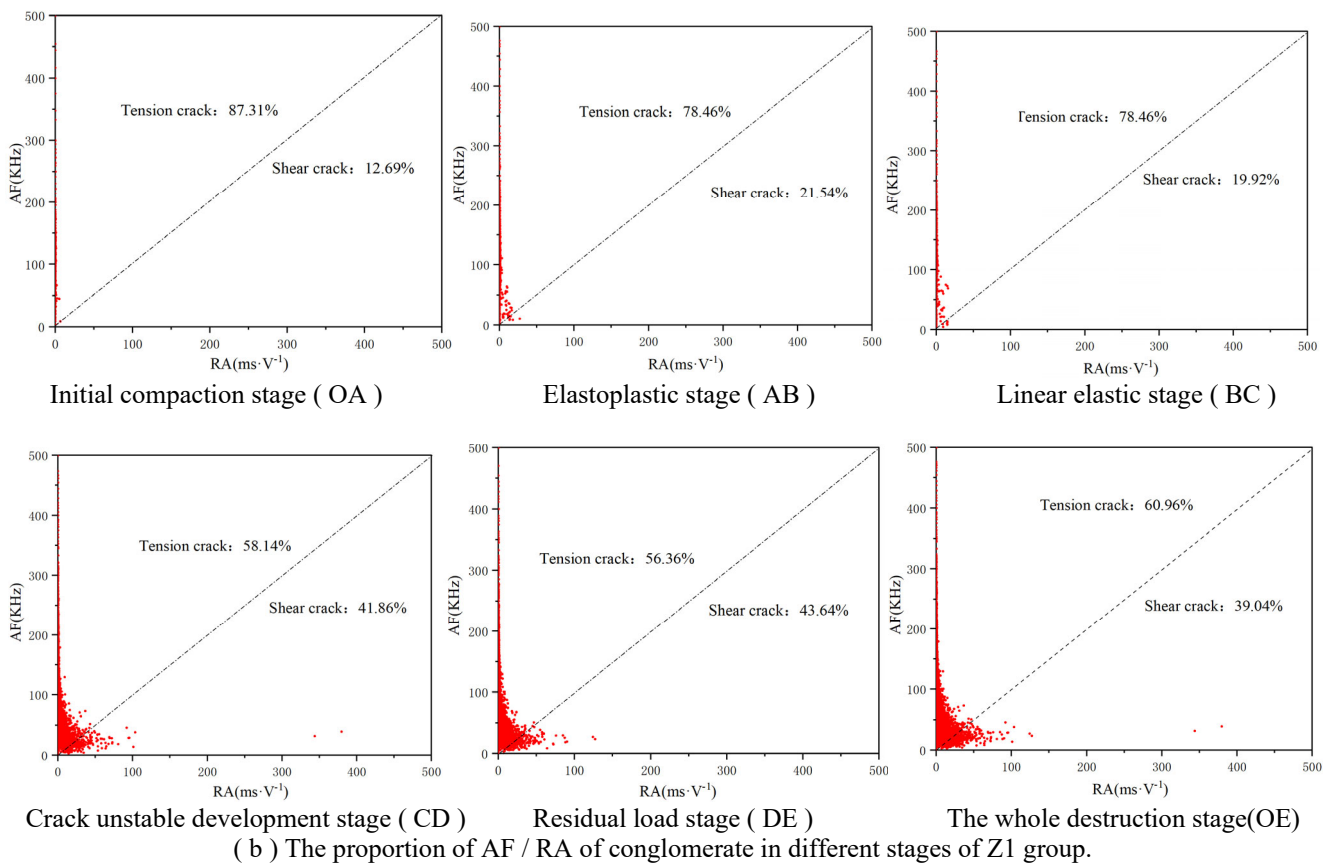
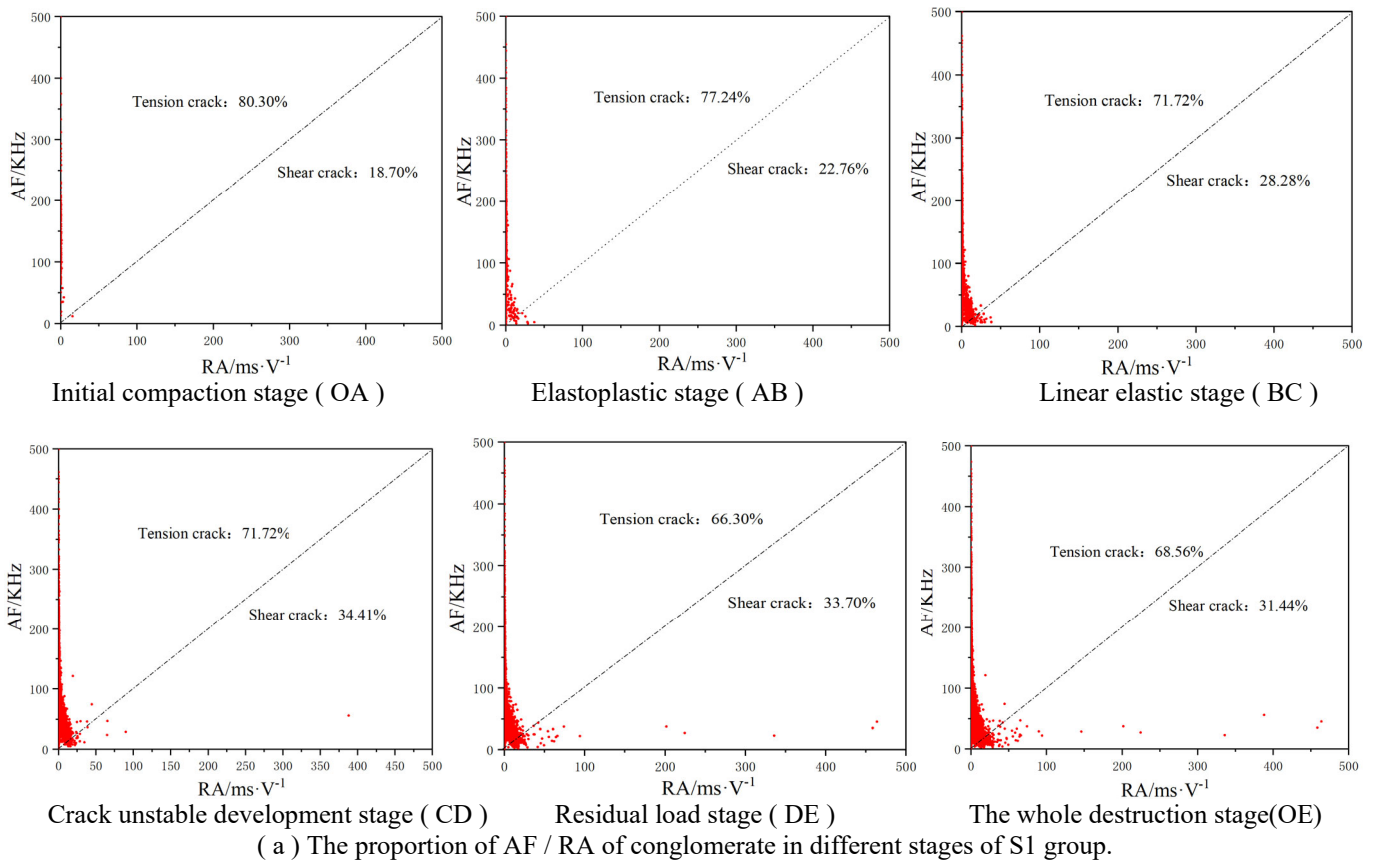


Figure 14. Rock fracture mechanism diagram

Grain size can influence the generation, development, expansion and penetration of microcracks within the rock, affecting the internal structure of the rock and the form of damage at the time of destruction. The ratio of the rise time to the amplitude of the rock acoustic emission is the RA value of the rock (equation 4):

$$RA = \frac{\text{Rise time}}{\text{Amplitude}} \quad (4)$$

Calculate the AF-RA values of conglomerate specimens with different grain sizes, the distribution of AF-RA in each damage stage of each group of grain size specimens is basically the same, and 1 case of each group of grain size specimens is selected to draw the scatter distribution map of AF-RA in the damage stage, and the results are shown in Fig. 15.



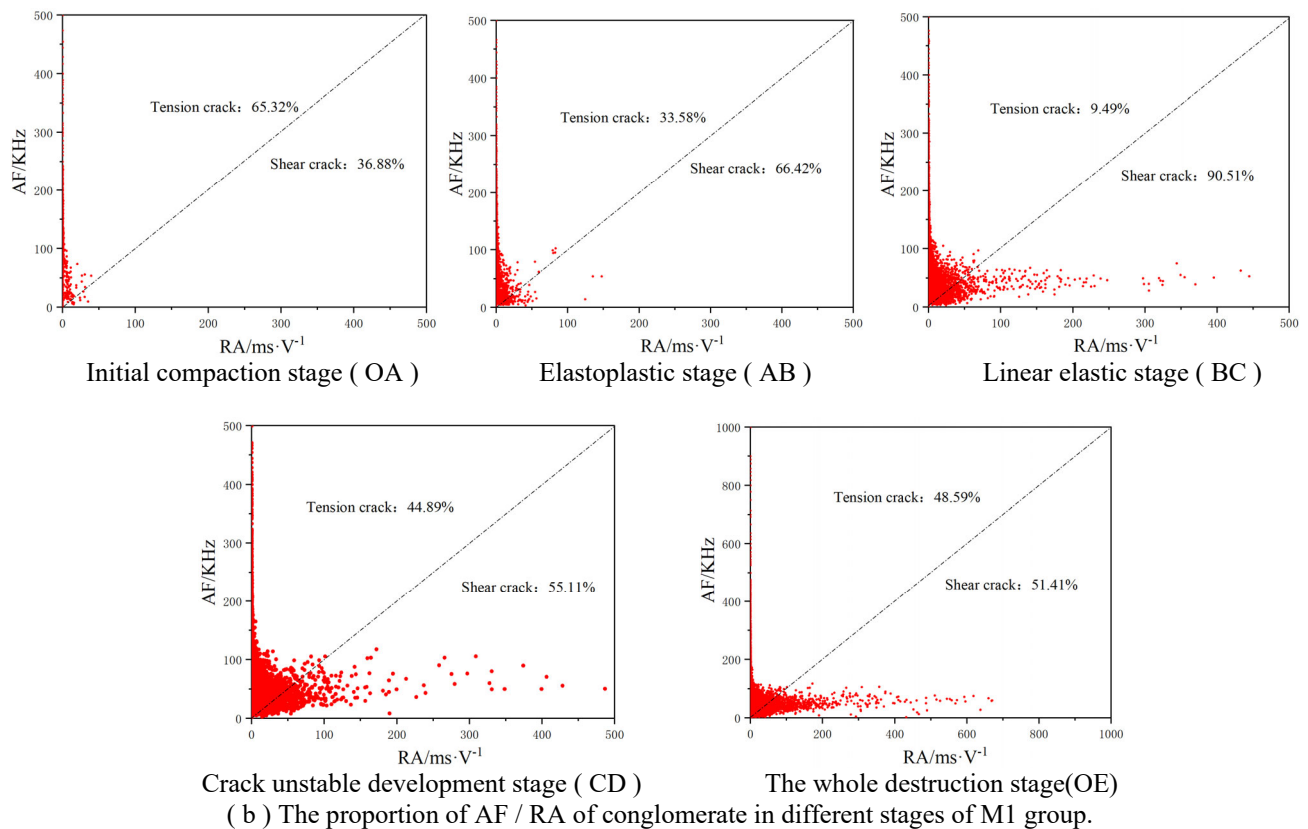


Figure 15. The proportion of AF / RA in conglomerate at different stages

The AF-RA scatter distribution patterns of conglomerate specimens with different grain sizes are analyzed as follows:

In the crack compaction stage (OA), in which the AE events mainly originate from the closure of primary cracks, the AE event rate of the specimens is low. The fine-grained specimens have the lowest number of AE events, while the medium- and coarse-grained specimens have slightly more AE events, and the scatters are mostly distributed in the upper half of the AF-RA plot. This phenomenon suggests that the crack closure process of conglomerate specimens is similar to tensile cracking, and the distribution of cracks in fine-grained specimens is less.

In the elastic deformation stage (AB), the rock deformation is mainly elastic, accompanied by a small amount of microcrack generation. At this time, the AE events mainly originated from the germination and expansion of microcracks, and the AF-RA scatters were distributed in both the upper and lower parts, indicating that the crack forms included tensile cracks and shear cracks.

In the stage of crack stabilization and expansion (BC), the number of cracks increased significantly and the AE events increased. The crack forms of the fine-grained conglomerate specimens still include tensile and shear cracks, while the cracks of the medium- and coarse-grained specimens are mainly shear cracks with relatively few tensile cracks.

In the stage of unstable crack extension (CD), when the load exceeds the damage intensity, the rock approaches peak damage and the AE events surge. The AF-RA scatters of the three grain sizes of the specimens are distributed in both the upper and lower parts, but the distribution in the lower part is more concentrated, indicating that the crack form is dominated by shear cracks accompanied by a small amount of tensile cracks when approaching damage.

In the residual load stage (DE), after the peak load, the conglomerate with fine-grained and medium-grained grain

sizes showed strong residual bearing capacity and exhibited plastic damage characteristics. The coarse-grained conglomerates do not have this stage and show brittle damage characteristics. Due to the large number and uniform distribution of contact points between particles, when the rock is damaged to a certain extent, the contact force can be adjusted to maintain a certain bearing capacity. At this stage, tensile cracks dominate, while shear cracks account for a relatively low percentage (about 30%). This is due to the fact that the local stress concentration is more likely to lead to the expansion of microscopic tensile cracks.

Coarse-grained conglomerates have larger particles with fewer and sparsely distributed contact points. At the peak load, a few critical contact points bear most of the stress, and once the bearing limit is exceeded, the structure will be rapidly destabilized, triggering overall damage. Since the stress transfer between particles is not as uniform as that of fine-grained and medium-grained specimens, the coarse-grained specimens do not have an obvious residual load stage after the peak load, but rather a sharp drop. In addition, the damage process of the coarse-grained grain size conglomerate is mainly dominated by shear damage, with relatively little tensile damage. This is due to the fact that shear stresses are more easily generated on the contact surface of large grains, and when the shear stress exceeds the shear strength, shear cracks rapidly expand to dominate the damage.

Through comparative analysis, it is found that with the increase of grain size, the acoustic emission characteristic points located below the straight line $y=x$ in the AF-RA diagram increase, indicating that the shear damage accounts for an increased proportion in the whole loading and damage process. The damage characteristics of the coarse-grained grain size conglomerate show that shear cracks dominate and tensile cracks are supplementary.

5. Conclusion

(1) Under uniaxial loading, conglomerates with different grain sizes show different acoustic emission (AE) energies and ringing counts. As the grain size increases, the AE energy and ringing counts of conglomerates increase, and conglomerates with large grain sizes show stronger shear damage characteristics in the damage process.

(2) For the same type of rock materials, the damage process of rocks with larger grain size is accompanied by a higher AE event rate; when the load exceeds the strength, the specimens with smaller grain size has a lower damage variable D , which indicates that the rock with smaller grain size has a higher load-bearing capacity after the damage strength; before approaching the destabilizing damage, the AE event rate exhibits an abrupt decrease.

(3) The evolution law of AF value in the whole process of rock damage is roughly fluctuating at a high level first, then gradually decreasing and stabilizing, and slightly increasing before the damage, while the evolution law of RA value is roughly at a low level in general, and surging before the damage, therefore, the increase of AF value after the stable state and the surge of RA value can be taken as one of the precursor indexes of the destabilization damage of the rock.

(4) The dominant forms of cracks in conglomerate specimens before crack initiation strength include tensile cracks and shear cracks, and the forms of cracks in the proximity of destabilization damage are dominated by shear cracks, accompanied by part of the tensile cracks, and the surge phase of shear cracks appears after the crack initiation strength for medium and coarse grain specimens with large grain sizes and after the damage strength for specimens with small grain sizes. For the smaller grain size specimens, the surge phase of shear crack occurs after the damage strength.

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