Study on Acoustic Emission Characteristics and Damage Evolution Law of Red Sandstones under Different Loading Rates

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Abstract: Uniaxial compression experiments with different loading rates and acoustic emission tests were conducted to study the loading rate effects on the mechanical and acoustic emission characteristics of red sandstones. The mechanical and acoustic emission parameters of red sandstones were analyzed with varying loading rates. Furthermore, the red sandstone damage evolution model was established based on the acoustic emission cumulative ringing count. The results show that: (1) The elastic modulus decreases linearly with the increase of the logarithm of loading rate, while the peak strength generally shows a gradually increasing trend with the logarithm of the loading rate. (2) With the increase of loading rate, the AE event rate's peak value increases gradually, and the cumulative number of AE events decreases. (3) The evolution law of the characteristic stresses determined by the AE event rate and cumulative AE event number is the same as that of the loading rate. That is, with the increase of the loading rate, it shows a gradually decreasing evolution trend. (4) The damage evolution model of red sandstone can better describe the damage evolution process of red sandstone. According to the evolution characteristics of damage variables, the damage evolution process of red sandstone can be divided into three stages: the initial damage stage, the damage stable development stage, and the damage accelerated stage. (5) The damage variable at the damage stress point can reflect the actual damage degree of rock, and the size of the damage variable is closely related to the initiation, propagation, and transfixion of microcracks inside the rock. When the loading rate is low, the damage degree of red sandstone at the damage stress is usually more prominent because the rock's microcrack develops more fully.

Keywords: red sandstone; loading rate; acoustic emission; characteristic stress; damage evolution

1. Introduction

In water conservancy and hydropower projects, highway tunnel projects, and mining projects, the rate of change of rock loading, induced by excavation and unloading, blasting vibration, and tectonic extrusion, has a significant impact on rock strength and deformation, which is a potential risk factor for a series of engineering geological disasters. It is of great engineering significance to study the
influence of loading rate on the mechanical properties of rocks. Fuenkajorn and Wisetsaen[1-2] studied the strength and deformation characteristics of salt rocks under different loading rates, and the results showed that the elastic modulus and strength of salt rocks increased with the increase of loading rate, and the strain at rock destruction gradually decreased with the increase of loading rate. The loading rate also has an essential influence on the acoustic emission characteristics in the process of rock failure. Deyi Jiang [3] studied the acoustic emission characteristics of salt rocks at different strain rates and found that the faster the loading rate, the lower the cumulative acoustic emission signal and the higher the acoustic emission frequency. Filimonov[4] performed uniaxial compression tests on the salt rock with a loading rate ranging from 0.05 to 1 MPa/s. The results showed that the AE impact rate reached the maximum at the highest loading rate, while the cumulative number of AE impacts was the largest at the low loading rate. In order to better understand the evolution of rock damage. Xianzhen Wu[5] studied the relationship between acoustic emission characteristics and its parameters with stress, strain, and damage variables under different damage modes of rocks. Baoxian Liu[6] conducted uniaxial compression acoustic emission tests on coal rocks, established a damage model based on acoustic emission characteristics, and derived damage evolution curves and equations for coal rocks.

In summary, a wealth of results have been obtained from indoor experimental studies on the mechanical properties and acoustic emission characteristics of rocks affected by loading rates. However, there are few researches on the joint analysis of the dependence of loading rate from the aspects of acoustics, mechanics and evolution process. Therefore, it is necessary to jointly analyze the effect of loading rate on red sandstone from various aspects. In this paper, we systematically analyze the mechanical properties and acoustic emission characteristics of rocks under different loading rates of uniaxial compression to investigate the damage evolution law during rock deformation and damage, taking red sandstone as the research object.

2. Test protocol
The red sandstone used in the test is taken from a mine in southern Jiangxi. The RMT-150C rock mechanics test system conducts the uniaxial compression test, and the YJZ-16+ intelligent digital strain gauge and Micro-II Digital AE System acoustic emission system are used for the acquisition of stress-strain information and acoustic emission signal, respectively. Two acoustic emission sensors were arranged in the middle of the vertical height of each rock sample, as shown in Figure 2. The type of transducer used for this acoustic emission signal acquisition is UT1000, which has a resonant frequency of 60~1000 kHz, a preamplification of 40 dB, a threshold voltage value of 35 dB, and a sampling rate of 1 MSPS. Four loading rates are set, 0.001mm/s, 0.005mm/s, 0.02mm/s and 0.1mm/s, and three tests are conducted for each loading rate.

![Figure 1. Schematic diagram of the experimental process](image-url)
3. Test results and data analysis

3.1. Mechanical properties of red sandstone under different loading rates

Figures 3 and 4 show the distribution of peak strength and modulus of elasticity versus the logarithm of loading rate, respectively. As shown in figure 3, the strength characteristics of rock samples under uniaxial compression are closely related to the loading rate. In a specific loading rate range, the peak strength shows a gradually increasing trend. The correlation coefficient between the mean value of peak strength and the logarithm of loading rate is satisfied: \[ \sigma_c = 71.19 - 5.088(\lg V) - 2.75(\lg V)^2. \]

From figure 4, it can be seen that the elastic modulus shows a linearly decreasing trend with the increase of the logarithm of the loading rate, indicating that the resistance to deformation of the red sandstone specimens weakened. The average value of elastic modulus and the logarithm of loading rate satisfy: \[ E = 9.13 - 0.76(lg V). \] The reason for the above phenomenon is that at a lower loading rate, the initial damage and primary fracture inside the rock sample can be fully evolved and developed, and its peak elastic energy is small. When the loading rate increases, the time required for the rock sample to reach the peak strength is shortened, and the microfracture inside the rock sample does not have time to expand further before a brittle fracture occurs, and the peak elastic energy is larger.

![Figure 3](image3.png)  
**Figure 3.** Curve of peak strength versus logarithm of loading rate

![Figure 4](image4.png)  
**Figure 4.** Curve of modulus of elasticity versus logarithm of loading rate

3.2. Acoustic emission characteristics of red sandstone deformation and damage processes under different loading rates

Figure 5 shows the stress, AE event rate, cumulative event number versus time curves for uniaxial compression conditions in red sandstone at each loading rate. From Figure 5, it can be seen that the evolution pattern of the AE event rate is similar under different loading rates. At the beginning of loading, the AE event rate starts to increase in a small way, and the cumulative AE event number curve slowly rises with a slight slope. The microcracks inside the rock gradually enter the linear elastic deformation section after being closed. At this stage, the acoustic emission signal is less, and the curve of the cumulative number of AE events is relatively stable. With the further increase of the load, many new microcracks begin to incubate and develop in the unstable expansion of micro-cracks to failure. The development of the cracks is rapid and uncontrollable. The AE event rate appears to fluctuate in a wide range, and the cumulative AE event number curve fluctuates up, and the slope gradually increases. After the rock reaches its peak strength, many microcracks and fractures expand and converge until they penetrate to form macroscopic cracks, and its stress-time curve decreases. Each drop in stress corresponds to a sharp increase in the number of AE events, and the cumulative AE event curve increases almost linearly. From the AE parameter versus time curves of red sandstone at

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**Figure 2.** AE sensors layout
different loading rates, the AE peak event rate gradually increases, and the cumulative AE event number gradually decreases as the loading rate increases.

![Graphs showing stress and AE events for different loading rates](image)

**Figure 5.** Axial stress-time curves, AE event rate, AE cumulative event under different loading rates: (a) 0.001 mm/s, (b) 0.005 mm/s, (c) 0.02 mm/s, (d) 0.1 mm/s.

4. Characteristic stresses and damage evolution patterns in rocks under different loading rates

4.1. Characteristic stress of rock

The crack closure stress $\sigma_{cc}$, crack initiation stress $\sigma_{ci}$, and damage stress of rocks $\sigma_{cd}$ are essential characteristic values characterizing the strength of rocks and are the demarcation points of different stages in rock damage by forces. Eberhardt[9] conducted uniaxial compression tests on granite and designated the stress when the acoustic emission signal first rises significantly as the crack initiation stress and the stress when the acoustic emission signal appears to increase dramatically as the damage stress.
Figure 6. The curve of characteristic stress versus the logarithm of loading rate

The characteristic stresses of the red sandstone specimens at different loading rates are determined by selecting the AE event rates and the cumulative AE event numbers. As shown in Figure 5, where point a corresponds to the closure stress, point b corresponds to the cracking stress, and point c corresponds to the damage stress. Figure 6 shows the logarithmic relationship between characteristic stresses and loading rate. From figure 6, it can be seen that the characteristic stresses determined by the acoustic emission method show an overall decreasing trend. The higher the loading rate, the lower the threshold value to reach each characteristic stress, indicating that the higher loading rate accelerates the damage rupture of the rock, which makes the stress level required for the crack instability expansion and release of critical energy to occur in the rock decrease.

4.2. Rock damage model based on acoustic emission

Rock materials under load will produce different degrees of micro-damage, that is, the internal micro-crack sprouting, expansion, and penetration, resulting in the degradation of the rock's mechanical properties, will have acoustic emission phenomenon. Therefore, there must be some connection between the damage of the rock and its acoustic emission, and the acoustic emission activity can better reflect the damage change of the rock material. So, this paper uses the acoustic emission information as the basis for establishing the damage model of rocks and then investigates the damage evolution law of rocks under different loading rates.

The damage variable $D$ is introduced to describe rock damage, and early Kachanov[14] defined $D$ as:

$$D = \frac{A_d}{A}$$  \hspace{1cm} (4.1)

where $A_d$ is the total area of microcracks on the load-bearing cross-section and $A$ is the area of the cross-section in the initial undamaged state.

Assuming that the AE ringing count per unit area of micro-element damage is $N_0$, the cumulative AE ringing counts when the micro-element damage area reaches $A_d$ and when the entire cross-section fully damage are:

$$N = A_d \cdot N_0$$  \hspace{1cm} (4.2)

$$N_f = A \cdot N_0$$  \hspace{1cm} (4.3)

From equations (4.1), (4.2) and (4.3), the damage variable based on the cumulative ringing count of AE can be obtained:

$$D = \frac{N}{N_f}$$  \hspace{1cm} (4.4)

In the above derivation formula, $N_f$ is defined as the AE cumulative ringing count when the cross-section of the rock material is completely destroyed.

Figure 7 shows the relationship curves of damage variable D-strain-stress for red sandstone at each loading rate. From the perspective of the whole process, the damage evolution of red sandstone can be divided into three stages: initial damage section, damage stable development section, and damage acceleration section. The initial damage section corresponds to the compaction stage of the red sandstone stress-strain curve. In this stage, the damage variable is tiny, and the curve rises slightly. The damage stable development section corresponds to the linear elastic deformation section of the stress-strain curve and the microcrack branching and stable extension section, where the damage variable changes steadily and the corresponding curve rises smoothly with a fixed slope. The damage acceleration section corresponds to the microcrack instability extension of the stress-strain curve to the damage phase and the post-peak damage phase. Starting from the damage stress point, the internal damage of red sandstone accumulates seriously, the damage variables change significantly, and the curve segments accelerate to jump up. After the above analysis, it can be seen that the internal damage of red sandstone has a dramatic change from the microcrack instability expansion to the damage stage,
which shows that the damage variable at the damage stress point can genuinely reflect the degree of rock damage, for which the damage variable $D$ corresponding to the damage stress at different loading rates is counted. It can be shown that the damage accumulation in red sandstone at the damage stress is more significant than that at higher loading rates due to the adequate development of microcracks within the rock when the loading rate is low. According to the principle of strain equivalence proposed by Lemaitre: based on the original non-destructive material constitutive equation, as long as the stress is replaced with equivalent stress\[17\], there is:

$$\sigma = E\varepsilon (1 - D) \quad (4.5)$$

Where $\sigma$ is the stress, $E$ is the modulus of elasticity and $\varepsilon$ is the strain. From Figure 6, it can be seen that the fitted curve of the damage variable $D$ versus strain at each loading rate conforms to the exponential function, so the fitted equation of the damage variable $D$ versus strain can be obtained as:

$$D = a\varepsilon^b + c \quad (4.6)$$

Combining equations (4.5) and (4.6) can obtain the red sandstone damage constitutive equation:

$$\sigma = E\varepsilon \left(1 - a\varepsilon^b - c\right) \quad (4.7)$$

where $\sigma$ is the stress, $E$ is the modulus of elasticity, $\varepsilon$ is the strain, and $a$, $b$, and $c$ are the fitted correlation parameters.

![Damage variable D-strain-stress relationship for red sandstone with different loading rates](image)

**Figure 7.** Damage variable $D$-strain-stress relationship for red sandstone with different loading rates

The damage variables $D$ and strain curves of red sandstone at different loading rates are fitted to obtain the fitting parameters $a$, $b$ and $c$. And the elastic modulus $E$ of the corresponding specimens are substituted into equation (4.7) to obtain the damage evolution equation based on cumulative ringing.
counts for red sandstone at different loading rates, as shown in Table 1.

| Loading rate | a    | b    | c    | E/GPa | \( \sigma = E \varepsilon \left(1-ae^{b-\varepsilon}\right) \) |
|--------------|------|------|------|-------|--------------------------------------------------|
| 0.001 mm/s   | 8.16 | 18.31| 0.163| 12.061| \( \sigma = 12.061 \varepsilon \left(1-8.16 \varepsilon^{18.31-0.163}\right) \) |
| 0.005 mm/s   | 3.21 | 10.56| 0.06951| 10.132| \( \sigma = 10.132 \varepsilon \left(1-3.21 \varepsilon^{10.56-0.06951}\right) \) |
| 0.02 mm/s    | 0.2975| 21.49| 0.06589| 10.038| \( \sigma = 10.038 \varepsilon \left(1-0.2975 \varepsilon^{21.49-0.06589}\right) \) |
| 0.1 mm/s     | 0.8113| 13.26| 0.1003| 10.295| \( \sigma = 10.295 \varepsilon \left(1-0.8113 \varepsilon^{13.26-0.1003}\right) \) |

In order to verify the correctness of the damage evolution equation, the theoretical damage evolution curve is plotted for comparison with the actual stress-strain curve obtained from the test, and the results are shown in figure 6. It can be seen from the figure that there is an apparent upward concavity in the initial compacting stage of the test curve, while the theoretical curve is rising in a straight line at the initial stage, and it fails to reflect the state of the rock microcracks being compacted effectively. Because the compaction of microcracks inside the rock is a localization process, the theoretical damage model is a continuous variation function, which has some limitations for describing the local deformation process. However, in general, the theoretical curves based on acoustic emission ringing counts at different loading rates are generally consistent with the overall trend of the experimental curves. It shows that the damage model can better describe the damage evolution during the uniaxial compression of red sandstone at different loading rates.

5. Conclusion
(1) The elastic modulus decreases linearly with the increase of the logarithm of loading rate, while the peak strength generally shows a gradually increasing trend with the logarithm of the loading rate.
(2) With the increase of loading rate, the AE event rate's peak value increases gradually, and the cumulative number of AE events decreases.
(3) The evolution law of the characteristic stresses determined by the AE event rate and cumulative AE event number is the same as that of the loading rate. That is, with the increase of the loading rate, it shows a gradually decreasing evolution trend.
(4) The damage evolution model of red sandstone can better describe the damage evolution process of red sandstone. According to the evolution characteristics of damage variables, the damage evolution process of red sandstone can be divided into three stages: the initial damage stage, the damage stable development stage, and the damage accelerated stage.
(5) The damage variable at the damage stress point can reflect the actual damage degree of rock, and the size of the damage variable is closely related to the initiation, propagation, and transfixion of microcracks inside the rock. When the loading rate is low, the damage degree of red sandstone at the damage stress is usually more prominent because the rock's microcrack develops more fully.

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