Study on three-point bending mechanics and acoustic emission characteristics of impure salt rocks

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Abstract. In order to study the mechanics and deformation characteristics of salt rock under bending conditions, two groups salt rocks with different impurity content were subjected to three-point bending cycle loading and unloading test and simultaneous monitoring of acoustic emission based on MTS815 Flex Test GT rock mechanics test system and acoustic emission (AE) three-dimensional positioning real-time monitoring system. The research shows that: (1) The average tensile strength of pure salt rock bending tensile is 0.88MPa, and the impure salt rock is 1.72 times of pure salt rock. The impure salt rock has better resistance to crack propagation, and COMDmax and LPDmax are 82.31% and 83.47% of the pure salt rock, respectively. (2) The bending deformation failure of salt rock can be divided into four stages of linear elastic phase, nonlinear phase, post-peak crack stability expansion stage and residual phase. (3) The three-point bending deformation of salt rock is active except for the elastic phase of the line. In general, the three-point bending deformation of the polyhalite salt rock is more active. (4) Impurities weaken the plastic deformation ability of salt rock and increase the degree of brittleness.

1. Introduction

Because of the extremely low permeability and good self-healing ability [1-2], salt rock is widely regarded as the best place for strategic oil storage and gas storage [3]. Based on this engineering background, it is of great engineering significance to study the deformation and failure and mechanical properties of salt rock.

Three-point bending test is currently the main mean of measuring the bending tensile strength of rock. Jia Xueming et al. [4] studied three-point bending specimens with different incision methods, and the V-shaped slit was obtained as an ideal test method. Zuo Jianping [5-6] studied the fracture toughness characteristics of Beishan granite under the influence of temperature through three-point bending test. Deng Zhaofu [7] conducted a three-point bending test on four different grain size Beishan granites, and systematically studied the effect of particle size on the fracture mechanical behavior and acoustic emission of granite. In recent years, Zuo Jianping et al. [8-14] conducted a large number of fracture tests on granite and coal rock, and systematically studied the fracture properties of granite and coal rock. T. Funatsu et al. [15] studied the fracture characteristics of sandstones at different room temperatures by different methods.

However, most of the researches on salt rock only focus on the uniaxial compression and triaxial compression stress of salt rock. The research results on the bending and tensile test of salt rock are very few at home and abroad. Domestic scholar Lu Guosheng et al. [16] conducted bending and
tensile tests on salt rocks, and obtained the fracture toughness value of salt rock. Jing Yang Ding et al. [17] used a SEM (Scanning Electron Microscope) monitoring system to perform a three-point bending test on layered salt rock samples. Compared with the bending tests of rocks such as granite and sandstone, the bending test of salt rock is obviously insufficient. Therefore, it is necessary to carry out a three-point bending test on salt rock to explore the deformation and failure process and acoustic emission characteristics of salt rock under bending conditions.

2. Experimental equipment and scheme

2.1 Experimental equipment and test piece preparation

The experimental equipment was loaded by MTS815 Flex Test GT rock mechanics test system, and the acoustic emission signal during the deformation and destruction process of the sample was synchronously monitored by the American Society of Physical Acoustics' PCI-II acoustic emission system. 8 Micro30 type acoustic emission probes were distributed on both sides of the incision to receive the AE signal, the operating frequency is 150 kHz, the threshold is set to 30 dB, and the preamplifier gain is 40 dB.

The preparation of the test piece is referred to the “Code for Engineering Rock Mass Test Methods” GB/T 50266–2013 [18] and the “Water Test Regulations for Water Resources and Hydropower Engineering” SL264-2016 [19] (hereinafter referred to as “Standards” and “Procedures”). The test piece is processed by dry cutting and car. The three-point bending specimen adopts a rectangular parallelepiped test piece, and a straight cutting groove is prefabricated in the middle of the sample, and the span ratio is in accordance with the provisions of the Regulations. The sample dimensions are shown in Table 1. The sample three-point bending loading test is shown in Figure 1. The loading control method of the three-point bending loading and unloading test is set according to the "Procedure" [19]. The CMOD sensor is used to measure the slit opening displacement, and the axial deformation is measured by the LVDT sensor. During the test, 8 acoustic emission probes distributed on both sides of the slit of the test piece were used for acoustic emission monitoring.

| Type | No. | Length (mm) | Width (mm) | Height (mm) | Grooving height (mm) | Grooving width (mm) | Weight (g) |
|------|-----|-------------|------------|-------------|---------------------|---------------------|------------|
| Pure salt rock without polyhalite | d-1 | 207.3       | 96.1       | 45.3        | 14.3               | 1.5                | 2044.32    |
|      | d-2 | 207.5       | 97.2       | 47.6        | 15.5               | 1.5                | 2084.09    |
|      | d-3 | 210.5       | 98.3       | 46.5        | 15.8               | 1.6                | 2045.84    |
|      | d-4 | 211.1       | 98.4       | 48.9        | 15.5               | 1.2                | 2099.08    |
|      | d-5 | 207.4       | 99.7       | 46.5        | 16.5               | 1.6                | 2056.89    |
| Pure salt rock with polyhalite | d-6 | 213.8       | 98.5       | 48.5        | 16.6               | 1.5                | 2147.57    |
|      | d-7 | 210.4       | 100.3      | 46.5        | 20.3               | 2.1                | 2159.34    |
|      | d-8 | 210.5       | 98.3       | 47.3        | 17.7               | 2.0                | 2169.54    |
|      | d-9 | 210.5       | 98.3       | 47.1        | 16.8               | 2.1                | 2158.92    |
|      | d-10| 210.8       | 101.2      | 48.0        | 17.6               | 1.3                | 2178.26    |
2. Experimental plan

The whole process of loading and unloading cycle is operated manually, loading is controlled by CMOD, the pre-peak cycle loading rate is 0.05 mm/min, the post-peak cycle loading rate is 0.15 mm/min, the unloading is force control, and the unloading rate is 30 kN /min in each cycle, when unloading decrease to 0.1 kN, stop unloading and start reloading. The test stops when the load drops to 10% of the peak value.

3. Experimental results and analysis

3.1 Analysis of strength and deformation characteristics

In this paper, typical samples d-5 (pure salt rock) and d-8 (rock salt with polyhalite) are taken as examples to study the three-point bending mechanics and deformation characteristics of different polyhalite. The relationship between Crack Mouth Opening Displacement (CMOD), Load Point Displacement (LPD) and mechanical strength is shown in Figure 2:

(a) Polyhalite-free pure salt rock (d-5)

(b) Polyhalite-bearing pure salt rock (d-8)

Figure 2. CMOD, Load-LPD Curves of Salt Rocks Affected by Polyhalite
The polyhalite has a strengthening effect on the mechanical properties of the salt rock. Compared with the pure salt rock sample, the polyhalite salt rock sample shows obvious strengthening characteristics in the test curve. According to the relationship between the load of the salt rock three-point bending test and the CMOD deformation, the load change and the slit opening process the load-CMOD curve can be divided into four development stages:

1. The loading and unloading curves of the pure salt rock and the polyhalite salt rock sample are in the linear elastic stage in the pre-loading stage, and the loading curve and the unloading curve are basically coincident, and the irreversible shape is small. However, there is a significant difference in the slope of the elastic phase of the two sample lines. The stiffness of the pure salt rock sample is significantly smaller than that of the polyhalite salt rock sample. The yield phenomenon of the pure salt rock sample first appeared, the yield load of the polyhalite salt rock sample was 1.6 kN, and the pure salt rock sample was only about 0.7 kN. It indicates that the presence of impurities increases the stiffness of the salt rock, resulting in a higher yield load. The flexural modulus of the polyhalite salt rock is higher than that of the pure salt rock. The flexural modulus is the ratio of the increment of the elastic section to the increase of the bending deflection. The bending deflection is the amount of deformation of the section centroid in the vertical direction (LPD increment). The amount of the polyhalite salt rock bending elastic modulus is 0.76 MPa, and the pure salt rock bending modulus is 0.25 MPa. Under the condition of bending and stretching, the deformation generated before the peak of salt rock is mainly elastic deformation.

2. After the yielding, the pure salt rock and the polyhalite salt rock samples enter a nonlinear stage, the microcracks begin to develop and expand, and the irreversible shape increases gradually until the peak. However, there are significant differences in strength and deformation between the two rock samples at this stage. The deformation of the pure salt rock sample is greater than that of the polyhalite salt rock sample. The CMOD deformation of the pure salt rock sample is 0.12 mm at this stage, while the polyhalite salt rock sample is only 0.05 mm. Meanwhile, the peak load of the pure salt rock sample is lower than that of the polyhalite salt rock sample. The peak load of the pure salt rock sample is 1.21 kN, and the sample of the polyhalite salt rock is 2.18 kN. It indicates that the existence of impurities causes the nonlinear process to become shorter, resulting in a decrease in plastic deformation and an increase in peak load.

3. After the reaching the peak value, it enters the stage of crack stability and expansion. The rock samples of the two states do not break immediately and still have a certain bearing capacity. There is a linear decrease in the bearing capacity of the two rock samples after the peak. In the figure, the G point is the end point of the linear descending segment (the stage of crack stability and expansion). At this stage, the crack expands and develops in a large amount and stably, resulting in the rock sample being pulled to broken. However, there is a significant difference between the two states of the rock in this decline process. The slope of the descending line of the pure salt rock sample is significantly lower than that of the polyhalite salt rock sample, indicating that the fracture process of the pure salt rock sample is significantly slower after the peak. The presence of impurities causes the fracture process to become faster, resulting in enhanced brittleness of the salt rock. The slope of the linear descending line at this stage determines the degree of brittleness of the salt rock fracture.

4. After the end of the linear descent phase, enter the final residual phase. In terms of total deformation, the total deformation of the pure salt rock sample during the whole experimental process is significantly larger than that of the polyhalite salt rock sample.

In order to study the tensile properties of salt rock under bending and tensile conditions, for rectangular grooving specimens, the tensile stress of the tension zone can be calculated by the material mechanics formula. The stress distribution during the three-point bending experiment is shown in Figure 3:
Figure 3. Schematic diagram of three-point bending stress distribution for square specimens

Where S is the span when loading, L is the height of the specimen, a is the height of the slit, $\sigma_n$ is the maximum compressive stress on the upper surface of the specimen, and $\sigma_t$ is the maximum tensile stress at the tip of the slit, and specimen width is expressed by K. According to the material mechanics formula, the maximum tensile stress occurs at the tip of the slot where the bending moment is greatest.

$$\sigma_{t\text{ max}} = \frac{M_{\text{max}}}{W_z} = \frac{3FS}{2K(L-a)^2} \tag{1}$$

In formula 1, $\sigma_{t\text{ max}}$ is the maximum tensile stress received by the tip, $M_{\text{max}}$ is the bending moment generated at the point of application of the load, and $W_z$ is the bending interface coefficient.

Assuming that the section stress is linearly elastic, the tensile strength is:

$$\sigma_t = \frac{\sigma_{t\text{ max}}}{2} = \frac{3P_{\text{max}}S}{4K(L-a)^2} \tag{2}$$

According to the formula 2, the tensile strength of the pure salt rock and the polyhalite salt rock is as shown in Table 2:

| Type                | No. | Peak load (N) | CMOD$_{\text{max}}$ (mm) | LPD$_{\text{max}}$ (mm) | Tensile strength (MPa) |
|---------------------|-----|---------------|---------------------------|--------------------------|------------------------|
| Pure salt rock      | d-1 | 892           | 1.53                      | 1.24                     | 0.87                   |
| without polyhalite  | d-2 | 974           | 1.47                      | 1.19                     | 0.95                   |
| d-3                 | 674 | 1.43          | 1.47                      | 1.23                     | 0.66                   |
| d-4                 | 1029| 1.42          |                           | 1.19                     | 1.01                   |
| d-5                 | 906 | 1.51          |                           | 1.21                     | 0.89                   |
| d-6                 |     | 1203          | 1.21                      | 1.02                     | 1.18                   |
| Pure salt rock      | d-7 | 1182          | 1.17                      | 1.11                     | 1.16                   |
| with polyhalite     | d-8 | 2181          | 1.19                      | 1.21                     | 0.99                   |
| d-9                 | 1575| 1.23          |                           | 0.96                     | 1.54                   |
| d-10                | 1541| 1.25          |                           | 0.97                     | 1.51                   |

3.2 Analysis of the characteristics of acoustic emission ringing count

In this section, the specific samples containing pure salt rock d-5 and polyhalite-containing pure salt rock d-8 are selected for specific analysis. The relationship between each acoustic emission parameter and stress and time during the three-point bending loading and unloading test of each lithologic salt rock is shown in Figure 4 and Figure 5.
Figure 4. AE Curve of Pure Salt Rock under Three Point Bending Loading and Unloading Conditions

(a) Ring counting rate                                (b) Cumulative ringing count

(a) Energy rate                                       (b) Cumulative Energy

Figure 5. AE Curve of Polyhalite salt rock Salt Rock under Three Point Bending Loading and Unloading Conditions

(a) Ring counting rate                                (b) Cumulative ringing count

(a) Energy rate                                       (b) Cumulative Energy
In the elastic phase, the acoustic emission characteristics of the two salt rocks are different. A large number of ringing count signals appear in the elastic phase of the pure salt rock at the beginning, while the ringing count signal of the polyhalite salt rock in the elastic phase is very weak. This is because the hardness of the polyhalite salt rock is increased under the influence of the impurity of the polyhalite, and the modulus of the loading process is increased. There is almost no microcrack inside the rock during the elastic stage of the pre-loading stage, so there will be only a comparison in this process. The weak acoustic emission signal is formed; while the pure salt rock is softer than the polyhalite rock, the crystal slippage and turbulence appear inside the elastic stage in the early stage of loading, even if the deformation is very small, it still shows a high value and densely generating ringing count signal.

In the yield stage, it can be seen from the cumulative graph that the cumulative ringing count rate and the cumulative energy rate of the two rock samples are greatly different, and the cumulative ringing count rate and cumulative energy rate of the pure salt rock are significantly higher than the polyhalite salt rocks, which indicates that the damage of pure salt rock during the pre-peak deformation process is significantly greater than that of the polyhalite salt rock.

During the crack development stage (linear decline phase), the cumulative ringing count rate curve is observed. The cumulative ringing count rate in this stage still maintains the rising trend of the pre-peak nonlinear phase, and the cumulative ringing count rate of pure salt rock still shows a gradually decreasing slope. The reduced nonlinear rise, while the cumulative ringing count rate of the polyhalite salt rock still shows a linear increase. At this time, the cumulative acoustic emission ringing rate of the polyhalite salt rock samples is significantly higher than that of the pure salt rock samples, which is 1.25 times that of the pure salt rock.

In the final residual failure stage, the polyhalite salt rock is numerically higher than the pure salt rock sample due to the presence of impurities, and the cumulative acoustic emission ringing rate curve of the polyhalite salt rock has a steep slope and high ringing count. The rate leads to rapid fracture instability of the polyhalite rock sample at this stage, while the pure salt rock sample is a slow fracture with a low ringing count rate.

From the above-mentioned increase in the ringing count value, the intensity and the cumulative ringing count rate, it can be concluded that the ringing rate of the polyhalite salt rock is more severe throughout the experiment. Relatively speaking, the polyhalite salt rock is a short-time, high-ringing count rate of rapid and severe fracture process; and the pure salt rock fracture process is a long time, the low ringing count rate is slowly broken.

In terms of energy rate, under the influence of polyhalite, the maximum energy rate of polyhalite rock is 16 times that of pure salt rock. The polyhalite salt rock exhibits high energy rate fracture. The cumulative energy of the polyhalite salt rock is twice that of pure salt rock. In the three stages of salt rock deformation, the acoustic emission energy rate is active except for the elastic section, but the characteristics are different: the active front is plastic deformation and crack initiation, and the maximum energy rate of the polyhalite salt rock appears before and after the peak. The pure salt rock energy rate is lower than that of pure salt rock, but there is still a higher energy rate after the peak; in the residual stage, the crack propagates to the plane stress region, the new crack propagation slows down, the plastic deformation is large and fast, and the high energy rate The signal energy rate is gradually reduced and the low energy rate signal is substantially stable. In general, the three-point bending deformation of polyhalite rock is more active, but it is different at each stage: the elastic section is inconsistent due to the presence of polyhalite; the plastic stage is due to pure salt rock. The rapid plastic deformation high-energy rate burst type signal should be stronger; while the crack stable expansion stage may be the impurity salt rock transgranular fracture and the pure salt rock intergranular fracture, so the polyhalite salt rock high energy rate burst type signal is stronger; The residual phase is that the impurities weaken the deformation of the salt rock.

3.3 Three-dimensional spatiotemporal evolution of acoustic emission

Figure 6 is a three-dimensional test real-time display of each stage of three-point bending of typical pure salt rock (a) and polyhalite salt rock (b). The AE three-dimensional real-time display map reflects
the spatial position distribution relationship of the acoustic emission positioning points. As shown in Figure 6, the pure salt rock with lower stiffness has more acoustic emission points than the polyhalite salt rock at the moment of yielding. At the peak time, the same pure salt rock has more acoustic emission points than the polyhalite salt rock. The more acoustic emission signals of the polyhalite rock are concentrated, while the pure salt rock has a divergent distribution from the central axis to the two sides; the peak to the G point is the stable development stage of the crack under the three-point bending condition. The acoustic emission location of the salt rock shows a steady increase, but the increase of the polyhalite salt rock is greater than that of the pure salt rock, indicating that the crack development of the polyhalite salt rock at this stage is more intense than pure salt rock. From the final three-dimensional space-time evolution map of acoustic emission, the pure salt rock is concentrated in the left and right sides of the central axis about -30~30mm, and the polyhalite salt rock is concentrated in the 15cm range on the left and right sides of the central axis. This indicates that the distribution area of pure salt rock acoustic emission source is larger than that of polyhalite salt rock, because the plastic zone is larger when the crack of pure salt rock expands, and there are more sub-crack extensions, while the impurity salt rock weakens the plastic deformation due to impurities. The ability to increase the degree of brittleness and thus the crack propagation is smoother and the plastic zone is smaller, which is consistent with the results obtained by the two salt rock failure characteristics.

![Figure 6. Three-dimensional Spatial-temporal Evolution of Three-point Bending and Tension](image)

4. Conclusion

(1) The average tensile strength of pure salt rock bending tensile is 0.88 MPa, and the impurity salt rock is 1.72 times. Under the condition of bending and stretching, the deformation before the peak is mainly elastic deformation. After the peak is over, the salt rock has a higher bearing capacity, and the fracture is mainly caused by the stable development stage of the crack behind the peak.

(2) The presence of polyhalite causes the bending tensile strength of the polyhalite rock to increase by 72%, COMDmax is 82.31% of pure salt rock, and LPD is 1.20 times of pure salt rock.

(3) Salt rock deformation and failure can be divided into linear elastic phase, nonlinear phase, post-peak crack stability expansion phase, and residual phase four phases.

(4) Under three-point bending conditions, the pre-peak acoustic emission signal is weak, and the acoustic emission signal mainly comes from the stable development stage of the post-peak crack. Three-point bending deformation of polyhalite salt rock is more active

(5) Containing polyhalite causes the pre-peak acoustic emission signal of the polyhalite salt rock to be suppressed, and the post-peak acoustic emission signal is improved. The pure salt rock acoustic emission source distribution area is wider than the polyhalite salt rock.

![Figure 6. Three-dimensional Spatial-temporal Evolution of Three-point Bending and Tension](image)
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