Study on Brazilian Splitting Mechanics and Acoustic Emission Characteristics of Impure Salt Rocks

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Abstract. In order to study the mechanical and acoustic emission characteristics of salt rock under indirect tension, we conducted indirect tension cyclic loading and unloading tests and acoustic emission monitoring on pure salt rock and impure salt rock respectively by using MTS815 Flex Test GT rock mechanics test system and PCI-II acoustic emission (AE) three-dimensional positioning system. The results show that: (1) Both salt rocks show strong plastic deformation characteristics, but the plastic deformation ability of salt rocks is weakened by impurities, which is 79% of the average deformation ability of pure salt rocks. (2) The peak load and tensile strength of impure salt rock are higher than those of pure salt rock. The average peak value is 11.18KN and the average tensile strength is 1.81MPa, which are 1.55 times and 1.60 times of pure salt rock respectively. (3) The indirect tensile deformation characteristics of salt rock can be divided into three stages: damage stage at contact site, tensile deformation stage and post-peak deformation stage. (4) The acoustic emission signal is the most intense near the peak value, but the maximum ring counting rate and energy rate of impure salt rock are higher than those of pure salt rock. (5) When salt rock is destroyed, the whole crack surface is destroyed by tension, but the crack area of pure salt rock is much larger than that of impure salt rock.

1. Introduction
Salt rock has strong anti-permeability and deformation ability, and has the ability of damage self-healing, which means that salt rock caves have excellent sealing performance, so salt cavern storage is widely recognized as an energy reserve site in the world [1]. Based on this, the indirect tension loading and unloading test of salt rock is carried out to investigate its mechanical behavior and acoustic emission characteristics.

Many scholars at home and abroad have studied the method of measuring rock tensile strength by splitting method and the deformation and failure process of rock during splitting test. The indirect tensile failure law and strength characteristics of rocks with different lithologies were studied by splitting tests of You Mingqing [2-4] et al. Deng Huafeng [5] et al. studied the relationship between the height-diameter ratio of indirect tension and the tensile strength. Wang Zhi [6] et al. conducted indirect tension tests on square specimens and studied the stress distribution in rock. Yang Yongming [7] and others conducted indirect tensile tests on porous rocks, and discussed the law of crack development of porous rocks. Fang Xinyu [8] et al. studied the acoustic emission characteristics of indirect tensile failure process of rock by numerical software. Pingqi [9] et al. analyzed the characteristics of energy dissipation in indirect tensile test of rock specimens. The influence of particle size flow on indirect tensile strength was studied by Meng Jingjing [10] et al. Luo Penghui [11] and
others have studied the damage and failure of rock splitting tests by means of acoustic emission. Liu Ning [12] studied the stress distribution and deformation characteristics of rock during splitting failure by numerical modeling software. Huang Xiaohong [13] et al. studied the phase spectrum of one of the acoustic emission parameters during indirect tension of rock. Guo Jianqiang [14] and others conducted Brazilian splitting tests on salt rock, tested the tensile strength of salt rock, and established yield criteria based on salt rock. Liang Weiguo [15] et al. carried out splitting tests on salt rock, and studied the tensile mechanical characteristics of salt rock. The research on salt rock splitting at home and abroad is obviously insufficient, so based on salt rock splitting test, this paper explores its mechanical and acoustic emission characteristics, in order to provide reference for practical engineering applications.

2. Sample preparation and test scheme

2.1. Sample preparation

The indirect tension sample is Brazilian disc sample. The samples are pure salt rock and Chinese impure salt rock. The impurities of impure salt rocks elected are relatively uniform distribution without weak structural plane. The impurities are mud impurities with impurity content ranging from 15% to 25%. The sample preparation refers to the GB/T 50266-2013, and the ratio of height to diameter is 1:2. The samples are shown in Fig. 1 and the sample size is shown in Table 1.

![Sample images](image1)

(a) Pure salt rock

(b) Impure salt rock

Fig. 1 Indirect tension salt rock sample

| Lithology          | No. | Diameter (mm) | Height (mm) | Mass (g)  |
|--------------------|-----|---------------|-------------|-----------|
| Pure salt rock     | d-1 | 91.0          | 44.7        | 618.93    |
|                    | d-2 | 90.3          | 45.3        | 623.42    |
|                    | d-3 | 89.5          | 44.8        | 614.12    |
|                    | d-4 | 88.7          | 45.6        | 608.32    |
|                    | d-5 | 90.4          | 44.4        | 618.09    |
|                    | d-6 | 89.2          | 46.1        | 616.19    |
| Impure salt rock   | zp-1| 88.9          | 44.1        | 675.79    |
|                    | zp-2| 91.1          | 45.3        | 681.74    |
|                    | zp-3| 90.7          | 46.3        | 705.63    |
|                    | zp-4| 89.3          | 47.5        | 672.01    |
|                    | zp-5| 90.1          | 46.9        | 690.41    |
|                    | zp-6| 90.7          | 46.1        | 675.16    |

2.2. Test equipment and scheme

MTS815 Flex Test GT rock mechanics test system is used for test loading equipment, and PCI-II acoustic emission (AE) three-dimensional positioning system of American Acoustic Physics Company.
is used for acoustic emission monitoring equipment. Eight micro30 acoustic emission probes are arranged on both sides of the circle at the bottom of the sample for receiving signals.

Indirect tension is tested by splitting method. The shape of the sample is cylindrical. The test scheme adopts cyclic loading and unloading mode. LVDT is used to control the whole process of the test. The loading rate is 0.3 mm/min, and the loading and unloading cycle is carried out manually at intervals of about 0.5 kN before the peak load. At least two loading and unloading cycles are carried out after the peak load, and each unloading is carried out at 0.3 KN before loading. In the test, eight acoustic emission sensors are fixed on both sides of the circle at the bottom of the sample through two square metal frames, as shown in Fig. 2. At the same time, the formula of tensile strength of samples derived from the theory of elasticity is shown in equation 1.

\[
\sigma_t = \frac{2P}{\pi DH}
\]

Where \(\sigma_t\) is the indirect tensile strength of rock, MPa; \(P\) is the indirect tensile load, N; \(D\) is the diameter of the sample, mm; \(H\) is the height of the sample, mm.

Fig. 2 Diagram of indirect tensile testing device for salt rock

### 3. Test results and analysis

#### 3.1. Effect of loading and unloading on mechanical behavior of salt rock splitting

Fig. 3 describes the failure state of two kinds of salt rock during splitting process, both of which show obvious tension failure. The cracks of pure salt rock are more irregular than those of impure salt rock, which shows typical soft rock failure characteristics of salt rock. Because of impurity, impure salt rock splits into two parts immediately after the end of the test, and the cracks are more straight than those of pure salt rock, showing brittle splitting.

Fig. 3 Photographs of indirect tensile failure of salt rocks with different impurities

| Lithology   | No. | Density g/cm³ | Maximum load F/KN | Vertical deformation/mm | Tensile strength MPa |
|-------------|-----|---------------|--------------------|-------------------------|----------------------|
| Pure salt rock | f-1 | 2.13          | 6.76               | 2.52                    | 1.063                |
|             | f-2 | 2.15          | 7.74               | 2.55                    | 1.217                |
|             | f-3 | 2.18          | 9.28               | 2.83                    | 1.459                |
|             | f-4 | 2.16          | 6.03               | 2.45                    | 0.948                |
|             | f-5 | 2.17          | 6.39               | 2.48                    | 1.005                |
|             | f-6 | 2.14          | 6.95               | 2.50                    | 1.093                |
From the tensile strength listed in table 2, it can be seen that the average peak value of pure salt rock is 7.19 KN and the average tensile strength is 1.13 MPa. The average peak value of impure salt rock in China is 11.18 KN and the average tensile strength is 1.81 MPa. The existence of impurities increases the tensile strength of salt rock under indirect tension to a certain extent. The indirect tensile strength of Chinese impure salt rock is 1.55 times that of pure salt rock. Under loading and unloading splitting load, both pure salt rock and impure salt rock show great plastic deformation characteristics. The average deformation of impure salt rock is 2.03mm, which is 79% of the average deformation capacity of pure salt rock.

The presence of impurities strengthens the splitting mechanical properties of salt rock. Compared with pure salt rock samples, Chinese impure salt rock samples show obvious strengthening characteristics in the test. The test curves of pure salt rock f-1 and impure salt rock zzp-1 are taken as examples for typical analysis.

![Convex type](image1.png) ![Concave type](image2.png)

**Fig. 4 Stress-deformation curve of salt rock under splitting loading and unloading conditions**

Fig. 4 shows typical loading and unloading splitting test curves of two types of salt rock. It is known from (a) (b) that when the stress exceeds the unloading load of the previous stage, the stress-deformation curve will rise along the original loading curve, which is the deformation memory phenomenon of rocks [16]. The indirect tension process of salt rock can be divided into three stages according to the deformation characteristics of salt rock:

1. **Damage stage at contact site.** The stress-deformation curve of indirect tension has a concave feature at the beginning stage of loading. The main reason is that the stepping bar loading is adopted in the test process. The contact mode of the salt rock loading contact part is line contact. The stress concentration and yield occur in this part, which makes the deformation increase rapidly under low stress conditions, and then this concave feature is shown.

2. **Tensile deformation stage.** This stage is the main stage of the development of tensile cracks, and micro-cracks begin to develop and expand. The pure salt rock samples show a longer yield deformation process, the stress level rises relatively smoothly, the slope of the curve decreases gradually, and the stress-deformation curve shows a convex type as shown in Figure 4(a); the stress development of the impure salt rock shows a steep increase. Under the same deformation condition, the stress develops more rapidly, and the slope of the curve increases gradually, showing a concave shape as shown in Figure 4 (b). It shows that the crack development of pure salt rock is faster than that of impure salt rock, and the cumulative process of damage is faster. At the same time, the peak value of pure salt rock samples is lower than that of impure salt rock samples, which indicates that the existence of impurities makes the stress increase sharply at this stage, resulting in the increase of stiffness and peak value.
(3) Post-peak deformation stage. After the peak value, the two rock samples did not split immediately, but still had a certain bearing capacity. After the peak, the load-bearing capacity decreases rapidly. At this stage, the cracks expand and develop steadily, resulting in the splitting of rock samples. However, there are obvious differences in this decline. The post-peak deformation of pure salt rock is obviously larger than that of impure salt rock, which indicates that the splitting process of impure salt rock is obviously faster after the peak value. The existence of impurities makes the splitting process faster, which leads to the increase of brittleness of rock samples and the decrease of total deformation during the whole test process.

3.2. Acoustic emission counting and energy evolution of salt rocks under loading and unloading

Fig. 5 and Fig. 6 are the acoustic emission ringing counting and energy curves of pure salt rock f-3 and impure salt rock zp-2 under indirect tensile stress respectively. It can be seen from the figure that before the load is added to the peak value, the curves of cumulative ringing counting, cumulative energy with respect to time are concave; after the peak value, the curves are convex, and the slope increases first and then decreases during the whole loading process. Acoustic emission activity of pure salt rock is much more intense than that of impure salt rock in the early stage of loading. Because pure salt rock is softer than impure salt rock, the acoustic emission signal at this time mainly comes from the initial damage of the contact area between the stepping bar and the sample, which shows that the initial damage of pure salt rock is larger than that of impure salt rock.

During loading and unloading, Kaiser effect is obvious in both salt rocks, which leads to a step-like rise in cumulative ringing counting rate curve and cumulative energy rate curve. As far as single cycle loading and unloading is concerned, the increment of cumulative ringing counting rate curve and cumulative energy rate curve increases gradually with the increase of stress, making the slope of the two curves increase continuously until the peak value reaches the maximum. After the peak load, the tensile strength of samples decreases rapidly, the increment of the cumulative ringing count and cumulative energy reaches the maximum, and the cracks originally formed under the peak tension stress expand rapidly. Therefore, the AE signal strength reaches the maximum when the samples are loaded to the peak load and the post-peak failure stage. During the cyclic loading and unloading process, the micro-cracks begin to penetrate and form a macro-fracture surface. There is no big difference between the two kinds of salt rocks. In terms of values, the difference lies in the ringing counting rate and energy rate of the peak and post-peak failure stages. The maximum ringing counting value produced by pure salt rocks is 720 times/s, while the maximum ringing counting value produced by impure salt rocks is 990 times/s.

In terms of value, both energy rate and ringing counting rate of impure salt rocks are higher than pure salt rocks. The maximum of energy rate occurs in the loading and unloading cycle before the peak. The maximum of ringing counting rate of pure salt rocks occurs before the peak, while the maximum of ringing counting rate of impure salt rocks occurs in the post-peak failure stage.
3.3. Three-dimensional spatial-temporal evolution of acoustic emission under indirect tension

Figure 7 shows the spatial-temporal evolution characteristics of AE of splitting pure salt rock sample f-2 and impure salt rock sample zp-2 under the condition of stepping bar loading. The main fracture direction of salt rock can be clearly seen from the figure, and the spatial-temporal evolution of AE matches the real fracture.
When salt rock is destroyed, the whole crack surface is destroyed by tension, and the crack lines are regular and straight. In the early stage of loading, only a small number of AE signals are produced at the contact part of the stepping bar. During the subsequent loading process, the tensile cracks gradually converge from the end to the middle, and the AE signals also develop from the two ends to the middle. According to the distribution of acoustic emission location points, the acoustic emission location points basically distribute along the macroscopic crack surface, but the distribution of signal points in pure salt rock is wider than that in impure salt rock, which indicates that the influence area of pure salt rock cracks is larger, while that of impure salt rock is relatively small, and the distribution of acoustic emission signal points in impure salt rock is relatively straight and narrow. In conclusion, compared with pure salt rock, the initial damage of impure salt rock samples appears later, and the damage process has less influence on the acoustic emission signal near the crack.

4. Conclusion

1) In the process of indirect tension cyclic loading and unloading, both pure salt rock and impure salt rock show strong plastic deformation characteristics and obvious tension failure, but impurity weakens the plastic deformation ability of salt rock, and impure salt rock is 79% of the average deformation ability of pure salt rock.

2) Pure salt rock is relatively uniform, and its tensile strength keeps at an average level. Due to the presence of impurities in domestic salt rock, the internal impurities in the sample lead to a great difference in the measured tensile strength. The peak load and tensile strength of impure salt rock are higher than that of pure salt rock, with the average peak value 11.18KN and the average tensile strength 1.81MPa, which are 1.55 times and 1.60 times of pure salt rock, respectively.

3) The indirect tensile deformation characteristics of salt rock can be divided into three stages: damage stage at contact site, tensile deformation stage and post-peak deformation stage. The development and expansion of tensile cracks mainly occur in the latter two stages. The presence of impurities accelerates the process of salt rock splitting, resulting in the increase of brittleness of rock samples.

4) Under indirect tension, the acoustic emission signal of salt rock is the most intense near the peak value, and the increment of cumulative ringing count and cumulative energy rate reaches the maximum at the peak value. The existence of impurities leads to the maximum ringing count rate and energy rate of impure salt rock are higher than that of pure salt rock. The maximum of ringing counting rate produced by pure salt rock is 720 times/s, while that produced by impure salt rock is 990 times/s.

5) Under the indirect tensile condition of stepping bar loading, the damage of pure salt rock and impure salt rock occurs from the contact point of the stepping bar loading and extends to the middle of the sample. Finally, the micro-cracks run through along the loading direction and form the failure surface. Acoustic emission locations are basically distributed along the macroscopic crack surface, but the signal points of pure salt rock are wider than those of impure salt rock, and the crack influence area is larger.

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