The rock mechanics and acoustic emission characteristics of rock salt under tension-compression alternating

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Abstract. In order to study the stress state and acoustic emission characteristics of salt rock energy storage during high frequency injection and production of compressed. the self-developed spring specimen limit tension and compression cycle test rock specimen fixing device based on the MTS815 Flex Test GT rock mechanics test system and acoustic emission (AE) three-dimensional positioning real-time monitoring system was used to study on mechanical characteristics and AE characteristics of pure salt rock and impurity salt rock under tension-compression alternating tests for the first time. The test results show that: (1) Under the stress path of tension-compression alternating, the tensile strength of pure salt rock is 0.95 MPa, impurity salt rock tensile strength increased by 47.37% compared with pure salt rock, axial deformation of impurity salt rock is 0.25mm, while pure salt rock is 1.40 times of it. (2) During the compression stage, AE signals with uniform distribution are produced by the effect of mutual dislocation, slip and micro-defect closure in salt rock, which has a certain end-restraint effect; In the stretching stage, the development of intercrystalline cracks is the main cause of AE signals in tensile stage, and AE signal followed hysteresis phenomenon. (3) Comparing with impurity salt rock, the cumulative ringing counts of the four compression loading and unloading stages are 3.13 times higher than impurity salt rock, AE signal of pure salt rock is weaker during tension loading and unloading, the cumulative ringing count increases slightly, a large number of acoustic emission signals accompany only the final tensile failure process. Under the condition of tension-compression alternating, AE signals of pure salt rock with the same tensile or compressive stress levels are more active than those of impurity salt rock, and the number of AE events in compression stage is larger than that in tension stage.

1. Introduction

Due to its characteristics of small porosity, low permeability, good self-healing ability and low cavitation cost [1-2], salt rocks are regarded as the best place for oil and other energy reserves and compressed gas storage [3]. In the process of studying the stability of salt rock storage, the buried depth, geometric shape, operating internal pressure and injection-production rate are all important influencing factors [4-7]. During the high frequency injection and production process in the compressed gas storage, the pressure reduction of gas production and the change rate of gas injection and production pressure produce fatigue cracks in the surrounding rock at the top of the pipe column of the cavity [7]. Especially in the process of high speed injection-production, the compressive and
tensile stress alternates in the surrounding rock of the injector and outlet at the top of the cavity. In the long run, the fatigue crack of the rock diffuses and eventually produces a penetrating crack, which is harmful to the engineering tightness and stability. Therefore, it is necessary to carry out experimental research on the mechanical properties of the rock under the cyclic loading of tension-compression alternating.

At the present stage, the tension-compression alternating tests mainly focus on metal research. Metal materials are more operable in the test process due to their extensibility. Zhang Jiazhen [8] et al. deduced the prediction model of fatigue crack growth rate of fiber-reinforced metal laminates under tension-compression alternating cyclic loading through the finite element model. Keita Goto[9] et al. proposed the fixture for biaxial stress testing to realize the combination of tensile load and alternating load, so as to realize the biaxial stress test of tensile load and compression load. However, rocks are different from metals. Due to the limitations of testing techniques, rock mechanics tests are dominated by conventional cyclic loading and unloading tests such as uniaxial tensile test or uniaxial compression test. Deng Chaofu et al. [10] obtained the whole process variation law of dissipated energy and elastic strain energy through the uniaxial compression loading and unloading test of salt rock and the analysis of stress-strain loading and unloading curve. Liu Jianfeng [11-12] et al. revealed the correlation between indirect tensile strength and direct tensile strength, as well as the correlation between them and uniaxial compressive strength by using the two test methods of indirect tensile strength and direct tensile strength. In the field of rock, there are few studies on tension-compression alternating. Liu Wei [13] conducted fatigue and creep tests on sandstone under cyclic loading of tension and compression to study the mechanical properties of sandstone under tension-compression alternating cyclic loading.

2. Test equipment and experimental scheme

2.1. Test equipment and test piece production

The test equipment adopts MTS815 Flex Test GT rock mechanics test system [14-15]. The axial load of the test machine is up to 4600kN, the tensile load is up to 2300kN, the LVDT range is ±2.5mm, and the precision is 0.5% RO. Acoustic emission monitoring uses eight Micro30 type acoustic emission sensors with a frequency of 100~600kHz and an amplifier gain of 40dB.

The test pieces with relatively uniform impurity distribution were selected. See figure 1 for the photos and table 1 for the specific parameters. The tension-compression alternating test pieces are pure salt rock C-1—C-3 (impurity content: < 3%) and impurity salt rock Z-1—Z-3 (impurity content: 22%~25%). The preparation of rock samples is strictly in accordance with the "Engineering Rock Mass Test Method Standard (GB / T50266-99)" [16], and the standard sample is processed with dry cutting and turning methods, with the size of φ100×H100mm. Considering the influence of end effect and stress concentration on the test results, the bonding method was used to bond the specimen to the metal stretching head. It is monitored in real time by AE acoustic emission probes arranged at both ends, and Vaseline is used as an AE sensor coupling agent to couple its contact with the sample to enhance the test results. The sample installation and the distribution of each test sensor are shown in figure 2.

| Lithology              | No. | Height (H/mm) | Diameter (D/mm) | Mass (M/g) |
|-----------------------|-----|---------------|-----------------|------------|
| pure salt rock        | C-1 | 103.5         | 98.1            | 1665.44    |
|                       | C-2 | 101.6         | 99.9            | 1711.32    |
|                       | C-3 | 102.2         | 98.4            | 1693.44    |
| impurity salt rock    | Z-1 | 98.7          | 101.5           | 1971.60    |
|   |   |   |   |
|---|---|---|---|
| Z-2 | 102.3 | 101.4 | 1907.37 |
| Z-3 | 102.8 | 103.5 | 1996.91 |

(a) Pure salt rock          (b) Impurity salt rock

Figure 1. Samples of specimen

Figure 2. Hydraulically supported tension-compression alternating test device

2.2. Test plan
The tensile chain is tightened before the test begins. The tension and compression alternating test was controlled by LVDT. The pre-peak control rate was 0.01 mm/min, and the post-peak control rate was 0.0025 mm/min. The compressive loads are divided into four stages of 5kN, 10kN, 15kN and 20kN, and the maximum compressive stress does not exceed the yield limit under compressive load. The tensile load is increased step by step until it is broken.

3. Experimental results and analysis

3.1. Analysis of strength and deformation characteristics
It can be seen from figure 3 that under the stress path of tension-compression alternating, the inelastic deformation of the pre-peak pure salt rocks is greater than that of the impurity salt rocks, and the stress-strain curves of the two kinds of salt rocks will rise approximately along the original loading curve during the step-by-step loading process, showing the deformation memory phenomenon of rocks [17-18]. Under the stress path of tension-compression alternating, due to the strong nonlinear characteristics of salt rock itself, even if the compression stress is at a low stress level, under the condition of cyclic loading and unloading of tension and compression, both the unloading curve and the loading curve do not coincide, and the tension curve and compression curve together form a closed hysteresis loop. Due to the low compression stress, the inelastic deformation of the specimen under compression condition is very small, and the inelastic deformation is basically generated by the tensile stage. Although there is a large inelastic deformation in the tensile stage, the compression loading and
unloading after the completion of the stretching process lead to no significant change in either the loading modulus or the unloading modulus in the subsequent tensile loading and unloading process compared with the last tensile loading and unloading. In the compression stage, the rock loading and unloading paths are not completely repeated, and the resulting "hysteresis loop" increases with the increase of the tensile loading level, and the area also increases continuously. In the two types of salt rocks, the deformation effect of the compression cyclic loading and unloading process is particularly significant for the pure salt rock. The area of "hysteresis loop" of the pure salt rock after tension-compression alternating cyclic load of tension and compression is obviously larger than that of the impurity salt rock, that is, the deformation of the pure salt rock in the compression stage is larger than that of the impurity salt rock. In the tensile stage, the slope of the stress-strain curve changes little before the peak, and failure occurs without obvious yield process. This shows that under the action of low compression stress, the salt rock is compacted internally, and the stiffness increases, so that the tensile modulus does not change much in the process of tensile loading and unloading. At the same time, in the process of tensile loading and unloading, the deformation is mostly elastic, and the increment of inelastic deformation is very small. During the tension-compression phase, the stress-strain curve remained smooth, but the modulus changed significantly. The tensile curve was gentler than the compression curve, and the tensile modulus was significantly lower than the compression modulus.

![Figure 3. Typical stress-strain curves](image)

Based on the data processing of each sample under the tension-compression alternating test, it can be seen from table 1 that under the stress path of tension-compression alternating, the tensile strength of the impurity salt rock increases by 47.37% compared with that of the pure salt rock, and the axial deformation of the pure salt rock is 1.40 times that of the impurity salt rock. Figure 4 shows the morphology of the impurity salt rock and pure salt rock after failure under tension-compression alternating. It can be seen from the macroscopic section after failure that the salt rock particles in the impurity salt rock are closely combined with the hard cemented impurity particles, and the particles at the fracture are denser.

The reason is analyzed as follows: as a kind of rock composed of grains, the micro-cracks at the cementation between the crystals in the salt rock are compacted under the compression stress, and a certain amount of micro-defect closure phenomenon occurs. The impurity salt rock is mainly composed of argillaceous and calcareous cement. From the compression mechanics research, the compressive strength of the impurity salt rock is higher [19-20], thus the hard cemented impurity particles are more tightly combined with the salt rock particles. The impurity particles can withstand greater strength during the process of tensile failure, resulting in an increase in the tensile strength of the impurity salt rock compared to the pure salt rock.
Table 2. Mechanics and deformation parameters of salt rock

| Lithology         | No. | Peak load KN | Axial deformation mm | Tensile strength MPa |
|-------------------|-----|--------------|----------------------|----------------------|
| pure salt rock    | C-1 | 6.91         | 0.28                 | 0.88                 |
|                   | C-2 | 7.38         | 0.27, 0.35           | 0.94, 0.95           |
|                   | C-3 | 8.01         | 0.49                 | 1.02                 |
| impurity salt rock| Z-1 | 11.23        | 0.19                 | 1.43                 |
|                   | Z-2 | 11.70        | 0.29, 0.25           | 1.49, 1.40           |
|                   | Z-3 | 10.13        | 0.29                 | 1.29                 |

Figure 4. Tension-compression alternating destruction of the sample

3.2. Analysis of the characteristics of acoustic emission ringing count
The relationship between AE ringing count rate, stress and time of typical pure salt rock and impurity salt rock is shown in figure 5 and figure 6. The whole process of tension-compression alternating of salt rocks can be roughly divided into three processes.

In the initial tensile loading and unloading process, it can be seen from figure 5 that in the first tensile loading and unloading process, the pure salt rock has a certain ringing count rate, and the cumulative ringing count curve has a small step from the beginning. As can be seen from figure 6, there is no obvious acoustic emission signal in the first tensile loading and unloading process of the impurity salt rocks.

In the compression-tension cycle, as shown in figure 5 and figure 6, acoustic emission signals appear in both pure salt rocks and impurity salt rocks at the beginning of the compression stage. As the compressive stress increases in each stage, acoustic emission signals gradually increase. When the compressive stress reaches a maximum, a large number of acoustic emission signals are accompanied. In the compression loading and unloading stage, the acoustic emission signal of pure salt rock is more obvious than that of the impurity salt rock. From the first compression loading and unloading stage, the cumulative ringing count of the pure salt rock is 2.71 times that of the impurity salt rock; to the fourth compression loading and unloading stage, the increase is 44.38%. The cumulative ringing count of the pure salt rock is 3.13 times that of the impurity salt rock during the four compression and unloading stages. In the subsequent tensile loading and unloading stage, AE signals show hysteresis, and a small number of AE signals are accompanied only when the tensile stress is close to the maximum value. It can be seen from the relation between cumulative ringing count and time that the cumulative ringing count curve of acoustic emission basically does not rise and remains horizontal in the tensile loading and unloading stage of both pure salt rocks and impurity salt rocks.

Finally, in the process of tensile fracture, it can be seen from figure 5 and figure 6 that with the increase of tensile stress, the acoustic emission signal gradually strengthens and the increasing slope gradually increases. When the stress reaches the peak, the increase slope is the largest, and with a large number of acoustic emission signals, the ringing count rate reaches the maximum value. The maximum value (381 times /s) of the impurity salt rock is greater than the maximum value (314 times/second) of the pure salt rock.
of the pure salt rock.

Figure 5. Relationship between tension-compression alternating stress, ringing count rate, cumulative ring count and time for pure salt rock

Figure 6. Relationship between tension-compression alternating stress, ringing count rate, cumulative ring count and time for impurity salt rock

The above mentioned acoustic emission variation rules in each stage correspond to the deformation mechanism and mechanical behavior in the process of salt rock test. From the above analysis, it can be seen that the impurity salt rock has greater stiffness and smaller inelastic deformation than the pure salt rock, so there is no obvious acoustic emission signal in the first tensile loading and unloading stage. In the compression stage, due to the mutual dislocation, slip and micro-defect closure effect in the salt rocks, the acoustic emission signal with uniform distribution is generated at the initial stage of compression, which has a certain end constraint effect. The impurity salt rock density (2.36 g/cm³) is higher compared to the pure salt rock density (2.15 g/cm³), the internal impurity particles are more tightly bound to the salt rock particles, and the micro-cracks at the cement joint are also smaller. Therefore, under the effect of compressive stress, the mutual displacement and slip between the grains in the pure salt rock are more obvious, and the acoustic emission signal is more active, so that the cumulative ringing count appears more obvious step-like development; in the tensile stage, the internal interstitial friction of salt rocks caused by tensile stress is less, and the micro-defect closure effect is weak. In this stage, AE signals are mainly generated by the development of micro-cracks between crystals, and AE signals have hysteresis phenomenon. The cumulative ringing count curve is basically kept in a horizontal state, i.e., the obvious Kaiser phenomenon occurs during the tensile loading and unloading stage [17], indicating that acoustic emission memory phenomenon exists in the specimen under the tension-compression alternating cyclic loading. In the final tensile fracture process, AE signals are concentrated near the peak stress, and the ringing count rate reaches the maximum value at the peak. The acoustic emission characteristics of tensile failure of pure salt rock under the tension-compression alternating no longer show the soft rock characteristics of pure salt rock, but show the acoustic emission characteristics similar to that of the tensile fracture process of impurity salt rock.
3.3. Analysis of spatiotemporal evolution characteristics of acoustic emission

Through the processing of acoustic emission signal, not only the change rules of characteristic parameters such as acoustic emission ringing count can be obtained, but also the whole process of salt rock damage and failure under the stress path of tension-compression alternating can be restored through the spatial location of acoustic emission event points. Some typical samples were selected for specific analysis. Figure 7 (a) and figure 8 (a) show the 3D space-time localization maps corresponding to the tensile stress of 0.26MPa, 0.39MPa, 0.52MPa, 0.65MPa and the end of the peak respectively.

Figure 7 (a) and figure 8 (a) shows that under the stress path of tension-compression alternating, sample damage first appears in the weaker part, the AE anchor point is mainly concentrated in this region, and the failure surface formed in this region. As the stress increases, the acoustic emission events increase. The final number of pure salt rock events is 3917, and the number of impurity salt rock final events is 2150. It is corresponding to the result mentioned above that the acoustic emission signal of pure salt rock is more active under the stress path of tension-compression alternating compared with the impurity salt rock. As can be seen from figure 7 (b) and figure 8 (b), during the compression process, a small number of AE events are generated in the two types of salt rocks, which are scattered in the specimen. However, with the increase of stress level, AE anchor points increase during the compression process and are more widely distributed. This is because the number of AE events is not generated by the generation of micro-cracks, but the acoustic emission signal generated by the micro-defect closure in salt rocks under compression stress. As can be seen from figure 7 (c) and figure 8 (c), in the stretching process, the number of AE events generated in the early tensile loading and unloading process is small and mainly concentrated around the weak part. With the
increase of tensile stress, the crack diffuses along with the weak part, and the number of AE events increases, and a large number of AE events were generated in the last tensile fracture process, with the spatial distribution concentrated on the fracture surface. In the process of tensile loading and unloading, the number of AE events comes from the formation, opening and convergence of cracks under tensile stress [10]. In the compression process, the compression stress leads to the micro-defect closure in the salt rock, which makes the salt rock more compacted. As a result, the number of AE events generated in the subsequent stretching process is less.

![Figure 9. Segmental statistics of alternating events of salt rock under tension-compression alternating](image)

It can be seen from figure 9 that under the stress path of tension-compression alternating, the number of AE events in both pure salt rocks and impurity salt rocks increases with the increase of cycle times, and the increase of AE events in pure salt rocks is more obvious than that in impurity salt rocks. Before the tensile failure, AE signals are mainly generated in the compression process, and the number of AE events reaches the maximum in the tensile fracture process. Under the same tensile or compressive stress, the pure salt rock produces more acoustic emission signals than the impurity salt rock, which is corresponding to the mechanical behavior characteristics of salt rock in the tension-compression alternating. In the compression process, the inelastic deformation of pure salt rocks is larger, and the micro-defect closure process is more obvious, thus generating more AE events (pure: 1300 times > impurity: 278 times). In the process of stretching, the number of AE events generated in the process of stretching loading and unloading in the early stage is lower than that in the compression stage with the same cycle number. The number of AE events in the first 4 cycles of pure salt rocks is still higher than that in the impurity salt rocks (pure: 610 times > impurity: 149 times). Only in the final tensile fracture, a large number of acoustic emission signals are generated, and the number of acoustic emission events in the pure salt rocks is greater than that in the impurity salt rocks at the stage of fracture failure (pure: 2007 times > impurity: 1723 times).

4. Conclusion

1) Under the stress path of tension-compression alternating, because the hard cemented impurity particles are more tightly combined with the salt rock particles, the impurity salt rock has the tensile strength 1.40MPa, which is 47.37% higher than that of the pure salt rock. However, the axial deformation of the pure salt rock is 0.35mm, 1.40 times higher than that of the impurity salt rock.

2) The main causes of AE signals in compression loading and unloading stage are mutual dislocation, slip and micro-defect closure effect in salt rocks. At the beginning, AE signals with uniform distribution appear and have a certain end constraint effect. In the process of tensile loading and unloading, there is less friction between internal pores of salt rocks, and the micro-defect closure effect is weak. AE signals are mainly generated by the development of inter-crystal cracks, and there is a hysteresis phenomenon in AE signals.

3) In the compression loading and unloading stage, the cumulative ringing count of the pure salt rocks is higher than that of the impurity salt rocks. In the stretching stage, the acoustic emission signals of the two kinds of salt rocks are weak, and a large number of acoustic emission signals are
generated only in the final tensile fracture.

4) Under the same tensile or compressive stress, the acoustic emission signal of pure salt rock is more active, and the number of events increases significantly with the increase of cycle times. Salt rocks are more sensitive to compression process and the number of AE events in compression stage is greater than that in stretching stage.

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