Experimental study on the evolution of rock strength and sealing properties under multi-cycles alternating loading

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Abstract. Different from the long-term and low-speed depletion of conventional gas fields or monotonous gas injection in carbon dioxide geological sequestration, the engineering background of multi-cycle intensive injection and production of underground gas storage (UGS) makes the dynamic sealing capacity and stability of the trap cap and pipe string under alternating load become the key problem that cannot be ignored. Firstly, the basic mechanical parameters of sandy mudstone and G-grade oil well cement were determined by conventional uniaxial tests, then different upper load levels and alternating times were set to carry out alternating mechanical tests for sandy mudstone and G-grade oil well cement stone. The deformation, failure and stress-strain curve characteristics of the two types of rocks were analyzed, and the variation laws of the strength and elastic modulus with the upper stress and the alternating times of the two types of rocks were obtained: The strength of cement stone decreases, while that of sandy mudstone increases with the increase of upper limit stress and alternating times, and the reasons for the different laws of the two types of rocks were further analyzed. Then, after undergoing different alternating times with different upper load levels, the dynamic breakout pressure tests of two types of rocks were carried out by the step-by-step method. The results show that the breakthrough pressure of the two types of rocks decreased gradually and significantly with the increase of the alternating times. The dynamic evolution prediction model of the breakthrough pressure with the alternating times was established. And because the breakthrough pressure of the cement stone in the nondestructive state exceeds the measuring range of the equipment, the initial breakthrough pressure of the cement rock was also predicted by the prediction model of the breakthrough pressure. All of these results above can be significant reference value for the sealing evaluation of gas storage site selection and the real-time monitoring after it is put into operation.

Key words. Underground gas storage; Sandy mudstone; Oil well cement; Alternating load; Dynamic sealing capacity
1. Introduction
Underground gas storage is an important part of the pipeline transportation system. It not only adjusts the balance between supply and demand in the daily natural gas supply to achieve stable supply, but also plays an irreplaceable role in the emergency state of accidents. The gas storage shall complete at least one injection and recovery of its working gas volume within a year. Such multi-cycle and large-flow operation mode of strong injection and strong production will lead to formation stress alternating, which will cause damage and even failure to the caprock and wellbore of the gas storage, further destroy the sealing property of the gas storage trap and cause natural gas leakage accidents[1].

Rock mechanics characterization under alternating loads is one of the key bases for quantitative evaluation of sealing capacity and integrity of gas storage. Low-cycle fatigue strength characteristics of rocks are studied mainly through mechanics tests under alternating loads, and their deformation and failure characteristics are also very different from those under static loads. Studies have shown that the fatigue life of samples under cyclic loading and unloading is closely related to the load waveform, loading rate, and the upper and lower stress levels [2-4]. Xu et al. [5] and Zhou et al. [6] carried out cyclic loading and unloading experiments, and compared the strength after cyclic loading and unloading and that of uniaxial compression. Some scholars [7-8] further analyzed the change law of Young’s modulus and Poisson's ratio of rock materials in the process of loading and unloading.

According to the working characteristics of multi-cycle alternating injection and production of gas storage, Ma et al. [9] put forward the concept of cap dynamic breakthrough pressure, which refers to the gas sealing capacity under the condition that the alternating stress causes the change of cap microstructure or the generation of micro-cracks, so as to quantitatively evaluate the capillary dynamic sealing capacity of gas storage. Sun et al. [10] carried out the dynamic breakthrough pressure test of cap rock, and preliminarily confirmed that the breakthrough pressure value of cap rock would be reduced to a certain extent after alternating cycles.

Based on the above analysis and the engineering background of gas storage, this paper carried out the alternating mechanical strength test and dynamic sealing test of sandy mudstone and G-grade oil well cement stone, which can provide reference for the follow-up study on the geomechanical effects of gas storage injection and production.

2. Characteristics of strength evolution under multi-cycle alternating loads

2.1. Uniaxial monotonous loading
Six samples of sandy mudstone and grade G-grade oil well cement were selected for uniaxial compression test. The loading method, displacement control and the loading rate, 0.001mm/s, were selected to obtain the peak loads and average value P. The average compressive strength of sandy mudstone is 76.32MPa, while that of cement stone is 53.7MPa. The load-displacement curves can be mainly divided into the compaction stage, elastic stage, yield stage and post-peak failure stage. The failure modes of the two kinds of materials are tensile failure (figure 1).

![Figure 1. Load-displacement curves of samples and states after failure of two kinds of materials under uniaxial compression.](image-url)
2.2. Uniaxial alternating loading

Three different sets of upper limit loads were set (0.6-0.8P for sandy mudstone; 0.5-0.7P for oil well cement). The loading and unloading rates were all 1kN/s, and the alternating times were 20, 40 and 60 times, respectively. At the end of cyclic loading and unloading, the sample was loaded at a displacement control rate of 0.001mm/s to failure (figure 2).

![Figure 2. Schematic diagram of uniaxial alternating loading.](image)

By comparing the stress-strain curves of uniaxial cyclic loading and conventional uniaxial compression (figure 1 and figure 3), it can be seen that, except for the cyclic process, the complete stress-strain curves of all samples are highly similar and can be divided into four stages: compaction stage, elastic stage, yield stage, and post-peak failure stage.

![Figure 3. Typical stress-strain curves and states before & after failure of two kinds of materials under uniaxial alternating loading.](image)

With the continuous cyclic loading and unloading, the stress-strain curves of the loading and unloading of the two kinds of materials both appear concave curves, and the stress-strain hysteresis loop continuously “migrates” forward and presents a trend from sparse to dense (figure 4). The analysis shows that for a single loading and unloading process, the stress increases gradually during the loading stage, the pore compacts gradually, and the elastic modulus increases dynamically. In the unloading stage, the stress decreases gradually, some of the compacted pores spring back, and the elastic modulus decreases dynamically. It is because only part of the compacted pores spring back that the residual strain is produced. During the first loading, the defects at the end of the sample were flattened and the internal defects were compacted, but some defects were still not compacted. With the increase of cyclic loading and unloading times, the pores inside the sample are gradually compacted. With the increase of loading and unloading times, the remaining pores that can be compacted decrease gradually, and the residual strain generated also decreases gradually. Therefore, the stress-strain hysteresis loop in the loading and unloading part of the stress-strain curve is a concave curve and migrates forward in a trend from sparse to dense.
Figure 4. Migration of stress-strain hysteretic loop (0.7P 60Cycles).

For the sandy mudstone, after the loading and unloading cycles, the residual strength of the sample increases with the increase of the upper limit load and the number of cycles (figure 5). Except for Sample (0.6P&20Cycles), which showed no significant difference between the residual strength and the uniaxial compressive strength, the residual strength of other samples after cycling increased in different degrees compared with the uniaxial compressive strength. The residual strength of Sample (0.6P&20Cycles) is 76.08MPa, which is 0.31% lower than the average uniaxial compressive strength of 76.32MPa. Therefore, it can be considered that the upper limit load of 0.6P cycles & 20 Cycles have no effect on the strength of sample.

Figure 5. Residual strength evolution of sandy mudstone under different upper limit loading and alternating cycles

For oil well cement, the residual strength decreases with the increase of the upper limit load and the number of cycles (figure 6). Except for the three samples with the number of cycles of 20, the residual strength of the other samples decreases in different degrees compared with the uniaxial compressive strength after the cycle. The residual strength values of Sample (0.5P, 0.6P, 0.7P&20Cycles) are
65.14MPa, 56.09MPa and 54.41MPa, respectively, which are 21.30%, 4.45% and 1.32% higher than the average uniaxial compressive strength of 53.7MPa, respectively.

The compaction can be characterized by the evolution relationship of Young’s modulus with the number of cycles. On the stress-axial strain curve, the minimum stress value (\(\sigma_{\text{min}}\)) and the corresponding axial strain (\(\varepsilon_{\text{min}}\)) of each cycle as well as the stress (\(\sigma_b, \sigma_e\)) and the corresponding strain (\(\varepsilon_b, \varepsilon_e\)) of the starting and ending points of the cycle can be determined, and the elastic modulus can be calculated according to:

\[
E = \frac{(\sigma_b + \sigma_e)/2 - \sigma_{\text{min}}}{(\varepsilon_b + \varepsilon_e)/2 - \varepsilon_{\text{min}}}
\]

(1)

According to the analysis, for the material with large porosity (e.g. sandy mudstone), low-cycle compression mainly plays a compaction role on the sample. The more cycles and the higher the upper limit load, the more obvious the compaction, the more obvious the Young's modulus increases (figure 7), and the higher the residual strength of the sample. If no obvious local failure inside the sample, during the unloading process, the inter-bedding structure of new fractures was restored and readjusted, and the friction strength between fracture surfaces was increased, thus, the phenomenon of strengthening after cyclic loading occurs, and this phenomenon is consistent with the conclusion drawn in reference [5].

**Figure 7.** Young’s modulus evolution law of sandy mudstone under different upper limit loading and alternating cycles.

For the material with small porosity (e.g. oil well cement), the samples were mainly compacted and Young's modulus increases slightly when the number of alternating cycles is small. With the increase of the number of cycles, the samples could not be further compacted, mainly due to the generation, expansion and penetration of new cracks, and Young’s modulus decreased accordingly (figure 8), thus the phenomenon of residual strength deterioration occurs.

**Figure 8.** Young’s modulus evolution law of oil well cement under different upper limit loading and alternating cycles.
3. Characteristics of sealing capacity evolution under multi-cycle alternating loads

A dynamic breakthrough pressure test was carried out (figure 9). A total of three sandy mudstones (upper limit of 0.6P, 0.7P and 0.8P, respectively) and one cement sample (upper limit of 0.5P) were selected, and the lower limit was set at 0.1P. First, the initial breakthrough pressure was tested according to SY/T 5748-2020 Rock Gas Breakthrough Pressure Measurement Method. Then, the breakthrough pressure was measured after each cycle of 20 times for a total of 60 cycles.

There is no crack in the sample at the initial stage of loading, but small cracks appear on the surface of the sample after the first cyclic loading. During the second cyclic loading, the intermittent cracking sound can be heard during the loading process, and many cracks appear on the surface of the sample after loading. When the gas pressure reaches 15.62MPa, it is found that 3 ~ 4 intermittent bubbles emerge. After the third cyclic loading (figure 10), more and larger cracks appear on the surface, and bubbles continue to emerge when gas breaks through (11.28MPa). At this time, large damage has been generated inside the sample. With the increase of the number of cycles, the gas breakthrough pressure gradually decreases, indicating that the damage inside the sample is gradually increasing (figure 11).

![Figure 9. Gas breakthrough pressure test device](image)

(a) Displacement-load curve

(b) Gas pressure loading curve

![Figure 10. The third cyclic loading](image)

The static breakout pressure value $P_{d0}$ was taken as the initial value of the dynamic breakout pressure, and the breakout pressure value $P_{dr}$ after cyclic alternating 60 times was taken as the residual value. According to the above test results of breakout pressure, at a certain alternating stress...
level, the breakout pressure of rock gradually decreased with the alternating cycles, and the power function model was used to fit, as follows:

$$P_d = P_{d0} - (P_{d0} - P_{d})\left(\frac{n}{60}\right)^m$$

Where, $n$ is the number of cycles and $m$ is the fitting parameter.

**Figure 11.** Breakthrough pressure changing with cycles

The fitting results and parameters of dynamic breakthrough pressure of the two types of rock materials are shown in figure 12, and the initial breakthrough pressure of cement is predicted. It can be seen that the greater the alternating stress level is, the more obvious the accumulated damage is with the increase of the alternating times, the obvious changes occur in the rock pores, and the breakthrough pressure value significantly decreases, and the decreasing rate is more obvious in the early stage and gradually becomes stable in the later stage.

**Figure 12.** Dynamic breakthrough pressure fitting curves of two kinds of materials under different upper limit loads

4. Conclusions

Based on the background of underground gas storage, the multi-cycle alternating loading mechanical test and dynamic breakthrough pressure test of sandy mudstone and G-grade oil well cement under different upper limit loads and cycle number have been carried out, and the following conclusions have been obtained:

(a) As the porosity of sandy mudstone is quite large, the low-cycle compression mainly plays a compaction role on the sample, and the more the cycles and the greater the upper limit loads, the more obvious the compaction and the more obvious the strengthening effect on the sample.

(b) As the oil well cement is relatively dense, the compaction mainly occurs when the number of cycles is relatively small. When the number of cycles is relatively large, the cracks in the sample gradually initiate, develop and coalesced, thus the strength of the sample deteriorates. The higher the upper limit load is and the more cycles are, the more obvious the deterioration phenomenon is.
(c) As for the breakthrough pressure, the higher the upper limit load is and the more cycles are, the smaller the breakthrough pressure is. The evolution model of the dynamic breakthrough pressure is established, which has a high correlation with the experimental data, and can provide a reference for the dynamic breakthrough pressure test of other materials.

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