Experimental study on creep behavior of rock salt under complex stress paths

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ABSTRACT: To study the effect of stress path on the creep behaviors of rock salt, multi-stage loading and unloading of confining pressure creep tests under constant axial pressure have been carried out on rock salt samples. The results as follows: (1) Confining pressure is the dominant factor of deformation and can effectively restrain the propagation of microcracks in rock salt. (2) Strain hardening behavior of rock salt samples is observed during the loading process. Internal stress with the property of self-weakening grows and changes constantly with loading time, and the time required for weakening is relevant to the stress state and loading history. (3) Creep of rock salt is caused by effective stress, which is the difference between differential stress and internal stress. Whether the initial creep stage occurs and the delay time to the entry of a steady-state creep stage is related to the loading path.

Keywords: rock salt; creep tests; stress path; loading and unloading; deformation mechanism.

1 INTRODUCTION

The United Nations Climate Change Conference, held in 2015, adopted the Paris Agreement, signed by 195 countries. It requires countries around the world to keep the global average temperature rise to within 2 °C of pre-industrial revolution levels (E. Liu et al., 2019). Using sustainable energy sources (like wind and solar energy) is an effective means to achieve this goal (Li et al., 2022). The use of energy storage devices for sustainable energy generation can effectively solve this problem (Parkes et al., 2018). Rock salt is considered as the best storage medium to build the compressed air energy storage (CAES) power plant, due to its small porosity, low permeability, high plasticity, self-healing characteristics (Li et al., 2023; Schlichtenmayer & Klafki, 2016). And underground salt cavern gas storages have been extensively used at home and abroad (Fan et al., 2019; van Thienen-Visser et al., 2014). Moreover, the abundance of domestic rock salt resources is advantageous for building new gas storages in China (W. Liu et al., 2019).

During the operation of cavern storages, the volume shrinkage of the cavern will occur and the shrinkage of the cavern is affected by the creep property of the salt rock. In order to control the volume shrinkage ratio within a certain range to ensure the economy and safety stability of the cavern storages, it is of great significance to study the creep property of the salt rock. The creep of salt rock determines the deformation of the surrounding rock of the cavern. In addition, the service life of the storage is usually longer than 50 years, during which the time effect of salt rock is very significant (Hunsche & Hampel, 1999). Many creep tests have been conducted to study the creep characteristics of salt rock under various stress conditions (Urai et al., 1986; Yang et al., 1999; Pouya et al., 2016).

However, the demand for natural gas are changing seasonally to meet the requirement of peak-shaving, and thus the actual stress state of surrounding rock changes with the injection and withdrawal of natural gas during the operation of a storage (Moghadam et al., 2013). For these reasons, creep tests under fixed stress path are too simple to fully reflect the stress state of salt rock in service. In order to study the creep characteristics of salt rock under complex stress path, two multi-stage creep tests were carried out in this paper, and the creep characteristics of rock salt under different loading paths were analyzed. This study is a basical reference for the natural gas storage in underground salt caverns.

2 EXPERIMENT

2.1 Samples and test equipment

Jintan salt mine of Jiangsu province is the first natural gas site in salt cavern in China and Asia, and a total gas storage capacity of 26×108 m^3 is planned in this mine. And the rock salt samples used in tests were obtained from Jintan salt mine and is located at a depth of 720~1035 m. These samples are grey-black with the main component of NaCl and evenly distributed impurities of argillaceous. According to the standard testing method of ISRM, all samples are processed into a cylinder with a diameter of 50 mm and a height of 100 mm, and the machining accuracy is 1%. The processed samples are shown in Fig.1(a).

Figure 1. (a) Processed rock salt sample for the creep tests, (b) Triaxial Rheological Test System RC-2000.

Creep tests are carried out with Triaxial Rheological Test System RC-2000 (Fig.1(b)). The fuel tank of the main engine is placed blow, and the loading frame with the shape of the doorframe is adopted for its high rigidity. The DOLI all-digital servo controller imported from Germany has the advantages of high control precision, complete protective functions, high reliability, and expansibility.

2.2 Test procedures

The depth of Jintan salt cavern gas storage is about 900~1,000 m and the in-situ stress is roughly 20 MPa. To simulate the creep behavior of the cavern surrounding rock under the influence of internal pressure changes when formation pressure is fixed, multi-stage loading and unloading of confining pressure creep tests under a constant axial pressure of 30 MPa are carried out. The initial confining pressure is 5 MPa/20 MPa and four stages of creep test with a gradient of 5 MPa per stage are carried out (two different tests with different initial confining pressure and loading order). Testing procedures are as follows.

1) The hydrostatic pressure is loaded at a speed of 0.1 MPa/s until the design confining pressure is reached. Axial strains and circumferential deformation are recorded and then cleared after stabilized.

2) Keep confining pressure σ3 unchanged, and σ1 is loaded to design axial stress at a speed of 0.1 MPa/s and then kept constant. Then carry out the first stage of creep test.

3) The confining pressure then loads/unloads to the design value at a speed of 0.1 MPa/s after the previous loading stage enters the steady-state creep stage. Meanwhile, the axial pressure is applied at a speed of 0.1 MPa/s to ensure that σ1 remains unchanged during the whole test.

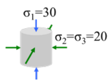
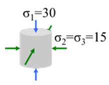
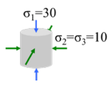
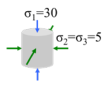
4) Save results after finishing the creep test. Unload the axial pressure first and then the confining pressure. Return the oil, then take out the sample and take photos.

3 TEST RESULTS

3.1 Analysis of results of multi-stage unloading of confining pressure creep test under constant axial pressure

To simulate the creep behavior of the cavern surrounding rock under the influence of internal pressure decreases when formation pressure is fixed, multi-stage unloading of confining pressure creep test under a constant axial pressure of 30 MPa is carried out. The confining pressure is loaded to 5 MPa from 20 MPa in four successive stages, and the gradient is 5 MPa per stage. This test lasted 655 hours (roughly 27 days), and details of four stages in this creep test are listed in Table 1.

Table 1. Details of multi-stage unloading of confining pressure creep test.

Stage	1st	2nd	3rd	4th
Stress state				
Confining pressure	20 MPa	15 MPa	10 MPa	5 MPa
Axial pressure	30 MPa	30 MPa	30 MPa	30 MPa
Differential stress	10 MPa	15 MPa	20 MPa	25 MPa
Duration	155 h	185 h	190 h	125 h
Steady-state creep rate /%/h	2.344E-5	3.829E-4	0.00375	0.092

The variation of axial strain with time in the multi-stage unloading of confining pressure creep test under constant axial pressure is shown in Fig.2. For brittle material, its creep can be generally divided into instantaneous creep and accelerated creep. While for soft rock, such as rock salt, having a significant time effect under constant stress, its creep can be divided into initial creep with decreasing creep rate and steady creep with basically constant creep rate.

During the first three stages of creep test (t_{total} = 530 h) with confining pressure higher than 10 MPa, the creep is slow and the total axial strain of these three stages is less than 2%. During the first stage, the creep rate decreases continuously during the early 20 hours, and then remains basically constant and enters the steady-state creep stage. However, creep of the salt rock sample enters the steady-state stage quickly and shows remarkable deformation capability during the fourth stage of the creep test with a low confining pressure of 5 MPa. In this stage, the creep of the sample doesn't enter the accelerated creep stage even if the axial strain reaches 15%. With the existence of confining pressure, deformation of rock salt is mainly dislocations rather than the propagation of cracks, thus failure is hard to occur in rock salt.

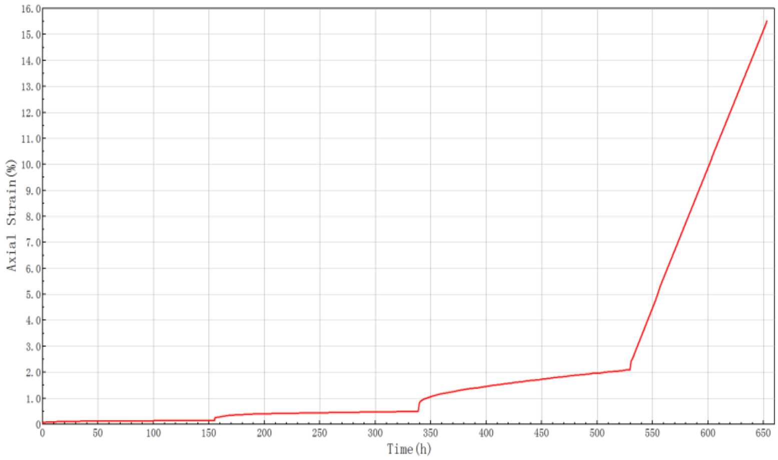
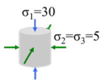
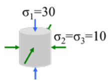
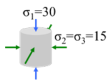
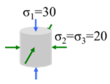


Figure 2. The creep curve of multi-stage unloading of confining pressure creep test.

3.2 Analysis of results of multi-stage loading of confining pressure creep test under constant axial pressure

To simulate the creep behavior of the cavern surrounding rock under influence of internal pressure increases when formation pressure is fixed, multi-stage loading of confining pressure creep test under a constant axial pressure of 30 MPa is carried out. The confining pressure is loaded to 20 MPa from 5 MPa in four successive stages, and the gradient is 5 MPa per stage. The test lasted 140 hours, and details of four stages in this creep test are listed in Table 2.

Table 2. Details of multi-stage loading of confining pressure creep test.

Stage	1st	2nd	3rd	4th
Stress state				
Confining pressure	5 MPa	10 MPa	15 MPa	20 MPa
Axial pressure	30 MPa	30 MPa	30 MPa	30 MPa
Differential stress	25 MPa	20 MPa	15 MPa	10 MPa
Duration	25 h	40 h	35 h	40 h
Steady-state creep rate /%/h	0.0759	0.00411	0	0

The variation of axial strain with time in the multi-stage loading of confining pressure creep test under constant axial pressure is shown in Fig.3. With higher differential stress and lower confining pressure, the axial strain of the first stage is much larger than of the latter three stages with an incredibly small variation. The variation range of axial strain of the second, third and fourth stage is 3.4%-3.5%, and the interval of each stage is no larger than 0.05%. The results of this creep test are quite different from the multi-stage unloading of confining pressure creep test with opposite loading order in Section 3.1 (Fig.2), which reflects the impact of confining pressure and its loading order on creep behavior of rock salt. Confining pressure can effectively restrain the deformation of the sample, and the way of unloading confining pressure can accelerate creep.

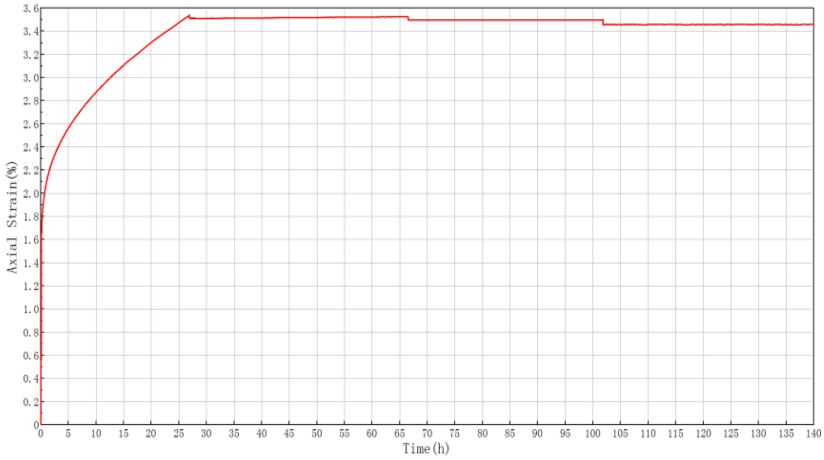


Figure 3. The creep curve of multi-stage loading of confining pressure creep test.

4 DISCUSSION

Mechanical properties and dilatancy properties of rock salt depend on hydrostatic pressure (Cristescu, 1994). Under low confining pressure and high differential stress, strain accumulation of intragranular and intergranular microcracks, grain rotation and intergranular slip is the cause of brittle failure of rock salt. Microcrack propagation and dilatancy of rock salt samples are restrained by high confining pressure (Chan et al., 1997), and the crystal plasticity plays a dominant role in this process. Under high confining pressure, influences caused by micro-crack and local damage at the beginning of loading can be eliminated by deformation coordination in the later stage of creep, without affecting overall bearing capacity.

Analyzing the steady creep rate of rock salt is of great engineering significance in studying the long-term operation of salt cavern gas storages. The differential stress of stage 1 (or 2) of multi-stage loading-unloading creep test is the same with that of stage 2 (or 3) of multi-stage unloading of confining pressure creep test, and steady creep rates of these two stages are of the same order of magnitude. The former stage with lower confining pressure than the latter has a larger steady creep rate, and this indicates that the steady creep rate is mainly influenced by confining pressure when differential stress is the same. The steady-state creep rate is affected by both differential stress and confining pressure, and the former is the main factor.

5 CONCLUSION

To study the effect of stress path on creep behavior of rock salt, multi-stage loading and unloading of confining pressure creep tests under constant axial pressure have been carried out on rock salt samples from Jintan, the following conclusions were drawn:

(1) Confining pressure is the dominant factor of deformation and can effectively restrain the propagation of microcracks in rock salt. Volume expansion of samples is more likely to occur when confining pressure is lower than 10 MPa, and local damage is prone to occur during unloading of confining pressure. The steady-state creep rate is the function of confining pressure and differential stress, and it is independent of loading history.

(2) Strain hardening behavior of rock salt samples is observed during the loading process. Internal stress with the property of self-weakening grows and changes constantly with loading time, and the time required for weakening is relevant to the stress state and loading history.

(3) Creep of rock salt is caused by effective stress. When effective stress is higher than 0, the test enters the initial creep stage of the next creep stage test; if the effective stress is lower than or equal to 0, the creep stagnates or delays, and directly enters the steady-state creep stage with constant creep rate. The initial creep stage is related to the loading path.

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