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Experiments on mechanical properties of salt rocks under cyclic loading

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Abstract: The primary purpose of underground gas storages is to provide gas for seasonal consumptions or strategic reserve. The periodical operations of gas injection and extraction lead to cyclic loading on the walls and surrounding rocks of gas storages. To investigate the mechanical behaviors of different host rocks in bedded salt deposit, laboratory experiments were conducted on the samples of rock salt, thenardite, glauberite and gypsum. The mechanical properties of rock samples under monotonic and cyclic loadings were studied. Testing results show that, under monotonic loading, the uniaxial compressive stress (UCS) of glauberite is the largest (17.3 MPa), while that of rock salt is the smallest (14.0 MPa). The UCSs of thenardite and gypsum are 16.3 and 14.6 MPa, respectively. The maximum strain at the peak strength of rock salt (halite) is much greater than those of the other three rocks. The elastic moduli of halite, thenardite, glauberite and gypsum are 3.0, 4.2, 5.1 and 6.8 GPa, respectively. Under cyclic loading, the peak strengths of the rock specimens are deteriorated except for rock salt. The peak strengths of thenardite, glauberite and gypsum decrease by 33.7%, 19.1% and 35.5%, respectively; and the strains of the three rocks at the peak strengths are almost the same. However, the strain of rock salt at the peak strength increases by 1.98%, twice more than that under monotonic loading. Under monotonic loading, deformation of the tested rock salt, thenardite and glauberite shows in an elastoplastic style. However, it changes to a ductile style under cyclic loading. Brittle deformation and failure are only observed for gypsum. The results should be helpful for engineering design and operation of gas storage in bedded salt deposit.

Key words: salt rock; mechanical behavior; bedded salt deposit; gas storage; cyclic loading

1 Introduction

To meet seasonal demand or crisis requirement on gas consumption, underground gas storages become indispensable. Gas is injected into the storages and reserved in off-seasons. When demanded, the stored gas will be extracted to supply the markets and consumers, thus periodical injection and extraction of gas are frequently encountered. From the point of view of rock mechanics, the periodical injection and extraction actually lead to cyclic loading on the storage walls and surrounding rocks.

It has been widely reported that cyclic loading may deteriorate the strength of rocks (granite, sandstone, marble, mudstone, etc.) because of crack initiation and propagation as cyclic loading proceeds (Xi et al., 2004; Navarro et al., 2005; Wang and Yin, 2005; Xu et al., 2005; Yu et al., 2005; Choi et al., 2006; Zhou et al., 2006; Xu et al., 2008; Yun and Palazotto, 2008; Ladani and Dasgupta, 2009; Chen et al., 2011). For newly formed cracks are orientated predominantly in parallel or sub-parallel to the cyclic loading axis, damage occurs in the same zones and increases with cycle number (Chow et al., 1995). Consequently, the strength of rocks gradually decreases with the increase in cycle number (Dubey and Gairola, 2000).

It is found that loading frequency, as well as loading amplitude, is of significance and has great influences on the rock behaviors under dynamic cyclic loading conditions. The dynamic strength and dynamic axial stiffness of rocks decrease with loading frequency and amplitude (Bagde and Petros, 2005), while the dynamic modulus increases with loading frequency but decreases with loading amplitude. Therefore, rock deformation under cyclic loading is controlled by loading frequency and amplitude, as well as by

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geometry of intermittent cracks (Xu et al., 2006). Under cyclic loading, rock can fail in different modes, varying from brittle to ductile in response to microcracking, which are influenced by initial anisotropy, especially under unconfined conditions (Dubey and Gairola, 2000; Gatelier et al., 2002).

Due to limitation of salt dome available in China, underground gas storages have to be constructed in bedded salt deposits where interlayers are frequently observed. The lithologies of interlayers are basically thenardite, glauberite, gypsum, mudstone, etc. In the literature, the physico-mechanical properties of halite and thenardite have been tested (Yoshinaka and Tran, 1997; Liang and Zhao, 2004; Liang et al., 2007, 2008, 2009, 2011; Xu et al., 2008b, 2009; Yang et al., 2009; Gao et al., 2011). However, the mechanical properties of salt rocks under cyclic loading were less reported. Here, we use “salt rock” or “evaporite” to refer to any lithotype found in a salt rock sequence, whereas “rock salt” specifically refers to a bed or specimen of halite. To investigate the mechanical behaviors of different salt rocks under cyclic loading, laboratory uniaxial compression tests were conducted on four common lithologies in bedded salt deposits. The testing process and results are presented and preliminarily analyzed in this paper.

2 Sampling and testing methodology

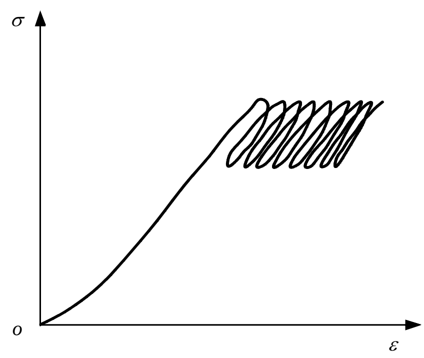
In bedded salt deposits, interlayers of glauberite and gypsum are commonly found apart from salty mudstone. To compare the mechanical properties of these evaporites, samples of halite, thenardite, glauberite and gypsum were collected from salty sedimentary deposits in Jiangsu, Sichuan and Shanxi provinces of China, respectively. A set of three to five standard cylindrical specimens, in sizes of ϕ50 mm×100 mm, was prepared in laboratory for each lithology. By using the servo-controlled mechanical test equipment TYT-600, uniaxial compression tests on the prepared specimens were carried out under cyclic loading and monotonic loading, respectively. The tested four lithologies are representatively shown in Fig.1.

Two types of cyclic loading tests are often performed in laboratory as shown in Fig. 2. For the first type, the cyclic loading is performed between two prescribed limits; while for the second type, the upper limit of cycles is increased from one cycle to the next. The cyclic loading performed in our experiments combined

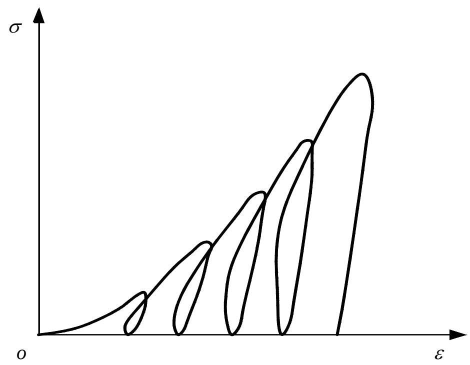
(a) Halite. (b) Thenardite.

(c) Glauberite. (d) Gypsum.

Fig. 1 Samples of four lithologies in bedded salt deposits.



(a) Cyclic loading between two prescribed limits (the first type).



(b) Increasing loads from one cycle to the next (the second type).

Fig. 2 Schematic diagrams of axial strain-axial stress curves for cyclic loading tests.

the above two types of loadings, namely, the lower limit of cycles was prescribed but the upper limit was increased in each cycle. The lower limit was prescribed at 4–5 MPa, and the upper limit at 2–3 MPa greater than the former one in each cycle till the test specimens fail at the peak strength. The loading frequency and amplitude in the tests were artificially controlled. In addition, the cycle number was also limited due to function limitation of the test equipment. However, the cyclic loading paths could still be traced to well simulate the loading-unloading process of gas storage in salt caverns during gas injection and extraction operations.

In the tests, the loading strain rate for cyclic or monotonic loading was controlled at 2×10^{-5} s^{-1}, and the unloading ratio was automatically controlled by the testing system. The stress-strain curves of the tested specimens were automatically recorded.

3 Testing results

3.1 Peak strength and elastic modulus

Table 1 shows the testing results of specimens under uniaxial compression by monotonic loading. It shows that the glauberite has the largest peak strength (17.3 MPa) and the smallest peak strain (0.3×10^{-2}), while the halite has the smallest strength (14.0 MPa) and the largest strain (0.86×10^{-2}). The peak strength of thenardite is close to that of glauberite. For gypsum, the average peak strength is small (14.6 MPa), due to numerous fabrics scattered in the rock, which can be observed on its surface (Fig. 1(d)). Elastic modulus represents the mechanical behaviors of materials in the period of elastic deformation. It is directly proportional to stress difference while inversely proportional to strain. In this study, the elastic moduli of halite, thenardite, glauberite and gypsum are 3.0, 4.2, 5.1 and 6.8 GPa, respectively. It demonstrates that great deformation differences occur between halite and other interlayers when they are subjected to the same loading.

Table 1 Testing results of salt rocks under uniaxial compression by monotonic loading.

Lithology	UCS (MPa)	Strain (10^{-2})	Elastic modulus (GPa)
Halite	14.0	0.86	3.0
Thenardite	16.3	0.45	4.2
Glauberite	17.3	0.3	5.1
Gypsum	14.6	0.39	6.8

However, the mechanical parameters of halite and other interlayers change greatly under cyclic loading. As shown in Table 2, halite becomes strongest with the largest peak strength of 15.6 MPa, a value even larger than that under monotonic loading. Such a variation in strength is definitely different from that of other interlayers. The peak strength of all other tested interlayers decreases significantly under cyclic loading. The strengthening of halite under cyclic loading could be mostly resultant from the physical difference of the test specimens, as shown by Yang et al. (2009) in experiments. The size and cohesion of mineral grains are different for each halite specimen, which leads to different mechanical responses under different loading paths. The deformation mechanism of evaporite sedimentary rocks under cyclic loading, including halite and salty interlayer, needs further studies.

Table 2 Testing results of salt rocks under uniaxial compression by cyclic loading.

Lithology	UCS (MPa)	Strain (10^{-2})	Elastic modulus (GPa)	E_d (GPa)	A_m (10^{-2})
Halite	15.6	1.98	2.27	8.64	<0.001
Thenardite	10.8	0.42	4.37	14.0	0.008
Glauberite	14.0	0.25	7.43	14.68	0.005
Gypsum	9.42	0.24	4.05	11.13	0.005

Note: E_d is the deformation modulus, defined as the average ratio of stress difference to strain difference in each cycle during loading and unloading; A_m is the maximum magnitude of strain, which is defined as the strain difference at the maximum aperture of hysteresis loops between loading and unloading in each cycle.

Compared with the results under monotonic loading, the peak strengths of four rock samples under cyclic loading are decreased to various extents. The decreasing amplitudes for thenardite, glauberite and gypsum are 34%, 19% and 35%, respectively. The effect of loading paths on the mechanical behaviors of rocks is demonstrated. Under cyclic loading, the elastic modulus, defined as the slope gradient of linear segment of stress-strain curves, of the test salt rocks is in the same order of magnitude as that under monotonic loading, showing a general elastic property of rocks in the period of elastic deformation.

These changes in elastic modulus under different loading conditions are clearly related to mineral constitutions and internal structures of the test specimens. Halite and thenardite are in the form of crystal structure and relatively pure in composition. However, glauberite and gypsum are heterogeneous and consequently anisotropic. Glauberite contains more than 30% of clay or other impurities, which controls its mechanical behavior. In gypsum, distinct nervations of calcium sulphate with the width of 1 mm are often found on the surface. The nervations form weak joint planes in the glauberite. Shear sliding can easily take place along the weak planes under exterior loads. The geometry and density of weak joint planes consequently determine the mechanical behavior of gypsum. Heterogeneity and anisotropy substantially affect the mechanical behavior of salt rocks under different loading schemes, as demonstrated by Dubey and Gairola (2000).

3.2 Deformation and failure

Different rocks have different mineral grains and inner-structures, which response to different loading paths in different ways. Testing results by Yoshinaka et al. (1997) demonstrated that deformation is strongly dependent on rock lithologies and loading paths. This is typically the case for the evaporite sedimentary rocks. Yang et al. (2009) found that the unloading deformation modulus is higher than the loading deformation modulus, while the loading Poisson's ratio is higher than the unloading one. Tang et al. (2010) also suggested that the elastic modulus measured by cyclic loading-unloading curve is better than that measured directly from the primary loading curve.

Fig. 3 shows the stress-strain curves of salt rocks under uniaxial compression by monotonic loading. It indicates that halite, thenardite and glauberite behave in elastoplastic properties under monotonic loading, and they fail in a similar ductile way except for gypsum. The strains at the peak strengths of halite, thenardite and glauberite are 0.86×10^{-2}, 0.45×10^{-2} and 0.3×10^{-2}, respectively. The differences of mineral grains and inner-structure among the salt rocks are preliminarily demonstrated. Halite and thenardite are crystallized salt rocks, the composition of which are relatively pure and the crystal grains are directly bonded with each other. Thus, the main deformation mechanisms of crystallized salt rocks are grains sliding along boundaries, as observed by Chen et al. (2011). Large grains generally have long boundaries and large deformations under proper loading. Halite is just the case. The grain size of halite is often several times as that of thenardite. Consequently, halite has a larger strain at peak strength than thenardite.

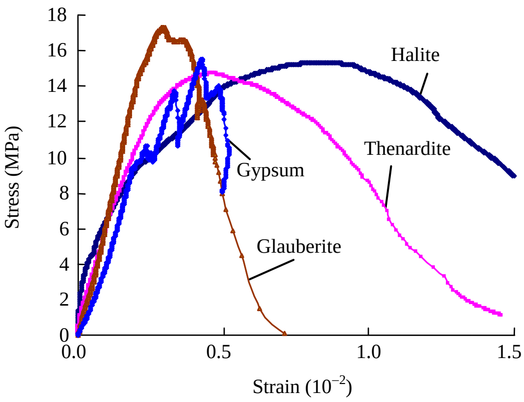


Fig. 3 Stress-strain curves of salt rocks under uniaxial compression by monotonic loading.

Glauberite is a combination of sodium sulfate and calcium sulphate, and it also contains 30% of other impurities such as clay. The mineral grains are cemented by the contained clay. Thus, the deformation characteristics of glauberite depends on the cementation to a great extent. For gypsum, distinct brittle failure from the other three rocks is illustrated in Fig. 3. Three yielding stages of glauberite occur during loading process, as shown in Fig. 3. In Fig. 4, clear white thin structures are shown on the surfaces. The thin pure calcium sulphate nervation bands are mechanically weak, and shear sliding can easily occur when the applied stress exceeds its strength, especially under lower confining stresses. The deformation of gypsum in the tests clearly demonstrates its anisotropy and heterogeneity.

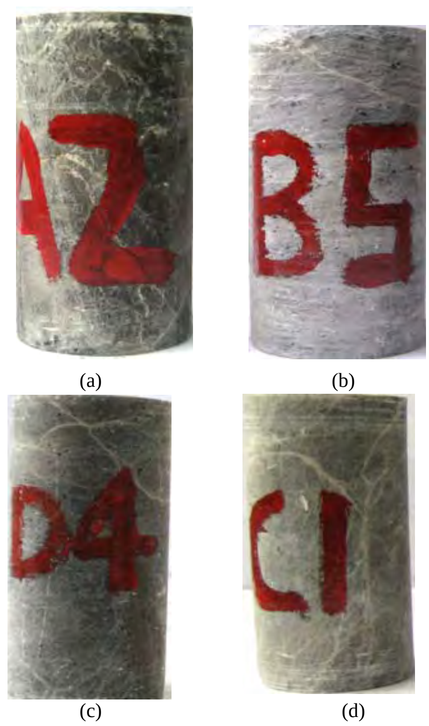
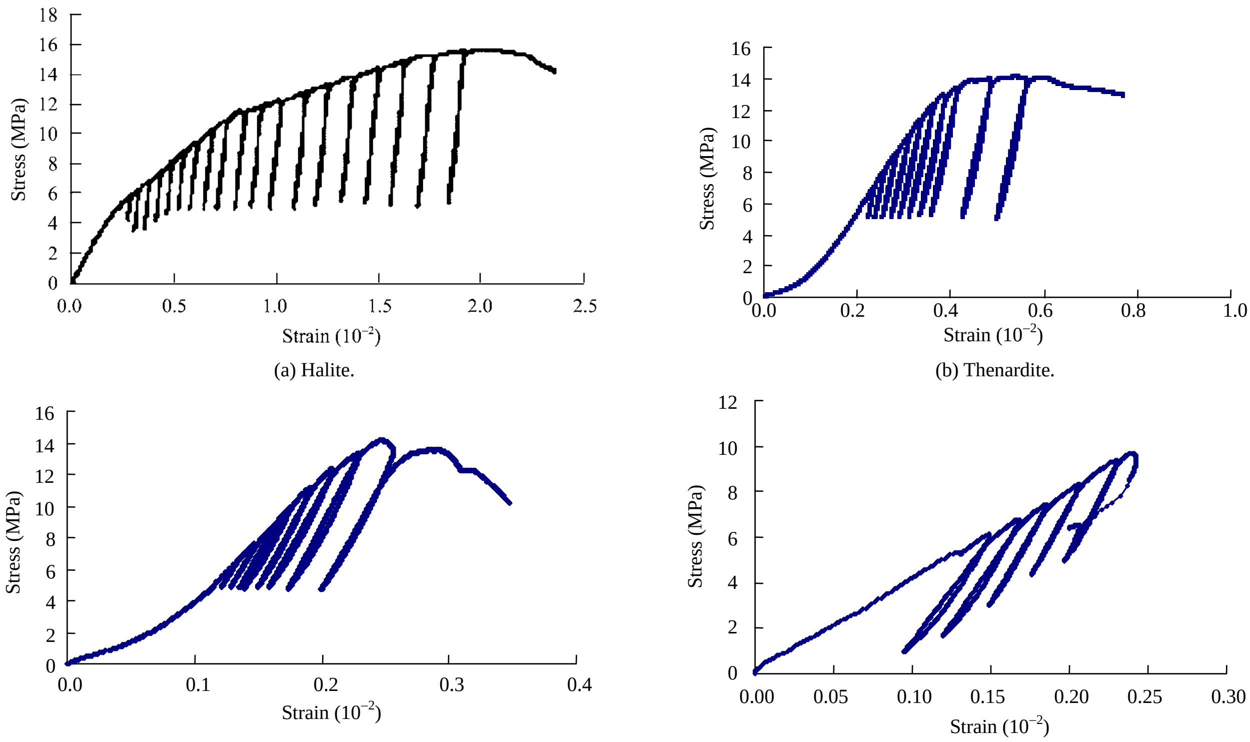


Fig. 4 Gypsum specimens before testing (clear white thin structures are shown on the surfaces).

During the process of cyclic loading (compression), deformation and failure modes of salt rocks are altered, compared to those under monotonic loading. Figs. 5(a) and (b) show the stress-strain curves of halite and thenardite. Under cyclic loading, the deformation of crystal salt rocks shows the characteristics of elastoplastic and viscous flow as intragranular cracks develop (Chen et al., 2011). The strain at the peak strength is also larger than that under monotonic loading. For glauberite and gypsum, since the component and inner structure are different from those of crystal halite and thenardite, less change occurs in deformation and failure mode, compared with those under monotonic loading. This demonstrates that the effect of loading schemes on rock deformation and failure for crystal sedimentations is more remarkable than that for other mineral rocks. The behavior difference of the rocks inevitably affects their responses to different loading modes in salt caverns constructed in bedded salt deposits. Consequently, the integrity and stability of the caverns should be carefully evaluated in different situations.

Fig. 6 shows parts of the test specimens under cyclic loading. It can be found that the thenardite and halite specimens are damaged mainly along grain boundaries while gypsum along large pure calcium sulphate nervation bands.

In practice, gas injection and extraction operations can last for several months in each cycle. In this case, the behavior of cavern is more important, and hence attention should be paid to the stress-strain curves in the process of loading and unloading. Here, a parameter of deformation modulus is defined as an average ratio of stress difference to strain difference in each cycle. The calculated results are shown in Table 2. The average ratios are 8.64, 14.0, 14.68 and 11.13 GPa for halite, thenardite, glauberite and gypsum, respectively. Evidently, it is 2–3 times the general elastic modulus for each rock. The deformation



(a) Halite. (b) Thenardite.

(c) Glauberite. (d) Gypsum.

Fig. 5 Stress-strain curves of different rock samples during cyclic loading (compression).

(a) Specimens of thenardite and halite after failure. (b) Specimens of gypsum after failure.

Fig. 6 Specimens of thenardite, halite and gypsum after failure.

modulus is suggested for performance assessment of salt caverns during the long-term procedure of gas injection or extraction. Choice of general elastic modulus and deformation modulus in studies of cavern behaviors under cyclic loading with low frequency should be carefully considered.

Under cyclic loading, attention should also be paid to the hysteresis loops in stress-strain curves, which show some fundamental properties of the materials. Different loops can be produced, depending on the tested material and loading schemes, including loading frequency and loading amplitude. In the tests, the lower limit of unloading was prescribed at 4–5 MPa, as shown in Figs. 5(a)–(c), and it was gradually increased with cycle (Fig. 5(d)). Loading/unloading was manually controlled, depending on stress level during the tests, which means that the loading amplitude changes from cycle to cycle. From Fig. 5, it can be found that some differences exist between the hysteresis loops for different rocks. For halite, almost all the hysteresis loops are tightly closed and the maximum strain in each cycle is less than 1×10^{-5}. For the other three interlayers, however, distinct loops can be observed in each cycle, and they become wider as loading amplitude increases. This agrees well with the results by Gatelier et al. (2002).

The maximum strains are 8×10^{-5}, 5×10^{-5} and 5×10^{-5} for thenardite, glauberite and gypsum, respectively, 5–8 times that of halite. The cycle number in the tests remains small as it is manually controlled. The effect of closing and opening hysteresis is less significant due to small crack density for few loading cycles. As the cycle number increases, the hysteresis, i.e. crack closing and opening, becomes distinct (Urban et al., 2004). In that case, cavern integrity and gas leakage will be significantly affected and the cycle number in each year should be limited.

4 Discussion

In rock engineering, stresses applied on rocks or rock structures should generally be lower than their peak strengths or elastic limits, which often refer to the value under static loading. However, the values are found to be larger than those under cyclic loading. Therefore, loading schemes, proper parameters and their values should be carefully chosen in engineering design and stability evaluation in rock engineering.

A large number of testing results demonstrate that the peak strength of rocks decreases by 65% due to crack growth when cyclic loading is considered. Furthermore, deformation of rocks is affected by loading frequency and amplitude, and geometrical properties of interior fractures. These interior and exterior factors have to be considered in engineering design, operation and evaluation.

For underground gas storage caverns in bedded salt deposits, the effect of loading schemes on mechanical behaviors of different salt rocks should be considered in storage design and operation. Testing results in this paper demonstrate that, under cyclic loading, rocks fail at a stress close to 65%–70% of the peak strength under monotonic loading. Larger deformation is also observed under the situation. This will undoubtedly facilitate the contraction of storage cavern and decrease the effective volume of stored gas. On the other hand, the minimum volume of residual gas in the storage has to be increased furthest to keep the cavern tight and the storage safe. For a sustainable storage cavern, all the mechanical parameters of the surrounding rocks should be carefully determined and the operation modes of field storage should be properly evaluated.

During the operation of gas storage, the maximum stress fluctuation around the gas storage can be as large as 10–15 MPa due to periodical gas injection and extraction. Influenced by the difference of mechanical properties of surrounding rocks and the cyclic loading schemes of the storage, halite and other interlayers have different mechanical response. The different mechanical behaviors may cause damage to storage cavern, especially the interfaces between different rocks.

It should be noted that gas injection and extraction commonly last for several months. Therefore, the loading/unloading frequency should be strictly controlled, which is far lower than that in laboratory. In that case, the deformation of salt rocks will become much flatter and the hysteresis of unloading strain recovery will be less significant. So, it is believed that the deterioration of mechanical properties of salt rocks can be mitigated to a certain extent. However, the deformation difference between different lithologies cannot be ignored, and the interfaces between rock salt and interlayer are always the possible access for gas leakage. Mechanical experiments on salt rocks under cyclic loading/unloading with lower frequency close to field operation are strongly suggested in future.

5 Conclusions

Cyclic loading is a frequently-encountered loading style in rock engineering. The periodical injection and extraction of gas in gas storage is a typical example of cyclic loads acting on the storage cavern walls and surrounding rocks. Laboratory experiments on mechanical behaviors of salt rocks in bedded salt deposits were conducted under cyclic loading. The main conclusions are drawn as follows:

(1) Different rocks exist in bedded salt deposits where underground gas storage caverns are constructed. The difference in mechanical behaviors of rocks under cyclic loading is significant for storage safety and stability in long-term operation.

(2) Experimental results demonstrate that, under cyclic loading, the peak strength of halite keeps the same as that under monotonic loading. However, for interlayers such as glauberite and gypsum, it decreases to 65% of that under monotonic loading. Testing results also show that the strengths of glauberite, thenardite and gypsum decrease by 34%, 19% and 35%, respectively, compared with those under monotonic loading.

(3) Under cyclic loading, the elastic moduli of halite and thenardite keep the same magnitude as those under monotonic compression. However, due to the heterogeneity and anisotropy of glauberite and gypsum, the elastic modulus increases for the former while decreases for the latter.

(4) Deformation modulus is defined as an average ratio of stress difference to strain difference in each cycle under cyclic loading. It is 2–3 times greater than the general elastic modulus. It is suggested that this dynamic deformation modulus should be adopted for mechanical calculations of different rock behaviors around gas storage in bedded salt deposits during storage operation.

(5) During the process of cyclic loading (compression), deformation and failure modes of rocks change compared with those under monotonic loading. Under cyclic loading, viscous flow is predominated for halite, thenardite and glauberite, except for gypsum. The gypsum specimens remain a brittle response similar to monotonic loading.

(6) The experimental results in this paper preliminarily demonstrate that great changes in mechanical behaviors of different rocks in bedded salt deposit under cyclic loading could be induced. Precise calculation and detailed analysis of relevant parameters are strongly suggested for proper and safe operation of gas storages in bedded salt deposits.

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