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Effects of cyclic loading on mechanical properties of Maha Sarakham salt

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ABSTRACT

A series of laboratory testing has been performed to assess the effects of cyclic loading on compressive strength, elasticity and time-dependency of the Maha Sarakham rock salt. Results from the cyclic loading tests indicate that the salt compressive strength decreases with increasing number of loading cycles, which can be best represented by a power equation. The salt elastic modulus decreases slightly during the first few cycles, and tends to remain constant until failure. It seems to be independent of the maximum loads within the range used here. Axial strain–time curves compiled from loci of the maximum load of each cycle apparently show a time-dependent behavior similar to that of creep tests under static loading. In the steady-state creep phase, the visco-plastic coefficients calculated from the cyclic loading test are about an order of magnitude lower than those under static loading. The salt visco-plasticity also decreases with increasing loading frequency. Surface subsidence and cavern closure simulated using parameters calibrated from cyclic loading test results are about 40% greater than those from the static loading results. This suggests that application of the property parameters obtained from the conventional static loading creep test to assess the long-term stability of storage caverns in salt with internal pressure fluctuation may not be conservative.
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1. Introduction

Rock salt around storage caverns will be subject to cycles of loading due to the fluctuation of cavern pressures during product injection and retrieval periods. Depending on the types of stored products (e.g. petroleum, liquefied gas or compressed-air) and on the designed operating schemes, the injection–withdrawal durations can range from daily to annual, and the minimum and maximum cavern pressures can be as low as 20% and as high as 90% of the in-situ stresses at the casing shoe (cavern top). Due to the complexity of cavern ground geometry and the need to predict the future stability conditions (normally up to a few decades), the stability and operating pressures of the salt caverns have commonly been analyzed and designed via numerical modeling capable of handling time-dependent constitutive equations (Rokahr and Staudtmeister, 1996; Lux and Schmidt, 1996). A difficulty may arise in determining the representative properties of the salt under such cyclic loading states. Since the salt properties are loading path dependent (non-linear), the laboratory determined properties under static loads (as commonly practiced) may not truly represent the actual in-situ salt behavior under cyclic loading.

The effect of cyclic loading on the elasticity and strengths of geologic materials has long been recognized (Haimson, 1974, 1978; Allemandou and Dusseault, 1996; Bagde and Petros, 2004, 2005). A common goal of the previous studies is to determine the fatigue strength of the materials. It has been found that loading cycles can reduce the material strength and elasticity, depending on the loading amplitude and the maximum applied load in each cycle (Zhenyu and Haihong, 1990; Singh et al., 1994; Ray et al., 1999; Kodama et al., 2000). Rare investigation has, however, been made to identify the cyclic loading effect on the time-dependent properties and behavior of soft and creeping materials such as salt.

The objective of this research is to determine experimentally the effects of cyclic loading on compressive strength, elasticity, visco-elasticity and visco-plasticity of rock salt from the Maha Sarakham formation. The efforts primarily involve mechanical characterization testing, creep testing and compression testing under static and cyclic loads. Finite element analyses are performed to demonstrate the impact of cyclic loading on the deformation of salt around a compressed-air storage cavern.

2. Rock salt specimens

The specimens tested here were obtained from the Lower Salt members of the Maha Sarakham formation in the Sakhon Nakhon basin, northeastern Thailand. This salt unit is being considered as a host rock for compressed-air energy storage by the Thai Department of Energy. The rock salt is relatively pure halite with a slight amount (less than 1–2%) of anhydrite, clay minerals and ferrous oxide. The average crystal (grain) size is about 5×5×10 mm. Warren (1999) gives detailed descriptions of the salt and geology of the basin. The core specimens with a nominal diameter of 60 mm tested here were drilled from depths ranging between 250 and 400 m.

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Sample preparation followed the ASTM (D 4543) standard practice, as much as practical. Twenty-four specimens (L/D = 2.5) were prepared for uniaxial compression tests, 76 specimens (L/D = 0.5) for Brazilian tension tests, 14 specimens (L/D = 2.5) for cyclic loading tests, and 10 specimens (L/D = 2.5) for uniaxial creep tests. The samples were cut and ground using saturated brine as lubricant. After preparation, the specimens were labeled and wrapped with plastic film. The specimen designation was identified. Prior to mechanical testing, visual examination was made to determine the type and amount of inclusions.

3. Characterization testing

Uniaxial and triaxial compression and Brazilian tension tests were conducted to obtain data basis for the Maha Sarakham salt, and to determine the test parameters for the subsequent creep and cyclic loading tests. The test procedure followed relevant ASTM standard practices (ASTM D 3967 and D 7012). Fig. 1 shows the stress–strain curves monitored during the tests. The triaxial compressive strength tests use confining pressures between 5.5 and 19.3 MPa. Fig. 2 shows some stress–strain curves obtained from the triaxial testing. The elastic modulus (measured from unloading curves) of the salt is 25.2 ± 1.9 GPa and the Poisson's ratio is 0.37 ± 0.11. The uniaxial compressive and Brazilian tensile strengths are 34.7 ± 2.2 MPa and 1.5 ± 0.4 MPa. Based on the Coulomb criterion the internal friction angle is calculated as 39° and the cohesion as 15 MPa (Fig. 3). The figure also lists the magnitudes of the principal stresses at failure obtained from all characterization tests. The Maha Sarakham salt strengths and elasticity obtained here agree reasonably well with those obtained elsewhere (e.g., Hansen et al., 1984).

4. Creep testing

Short- and long-term uniaxial creep tests were performed to determine the time-dependent properties of the salt under isothermal condition. The test procedure followed the ASTM D 7070-08 standard practice. For the short-term testing, the applied constant axial stresses are relatively high, varying from 10 to 30 MPa with the maximum test duration of 7 h. For the long-term testing, the applied stresses vary from 7.8 to 12.6 MPa with the maximum test duration up to 30 days. The short-term test results are used to calibrate the visco-elastic parameters, and the long-term results calibrate the visco-plastic coefficient of the salt. Figs. 4 and 5 plot the axial strain as a function of time for the short- and long-term testing.

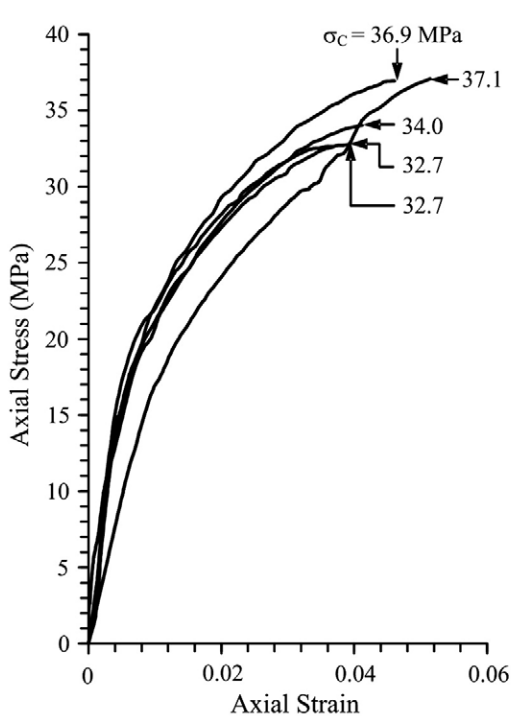

Fig. 1. Results of uniaxial compressive strength testing. Numbers indicate stress at failure.

5. Cyclic loading testing

A series of uniaxial cyclic loading tests were performed on the 60 mm diameter salt core specimens using a servo-controlled universal testing machine (Fig. 6). The maximum axial stresses vary among specimens from 15.9 MPa to 34.6 MPa (about 40% to 100% of the uniaxial compressive strength) while the minimum stress was maintained constant at 0.15 MPa for all specimens. This small minimum stress is required to ensure that the ends of the specimen remain in contact with the loading platens during the test. The nearly complete unloading used here represents a conservative approach to assess the impact of cyclic loading on the mechanical behavior of the salt. As suggested by Haimson (1978) the larger loading amplitude is applied, the lower fatigue strength is obtained. More discussions on this issue are given in the last section. The applied loading frequencies range from 0.001 to 0.03 Hz. It is recognized that this loading frequency range is significantly higher than those induced by the actual operation of gas or compressed-air storage caverns in rock salt. The application of the actually operated frequencies (e.g., daily, monthly or annually) is not practical to simulate in the laboratory, as it will take excessively long test duration. The effect of loading frequency on the salt creep will be discussed in the following section. The accumulated axial strain, fatigue stress (S) and time were monitored during loading. Some examples of axial stress–strain curves measured during loading for the frequency at 0.03 Hz are given in Fig. 7. Fig. 8 shows the decrease of the failure (fatigue) stress as the number of loading cycle (N) increases, which can be represented by a power equation: $S = 32.33N^{(-0.07)}$. The behavior is similar to those obtained elsewhere for other geologic materials (e.g., Costin and Holcomb, 1981; Thoms and Gehle, 1982; Passaris, 1982; Bagde and Petros, 2004, 2005).

Fig. 9 shows the axial strain–time curves compiled from the loci of the loading cycles for loading frequencies of 0.001 and 0.03 Hz. The curves show the transient, steady-state and tertiary creep phases which are similar to those obtained from the static creep testing. It is understood here that the transition point at which the strain rate changes from the steady-state phase (constant volume) to tertiary (volume increase) phase corresponds to the dilation strength of the salt (DeVries et al., 2003). The loading cycles also exponentially decrease the dilation strength of the salt, as shown in Fig. 8.

The salt elasticity exponentially decreases as the number of loading cycles increases, and nearly remains constant after about 50 to 100 loading cycles. Fig. 10 shows the elastic modulus values calculated from the series of unloading curves as a function of loading cycles for a loading frequency of 0.03 Hz. The calculated elastic modulus values range from 20 GPa to 35 GPa. They, however, tend to be independent of the applied maximum loads used here, as also evidenced by the normalized elastics modulus (E/E_0) as a function of N in Fig. 10, where E_0 is the modulus measured during the first loading cycle.

6. Salt property calibration

To assess the effect of cyclic loading on the time-dependent properties of salt, a simple rheological creep model is used to describe the constitutive behavior of the salt under isothermal condition. The

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