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Experimental investigation of mechanical behavior of bedded rock salt containing inclined interlayer

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ABSTRACT

Uniaxial and triaxial compression tests have been carried out on specimens of rock salt, interlayers, and composite rock salt (containing inclined interlayers). In combination with failure mechanism analysis of the stratified rock structures, the variation and impact factors of bonding stresses between the layers have been investigated, and the fracture properties and failure mechanisms of inclined bedded rock salt have been revealed. The research demonstrated that the inclined interlayer influences the deformation and fracture properties of rock salt. Due to the composite mechanical characteristics, cracks primarily initiate near the interface region, and then propagate to the interlayer and the rock salt adjacent to it. The thickness of the interlayer affects the entire performance of the composite specimen and governs the development of the local fractures. Macro-cracks tend to form more easily in the test specimens that contain a medium-thick interlayer than in the ones containing only a thin interlayer. Increasing confining pressure gradually changes the overall mechanical behaviors from brittle to more ductile at higher confining pressure. The ductile behavior is characterized by differences of strain-hardening behaviors and also the geometry of cracks at different locations in the interlayer as compared to the results of uniaxial compression tests.

1. Introduction

Rock salt has excellent ductility [1,2] and good self-healing features when damaged [3], as well as extremely low permeability [4,5]. Therefore, salt formations are commonly used as host rocks for storage of crude oil or natural gas [6,7], and are also considered for permanent disposal of radioactive and other, e.g. chemical, wastes [8,9]. For the most effective utilization of storage caverns in salt formations, the ideal physical and mechanical characteristics compared with other rock types, such as sandstone, limestone, granite, etc., have been regarded as a prerequisite for the licensing of a repository [10,11]. More recently, pre-evaluations have been promoted to study the feasibility of utilizing salt formations to store compressed air or hydrogen by taking advantage of the almost impermeable characteristics and rheological responses of rock salt [12,13].

The salt formations used for energy storage consist of either bedded rock salt [14,15] or salt domes [16]. The mechanical properties of rock salt vary greatly due to differences in the sedimentary deposition environments, in which they were formed, sediment components, crystal geometries, content and distribution of impurities, tectonic histories experienced, etc. [15]. Especially in China, the rock salts available for caverns are mainly of deep-water lacustrine deposits, which are characterized by containing numerous insoluble nonsaline interlayers (anhydrite, glauberite, mudstone, shale, dolomites, etc.), thin and low-grade salt layers, and variable complex structures. So the bedded rock salts in China are typically thinly interbedded formations. In addition, such formations of bedded rock salts are usually tightly correlated with graben structure basins, thus a difference of deposition exists between center and edges and then results in the formation of inclination, folds, minor faults, etc., which further complicates the structures of the formations. Compared to the salt domes with massive salt real estate, the total geo-sections of bedded rock salts in China available for cavern construction are usually less than 100–150 m thick, and their complex geo-structure increases further the difficulty of cavern construction.

Due to the difference in mechanical behavior of the adjacent interlayers and salt layers, especially after the excavation of a cavern, inharmonious deformation and also shear stress will be induced in the interface regions, which may result in slippage cracks developing along the interfaces [17,18]. Then the stability and tightness of the storage cavern may be seriously affected. DeVries et al. [14] studied the roof stability of storage caverns in bedded salt formations. Minkley et al. [19] established constitutive

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models to describe the mechanical behavior of rock salt with imbedded weakness planes. This model includes not only the hardening/softening behavior and dilatancy effects for rock salt, but also the displacement-and viscosity-dependent shear strength softening for salt bearing bedding planes. Yang and Li [20,21] established 2-D and 3-D Cosserat-like models for bedded rock salt, which take into account the compatibility of the meso-displacement between two different layers and also the bending-effect. In China, these models have been gradually used as an appropriate constitutive theory and failure criterion for rock salt imbedded with numerous thin interlayers [22].

The bedded salt mines used for study and for construction involve mainly horizontal interlayer lithology [15–17,19–23]. In more recent years, several rock salt mines in China with stratum dip angles of 10–30° have been selected as Strategic Storage Candidate Sites to construct deep storages cavern clusters. Mechanical properties of the rock salt are required for designing the caverns with the necessary stability, tightness and safety. However, the experimental and theoretical information resources available for bedded rock salt, especially the bedded rock salt with inclination, are still limited.

Generally, the dip angle of geological materials will influence their engineering features, which is a well recognized phenomenon in slope [24] and tunnel projects [25]. It may behave similarly for deep underground storage facilities in salt formations. In addition, due to the coupling effect of inclination and the mechanical characteristic differences of the rock salt versus the nonsaline interlayers, higher shear stress concentration may occur near the interface between the layers. This phenomenon may result in shear slippage, mechanical damage, and even cause new seepage channels to develop along these interface regions. Therefore, it is of urgent necessity to conduct experimental and theoretical investigations on the properties of these typical lithotypes and to include in these studies the fact that these formations frequently are dipping.

Based on the research background and project demands stated above, we conducted research to study the features of the inclined rock salt, especially the mechanical behavior of the interfaces and interlayers, with the expectation to supply some basic information support for the gas storage clusters to be constructed in such formations. The test matrix pursued in this paper has the main purpose of determining the deformation and fracture characteristics of inclined bedded rock salt. The results and analyses of the experiments are presented. We use the term “rock salt” to refer specifically to halite, and halite with impurities; we use the term “composite rock salt” to refer to the special lithotype consisting of rock salt and interlayer; and we use “interlayer” to refer to the nonsaline stratum intersecting or overlying the cavern.

2. Experimental methodologies

2.1. Specimen preparation

In order to study the deformation and fracture characteristics and also the crack initiation mechanism of interfaces in bedded rock salt with inclined interlayers, elemental components’ analysis, as well as uniaxial and triaxial compression tests, have been carried out on eighteen specimens. All the specimens were obtained from the same pilot well, whose coring depth ranges from 1400 to 1800 m, from the Pingdingshan Salt Mine in He'nan Province of China. Because of the crystallization matrix of rock salt, all the specimens prepared for testing were made by hand, by carefully using a steel saw and fine sandpaper. Then the samples are stored after being protected with paraffin. Any disturbance has been limited to the least possible. All the specimens have a length-to-diameter ratio of 2:1 (or with a slight deviation: 1.98–2.06) and a diameter of 100 mm (or less than 4 mm smaller). Based on the petro-physical characteristics of the core samples, the specimens have been classified into four types: (1) pure rock salt specimens (halite $\geq$ 95%); (2) impure rock salt specimens (halite $<$ 95%); (3) anhydrite mudstone interlayer specimens; (4) composite rock salt specimens (type a, containing a thin interlayer, with a thickness of $<$ 10 mm, and type b, containing a medium-thick interlayer, with a thickness of 10–40 mm).

The inclination angles of the interlayers range from 20 to 30°. Some petro-physical information on the specimens is listed in Table 1. Pictures of typical prepared specimens are shown in Fig. 1. Chemical elements determinations by solution methodology have been conducted. The results for each specimen are given in Table 2. We define the different locations on the interlayer respectively as top, middle, and bottom. Both the global coordinate system $(0-X_O Y_O Z_O)$ and the local coordinate system $(0-xyz)$, which will be used for the subsequent analyses, have been defined, as shown in Fig. 2.

2.2. Experimental procedure

The uniaxial and triaxial compression tests were carried out using an MTS815 FlexTestGT system. This system is capable of

Table 1
Petro-physical and dimensional information about the specimens prepared for testing.

Classification	Specimen no.	Diameter (mm)	Length (mm)	Lithotypes	Confining conditions
Rock salt	S-1	96.0	197.8	Pure rock salt	Uniaxial
	S-2	97.4	201.1	Pure rock salt	Uniaxial
	S-3	99.5	200.2	Impure rock salt	Uniaxial
Composite salt rock	C-1	100.2	198.5	Interlayer thickness: 5 mm	Uniaxial
	C-2	100.1	199.8	Interlayer thickness: 20 mm	Uniaxial
	C-3	99.4	200.1	Interlayer thickness: 35 mm	Uniaxial
Interlayer	I-1	98.9	198.6	Anhydrite	Uniaxial
	I-2	99.3	201.2	Muddy anhydrite	Uniaxial
	I-3	100.2	199.7	Muddy anhydrite	Uniaxial
	S-4	98.5	198.7	Pure rock salt	10 MPa (σ_3 stress)
Rock salt	S-5	99.3	197.9	Impure rock salt	10 MPa (σ_3 stress)
	S-6	99	200.1	Impure rock salt	10 MPa (σ_3 stress)
Composite salt rock	C-5	99.2	199.1	Interlayer thickness: 5 mm	5 MPa (σ_3 stress)
	C-6	99.9	200.4	Interlayer thickness: 4 mm	10 MPa (σ_3 stress)
	C-7	99.5	200	Interlayer thickness: 30 mm	10 MPa (σ_3 stress)
Interlayer	I-4	99	199	Anhydrite mudstone	10 MPa (σ_3 stress)
	I-6	99.7	199.8	Anhydrite mudstone	10 MPa (σ_3 stress)
	I-7	99.8	200.1	Anhydrite mudstone	10 MPa (σ_3 stress)