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True-triaxial compressive strength of Maha Sarakham salt

Tanapol Sriapai, Chaowarin Walsri, Kittitep Fuenkajorn *

Geomechanics Research Unit, Suranaree University of Technology, 111 University Avenue, Nakhon Ratchasima 30000, Thailand

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ABSTRACT

True triaxial compressive strengths of the Maha Sarakham salt are experimentally determined by using a polyaxial load frame. The salt specimens with nominal dimensions of $5.4\times5.4\times10.8$ cm^3 are loaded to failure with the minimum principal stress, σ_3, varying from 0 to 7 MPa, and the intermediate principal stress, σ_2, varying from 0 to 80 MPa. The major principal (axial) stress is increased at a rate of 0.5–1.0 MPa/s until failure occurs. Based on the Coulomb criterion the internal friction angle determined from the triaxial loading condition ($\sigma_2=\sigma_3$) is 50°, and the cohesion is 5.0 MPa. The elastic parameters of the salt tend to be independent of σ_2 for the applied stress range. The effect of σ_2 on the salt strength can be described best by the modified Wiebols and Cook criterion with a mean misfit of 3.5 MPa. The (power law) Mogi criterion underestimates the salt strength, particularly under high σ_3 values. The modified Lade and 3-D Hoek & Brown criteria overestimate the strength at all levels of σ_3. The Coulomb and Hoek & Brown criteria cannot describe the salt strengths beyond the condition where $\sigma_2=\sigma_3$, as they cannot incorporate the effects of σ_2. Both circumscribed and inscribed Drucker–Prager criteria severely underestimate σ_1 at failure for all stress conditions, showing the largest mean misfit of 19.5 MPa.

1. Introduction

The effects of confining pressures on the mechanical properties of rocks are commonly simulated in a laboratory by performing triaxial compression testing of cylindrical rock core specimens. A significant limitation of these conventional methods is that the intermediate and minimum principal stresses are equal during the test while the actual in-situ rock is normally subjected to an orthotropic stress state where the maximum, intermediate and minimum principal stresses are different ($\sigma_1\neq\sigma_2\neq\sigma_3$). It has been found that compressive strengths obtained from conventional triaxial testing cannot represent the actual in-situ strength where the rock is subjected to an anisotropic stress state [1–5].

From the experimental results on brittle rocks obtained by the researchers above [2,6] it can be generally concluded that in a σ_1–σ_2 diagram, for a given σ_3, σ_1 at failure initially increases with σ_2 to a certain magnitude, and then it gradually decreases as σ_2 increases. The effect of σ_2 is larger under higher σ_3. Cai [7] offers an explanation of how the intermediate principal stress affects the rock strength based on the results from numerical simulations on fracture initiation and propagation. He states that the intermediate principal stress confines the rock in such a way that fractures can only be initiated and propagated in the direction parallel to σ_1 and σ_2. The effect of σ_2 is related to the stress-induced anisotropic properties and behaviour of the rock and to the end effect at the interface between the rock surface and loading platen in the direction of the σ_2 application. The effect should be smaller in homogeneous and fine-grained rocks than in coarse-grained rocks where pre-existing micro-cracks are not uniformly distributed.

Several failure criteria have been developed to describe the rock strength under true triaxial stress states. Comprehensive reviews of these criteria have been given recently by Haimson [2], Colmenares and Zoback [6], Cai [7], Al-Ajmi and Zimmerman [8], Benz and Schwab [9], and You [10]. Among several other criteria, the Mogi and modified Wiebols and Cook criteria are perhaps the most widely used to describe the rock compressive strengths under true triaxial stresses. Obtaining rock strengths under an anisotropic stress state is difficult and expensive. A special loading device (e.g., polyaxial loading machine or true triaxial load cell) is required. Some recent ones include those developed by Haimson and Chang [5], Reddy et al. [11], Smart [12], Wawersik et al. [13], and Alexeev et al. [14]. Owing to the cost and availability of the equipment rock strength data under true triaxial stress conditions have been limited [6]. Most researchers above have used the same sets of test data (some obtained over a decade ago) to compare with their new numerical simulations, field observations (notably on breakout of deep boreholes) or to verify their new strength criteria and concepts. In common engineering practices however the application of a failure criterion that can incorporate the effect of σ_2 is rare. The effect of the true triaxial stress state on the rock deformability has also been inadequately investigated.

* Corresponding author. Tel.: +66 44 224 443; fax: +66 44 224 448.
E-mail address: kittitep@sut.ac.th (K. Fuenkajorn).

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The objective of this study is to experimentally determine the effect of σ_2 on the compressive strength and deformability of the Maha Sarakham salt. The effort involves performing series of true triaxial compression tests of the Maha Sarakham salt and determining the predictive capability of some strength criteria.

2. Test method

The salt specimens tested here were obtained from the Middle member of the Maha Sarakham formation in the Khorat basin, northeast Thailand. Warren [15] gives detailed descriptions of the salt and geology of the basin. The core specimens were drilled from depths ranging between 180 m and 250 m and have a nominal diameter of 100 mm. The salt is relatively pure halite with an average crystal (grain) size of about $5 \times 5 \times 10$ mm^3. The cores were dry-cut to obtain rectangular blocks with nominal dimensions of $5.4 \times 5.4 \times 10.8$ cm^3. Fig. 1 shows some salt blocks prepared for testing. No bedding plane was observed in the specimens. After preparation the specimens were wrapped with plastic film.

A polyaxial load frame [16] has been used to apply axial stress (σ_1) and constant lateral stresses (σ_2 and σ_3) to the rectangular rock specimens (Fig. 2). For the true triaxial testing the minimum principal stresses are 0, 1, 3, 5 and 7 MPa with the intermediate principal stresses varying from 0 MPa to 80 MPa. After installing the salt specimen into the load frame, the two principal stresses are laterally applied using the cantilever beams. Neophrene sheets are placed in all interfaces between the loading platens and specimen surfaces. The salt block is first subject to an isostatic stress equal to the pre-defined intermediate principal stress. One of the lateral stresses is then reduced to the pre-defined minimum principal stress. Then the axial stress (major principal stress) is increased at a constant rate of 0.5–1.0 MPa/s until failure occurs. The failure is defined as a drop of the applied axial stress. A photograph is taken of the post-test specimens and the modes of failure are identified. All tests are conducted under room temperature (24–27 °C).

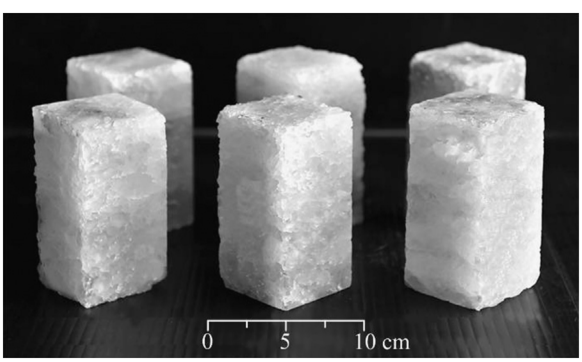

Fig. 1. Some of the salt specimens ($5.4 \times 5.4 \times 10.8$ cm^3) prepared for true triaxial compressive strength testing.

3. Test results

3.1. Salt compressive strength

Figs. 3 and 4 show stress–strain curves obtained from some specimens. The volumetric strains (ε_v) are calculated from initial loading to failure. Table 1 summarises the principal stresses (σ_1, σ_2, σ_3) and octahedral shear and mean stresses ($\tau_{oct,f}$ and σ_m) at failure for all specimens. They are calculated using the following relations ([17], p. 40):

$$\tau_{oct,f} = (1/3)\{(\sigma_1-\sigma_2)^2 + (\sigma_1-\sigma_3)^2 + (\sigma_2-\sigma_3)^2\}^{1/2} \quad (1)$$

$$\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3 \quad (2)$$

Some post-test specimens are shown in Fig. 5. Combinations of extension cracks and shear failures are usually observed from the specimens tested under low σ_2 and σ_3. These fractures tend to be perpendicular to the σ_3-axis (parallel to the σ_1–σ_2 plane). No relationship can be derived between the failure plane angle and the magnitudes and ratios of the applied stresses. Under high σ_2 and σ_3 values permanent deformations of the salt specimens and micro-fracture development can be observed visually.

Fig. 6 shows the failure stresses in the form of $J_2^{1/2}$–σ_m and σ_1–σ_2 diagrams, where J_2 is the second order stress invariant at failure

$$J_2^{1/2} = \{(1/6)[(\sigma_1-\sigma_2)^2 + (\sigma_1-\sigma_3)^2 + (\sigma_2-\sigma_3)^2]\}^{1/2} \quad (3)$$

The diagrams in Fig. 6 show failure stresses bound by the two extreme loading conditions: triaxial extension ($\sigma_1 = \sigma_2$) and triaxial compression ($\sigma_2 = \sigma_3$). The failure envelope under triaxial compression tends to be non-linear while a linear trend is observed under the triaxial extension. The effect of σ_2 on the failure stress σ_1 can be clearly seen in the σ_1–σ_2 diagram. Under low σ_3 values σ_1 at failure initially increases with σ_2 to a certain magnitude, and then it gradually decreases as σ_2 increases further. This behaviour agrees well with those of the brittle and hard rocks tested elsewhere (e.g., [2,5,10]). By applying the Coulomb criterion to the triaxial compression ($\sigma_2 = \sigma_3$) results the internal friction angle (ϕ) of the Maha Sarakham salt is determined as 50°, and the cohesion (c) is 5.0 MPa.

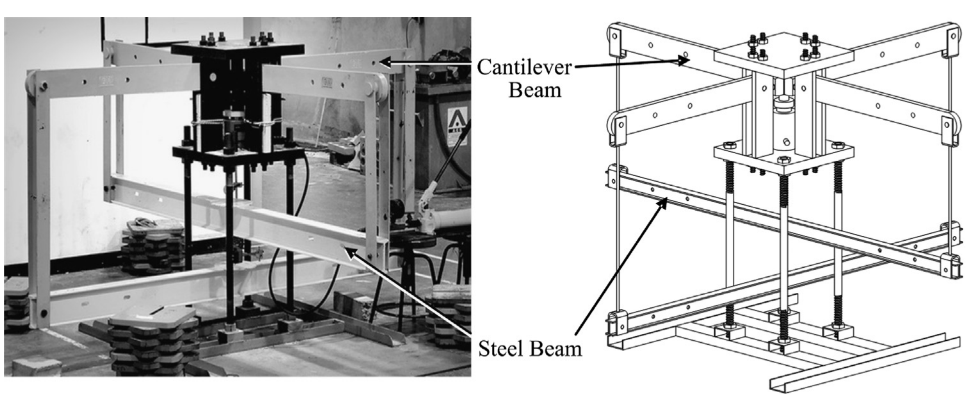

Fig. 2. Polyaxial load frame developed for true triaxial compression testing.