Effects of Stress Rate on Uniaxial Compressive Strength of Rock Salt under 0-100°C.

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ABSTRACT
Uniaxial compression test have been performed to assess the effects of loading rate on compressive strength and deformability of the Maha Sarakham salt under temperatures ranging from 273 to 373 Kelvin (0-100°C). The variation of the octahedral shear strength with the stress rates and temperatures can be described by logarithmic relations. The distortion strain energy criterion is proposed to describe the rock strength under varied stress rates and temperatures. The criterion can be used to determine the stability of rock around compressed-air energy storage caverns, where the loading rates and temperatures are continuously varied during air injection and retrieval periods.

KEYWORDS: Rock salt / Loading rate / Thermal effect / Strain energy

1. INTRODUCTION
The effects of loading rate on the compressive strength and deformability of intact rocks have long been recognized [1-4]. For rock salt such effects have been studied by various researchers [5-8]. It has been found that the rock strength increases with the applied stress and strain rates. The rock strength and elastic properties have been known to decrease as the temperature increases [9]. Several formulations have been proposed to describe the temperature-dependent behavior of rock salt [9-11]. Such knowledge is necessary for stability analysis and design of the salt storage caverns. During injection period the storage caverns may subject to temperatures as high as 140°C (414 K), depending on the injection rate and the maximum storage volume and pressure [9].

The objective of this study is to experimentally assess the influence of loading rate on the compressive strength and deformability of rock salt under constant temperatures of 273, 303, 343 and 373 K. This selected range of temperatures covers those likely to be encountered around salt storage caverns under operation. Uniaxial compression test have been performed on the Maha Sarakham salt under loading rates from 0.0001 to 0.1 MPa/s. The strain energy density criterion is proposed to describe the salt strength as affected by the loading rates and temperatures.

2. SALT SPECIMENS
The salt specimens are prepared from 47 mm diameter cores drilled from depths ranging between 270 and 330 m by Siam Submanee Co., Ltd. in the northeast of Thailand. The salt cores belong to the Lower salt member of the Maha Sarakham formation. Tabakh et al. [12] describe the origin and geologic sequence of the Maha Sarakham salt. The drill cores were dry-cut to obtain cylindrical shaped specimens with nominal dimensions of 47 mm diameter and 118 mm length.

To test the salt specimens under elevated temperatures, they are wrapped with heating tape, foil and insulator for 24 hours before testing. A digital temperature regulator is used to maintain constant temperature to the specimens. The low temperature specimens are cooled in a cooling system during the test. As a result the specimen temperatures are assumed to be uniform and constant with time during the mechanical testing i.e., isothermal condition.

3. TEST METHOD
The salt specimen is placed in a compression machine and loaded axially until failure (Fig. 1). The applied stress rates are constant at 0.0001, 0.001, 0.01 and 0.1 MPa/s. For the low temperature testing the loading frame is placed inside a cooling system (Fig. 2). The salt specimen is cooled for 48 hours before starting loading. It can cool the salt specimens down to 273 K. For the high temperature testing a heating tape with temperature regulator are used to apply constant elevated temperatures while loading (Fig. 3). Photographs are taken of the failed specimens.
Fig. 1 Salt specimen placed in a compression machine under room temperature (about 303 K).

Fig. 3 Salt specimen wrapped with the heating tape and insulator for high temperature testing at 343 and 373 K.

Fig. 2 Salt specimen placed in the consolidation load frame and inside the cooling system for low temperature at 273 K.

**4. TEST RESULTS**

Fig. 4 shows the stress-strain curves monitored from some of the salt specimens under different stress rates and temperatures. Tab. I gives the test results. The specimens tend to show nonlinear behavior, particularly under high temperatures. All post-test specimens show shear failure mode (Fig. 5). Under the same loading rate (dσ/dt), the compressive strength (σc) decreases with increasing specimen temperatures. The mean stresses (σm) and strains (εm) and octahedral shear stresses (τoct) and shear strains (γoct) at failure are determined using the following relations [13]:

\[

\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3
\]

where \( \sigma_1, \sigma_2 \) and \( \sigma_3 \) are the major, intermediate and minor principal stresses at failure.

The applied octahedral shear stresses are plotted as a function of octahedral shear strain in Fig. 6. The shear stress-strain relations are nonlinear, particularly under low loading rates and high temperatures. Higher shear strengths and lower shear strains are observed under low stress rates and high temperatures.

The variation of the shear strengths can be observed from the \( \tau_{oct} - \sigma_m \) diagram, as shown in Fig. 7. The linear relation between the octahedral shear strength and the mean stress at failure and can be best represented by:

\[

\tau_{oct} = 1.412 \sigma_m + 0.022 \quad \text{MPa}
\]

**5. SALT DEFORMATIONS**

The total compressive strain is divided here into two parts; elastic strain (linear and recoverable strain) and plastic creep strain (time-dependent and nonrecoverable strain):

\[

\varepsilon_c = \varepsilon'_c + \varepsilon''_c
\]

where \( \varepsilon_c \) is the total compressive strain, \( \varepsilon'_c \) is elastic strain and \( \varepsilon''_c \) is plastic creep strains.
Fig. 4 Stress-strain curves obtained from some salt specimens with different loading rates \( \frac{\partial \sigma_1}{\partial t} \) and temperatures \( T \).

The elastic strain can be calculated from the current stress state using classical elastic theory [13]:

\[
\varepsilon_{ce} = \frac{\sigma_c}{E}
\]  

(7)

where \( \sigma_c \) is the compressive stress, \( E \) is the elastic modulus. The exponential creep law is used to describe time-dependent strain of the salt [14]:

\[
\varepsilon_c = a \cdot \sigma^\beta \cdot t^\kappa \cdot \exp\left(\frac{-\lambda}{T}\right)
\]

(8)
where $\alpha$, $\beta$, $\kappa$ and $\lambda$ are empirical constants and $T$ is constant temperature in Kelvin. Substituting equations (7) and (8) into (6) we obtain:

$$\varepsilon_c = \frac{\sigma_c}{E} + \alpha \cdot \sigma_c^\beta \cdot t^\kappa \cdot \exp\left(\frac{-\lambda}{T}\right)$$  \hspace{1cm} (9)$$

Similarly the creep parameters can also be derived in the forms of the octahedral shear strain:

$$\gamma_{oct} = \frac{\tau_{oct}}{2G} + \alpha \cdot \tau_{oct}^\beta \cdot t^\kappa \cdot \exp\left(-\frac{\lambda}{T}\right)$$  \hspace{1cm} (10)$$

where $\gamma_{oct}$ is the octahedral shear strain, $\tau_{oct}$ is the octahedral shear stress, $G$ is shear modulus, $\alpha$ is stress constant, $\beta$ is stress exponent, $T$ is temperature (Kelvin), $t$ is time, $\kappa$ is time exponent and $\lambda$ is temperature constant.

For the stress-rate controlled condition the octahedral shear stress at any loading time ($t$) can be expressed as:

$$\gamma_{oct}(t) = \frac{\dot{\tau}_{oct} \cdot t}{2G} + \alpha \cdot \dot{\tau}_{oct}^\beta \cdot \exp\left(\frac{-\lambda}{T}\right) \cdot t^\kappa$$  \hspace{1cm} (11)$$

Assuming that the salt elasticity varies linear with temperature [9]:

$$G = \psi \cdot T + G_0$$  \hspace{1cm} (12)$$

where $G_0$ is shear modulus at zero Kelvin and $\psi$ is the empirical constant. Substitute equation (12) into (11) we obtain:

$$\gamma_{oct}(t) = \frac{\dot{\tau}_{oct} \cdot t}{2(\psi \cdot T + G_0)} + \alpha \cdot \dot{\tau}_{oct}^\beta \cdot t^{\kappa+\kappa} \cdot \exp\left(\frac{-\lambda}{T}\right)$$  \hspace{1cm} (13)$$

where $\dot{\tau}_{oct}$ is the octahedral shear stresses rate, $\psi$, $G_0$, $\alpha$, $\beta$, $\kappa$, $\lambda$ are empirical constants. Regression analysis on the test data using SPSS statistical software [15] these parameters are defined as: $\psi = -5.44$; $G_0 = 25.82$; $\alpha = 0.01$, $\beta = 2.018$, $\kappa = 0.129$ and $\lambda = 1559.24$.

The elastic parameters $E$, $G$ and $\nu$ can therefore be determined as:

$$E = -0.145T + 69.20 \hspace{1cm} \text{GPa} \hspace{1cm} (14)$$

$$G = -0.054T + 25.82 \hspace{1cm} \text{GPa} \hspace{1cm} (15)$$

$$\nu = (2 \times 10^{-4})T + 0.26 \hspace{1cm} (16)$$

The elastic and shear modulus linearly decrease with increasing temperature. The Poisson’s ratio however tends to be independent of the temperature (Fig. 8).

6. STRAIN ENERGY DENSITY CRITERION

The strain energy density principle is applied to describe the salt strength and deformability

Tab. 1 Salt strengths under various loading rates and temperatures.

<table>
<thead>
<tr>
<th>Average Temperature (K)</th>
<th>Stress rate (MPa/s)</th>
<th>Compressive Strength (MPa)</th>
<th>Mean Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>273</td>
<td>0.1</td>
<td>38.79</td>
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<td>8.39</td>
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</table>

Fig. 5 Post-test specimens from uniaxial compressive strength testing under different loading rates ($\dot{\sigma}_0 / \dot{t}$) and temperatures ($T$).
The following distortional strain energy at failure (\(W\)) can be calculated from the octahedral shear stresses and strains for each salt specimen using the following relations [13]:

\[
W_d = \frac{3}{2} \cdot \tau_{oc,t,f} / \gamma_{oc,t,f} 
\]  \hspace{1cm} (17)

The distortion strain energy at failure (\(W_d\)) is presented as a function of the mean strain energy density at failure (\(W_m\)) which can be calculated from \(\sigma_m\) and \(\varepsilon_m\) as follows:

\[
W_m = \frac{3}{2} \cdot \sigma_m \cdot \varepsilon_m 
\]  \hspace{1cm} (18)

Fig. 9 shows a linear relation of \(W_d\) - \(W_m\) which can be represented by:

\[
W_d = \omega \cdot W_m - \nu 
\]  \hspace{1cm} (19)

The parameters \(\omega\) and \(\nu\) are empirical parameters. Tab. 2 gives \(W_d\) and \(W_m\) values calculated from the test results. The proposed criterion considers both stress and strain at failure, and hence isolating the effect of stress rate and temperature. If the salt temperature is known its strength can be determined from equation (19) regardless the loading rate.

**Fig. 6** Octahedral shear stress (\(\tau_{oc}\)) as a function of octahedral shear strain (\(\gamma_{oc}\)) for various loading rates (\(\partial \sigma / \partial t\)) and temperatures (\(T\)).

**Fig. 7** Octahedral shear stress at failure (\(\tau_{oc,t}\)) of salt as a function of mean stress.

under different loading rates and temperatures. A similar approach has been used by Fuenkajorn et al. [5] to derive a loading rate-dependent strength for salt. The distortional strain energy at failure (\(W_d\)) can be calculated from the octahedral shear stresses and
7. DISCUSSIONS AND CONCLUSIONS

The effect of loading rate and temperature on the compressive strength and deformability are determined for cylindrical salt specimens obtained from the Maha Sarakham formation. The applied axial stresses increases at constant rates of 0.0001, 0.001, 0.01 and 0.1 MPa/s.

The temperatures ranging of 273, 303, 343 and 373 Kelvin (0-100°C).

The testing is assumed to be under isothermal conditions (constant temperature with time during loading). The decrease of the salt strength as the temperature increases suggests that the applied thermal energy before the mechanical testing makes the salt weaker, and more plastic, failing at lower stress and higher strain with lower elastic and shear moduli. The failure stresses increase with the loading rates, these agree with the experimental results on rock salt performed by Fuenkajorn et al. [5] and Dubey and Gairola [16]. The proposed criterion can be used to determine the stability of rock salt around compressed-air or gas storage cavens during product injection (high temperature, low deviatoric stress) and retrieval (low temperature, high deviatoric stress).

ACKNOWLEDGMENTS

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REFERENCES


Fig. 8 Elastic modulus ($E$), Poisson’s ratio ($\nu$) and Shear modulus ($G$) of salt as a function of temperature ($T$).

Fig. 9 Distortional strain energy at failure ($W_d$) as a function of mean strain energy ($W_m$).
Tab. 2 Octahedral shear strength and strains and strain energy.

<table>
<thead>
<tr>
<th>Average temperature (Kelvin)</th>
<th>Stress rate (MPa/s)</th>
<th>Octahedral shear strength (MPa)</th>
<th>Octahedral shear strain ($10^{-3}$)</th>
<th>Distortion strain energy density (MPa)</th>
<th>Mean strain energy density (MPa)</th>
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