



TIME-DEPENDENT BEHAVIOR OF MAHA SAKHAM SALT UNDER TRUE TRIAXIAL STRESS STATE

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ABSTRACT

True triaxial creep tests are performed to determine the effects of the intermediate principal stress on the time-dependent behavior of the Maha Sakham salt. The applied octahedral shear stresses vary from 5 to 14 MPa while the mean stress is maintained constant at 15 MPa. The loading conditions include triaxial compression, polyaxial and triaxial extension testing. Regression analyses of the results based on the Burgers model indicate that the instantaneous deformation tends to be independent of σ_2 . The visco-elastic and visco-plastic parameters notably increase with σ_2 . To calculate the σ_2 effect on the long-term closure of salt storage caverns the Burgers parameters are defined as a function of Lode parameter. The results suggest that the time-dependent deformation calculations based on the conventional creep test results may overestimate the actual closure of cylindrical and spherical caverns by as much as 16% and 35%, respectively.

KEYWORDS: Rock Salt, Creep, True Triaxial, Intermediate Principal Stress, Closure

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 behavior 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 objective of this study is to experimentally determine the effects of the intermediate principal stress on the instantaneous and time-dependent deformation of rock salt obtained from the Maha Sarakham formation. True triaxial creep testing has been performed on rectangular salt specimens with loading conditions varying from triaxial compression ($\sigma_1 > \sigma_2 = \sigma_3$), polyaxial ($\sigma_1 > \sigma_2 > \sigma_3$), to triaxial extension ($\sigma_1 = \sigma_2 > \sigma_3$). The Burgers model is used to describe the elastic, visco-elastic and visco-plastic deformations of the salt specimen tested under various stress states. Radial closure of spherical and cylindrical gas storage caverns in the Maha Sarakham salt is calculated to compare the results obtained from testing under different loading conditions.

2. Salt Specimens

The tested specimens have been prepared from 60 mm salt cores drilled from the depths ranging between 160 m and 270 m by Pimai Salt Co. in the northeast of Thailand. The salt cores belong to the Middle salt member of the Maha Sarakham formation in the Khorat basin. Warren [8] describes the origin and geological structures of the Maha Sarakham salt. The salt cores used here are virtually pure halite with average grain (crystal) sizes of $5 \times 5 \times 5 \text{ mm}^3$. The salt cores have been dry-cut to obtain rectangular blocks with nominal dimensions of $5.4 \times 5.4 \times 10.8 \text{ cm}^3$.

3. Test Method

The tests are categorized into three series based on the loading conditions: triaxial compression ($\sigma_1 > \sigma_2 = \sigma_3$), polyaxial ($\sigma_1 > \sigma_2 > \sigma_3$), and triaxial extension ($\sigma_1 = \sigma_2 > \sigma_3$). The applied constant octahedral shear stresses range from 5, 8, 11 to 14 MPa which are used, as much as practical, for all stress conditions. All specimens are tested under the same mean stress of 15 MPa, primarily to isolate the effect of confinement from the test results. Table 1 shows the magnitudes of the applied principal stresses and their corresponding octahedral shear stress for each specimen.

A polyaxial load frame [9] has been used to apply constant axial stress (σ_1) and lateral stresses (σ_2 and σ_3) to the salt specimens. The pre-calculated dead weights are placed on the two lower beams to obtain the lateral stress of 15

Table 1 Loading conditions used for true triaxial creep testing

Specimen No.	Depth(m)	Loading Conditions	Density (g/cm ³)	Applied Constant Stresses			τ_{Oct} (MPa)
				σ_1 (MPa)	σ_2 (MPa)	σ_3 (MPa)	
TC-2	209.68–209.80	$\sigma_1 \neq \sigma_2 = \sigma_3$	2.18	34.8	5.1	5.1	14.0
TC-11	255.67–256.02		2.18	30.6	7.2	7.2	11.0
TC-13	238.22–238.28		2.15	26.3	9.4	9.4	8.0
TC-16	162.82–162.88		2.17	22.1	11.5	11.5	5.0
TC-20	204.10–204.15	$\sigma_1 \neq \sigma_2 \neq \sigma_3$	2.14	34.6	7.2	3.2	14.0
TC-19	204.02–204.06		2.14	30.6	8.2	6.2	11.0
TC-14	268.32–268.38		2.17	26.3	10.3	8.3	8.0
TC-17	162.74–162.80		2.21	21.5	14.3	9.3	5.0
TC-4	253.64–253.75	$\sigma_1 = \sigma_2 \neq \sigma_3$	2.09	21.0	21.0	3.0	8.0
TC-8	208.30–208.40		2.15	20.0	20.0	5.0	7.0
TC-18	202.14–202.26		2.17	18.6	18.6	7.9	5.0

MPa along the two mutually perpendicular directions. Simultaneously the axial (vertical) stress is increased to 15 MPa. This uniform stress is maintained for a minimum of one hour primarily to ensure that the salt specimen is under isostatic condition. The applied stresses are then adjusted to obtain the pre-defined octahedral shear stresses (τ_{oct}) while the mean stresses are maintained at 15 MPa. Each specimen is tested up to 21 days. The deformations along the principal axes are monitored using displacement digital gages.

4. Test Results

Figure 1 shows the principal strains ($\varepsilon_1, \varepsilon_2, \varepsilon_3$) and volumetric strains (ε_v) as a function of time for all tested specimens. The curves show the instantaneous, transient and steady-state creep phases of the salt. For all loading conditions the axial strains increase with τ_{oct} . Under the triaxial compression loading ($\sigma_1 \neq \sigma_2 = \sigma_3$) the intermediate and minor principal strain curves are virtually identical. Under the triaxial extension loading ($\sigma_1 = \sigma_2 \neq \sigma_3$) the major and intermediate principal strain curves are comparable. These suggest that the test procedure and measurement techniques are sufficiently reliable.

The Burgers model is used to describe the test results primarily because it is simple and capable of describing the elastic, visco-elastic and visco-plastic phases of the salt creep under isothermal condition. It is recognized that numerous creep models or constitutive equations have been developed to represent the time-dependent behavior of rock salt. They are however complex and can not isolate each phase of salt creep. Figure 2(a) shows the physical components arranged in the Burgers model. Assuming that the salt is isotropic and linearly elastic a relation between octahedral shear strain and stress can be written as [10]:

$$\gamma_{oct} = \tau_{oct} / 2G \quad (1)$$

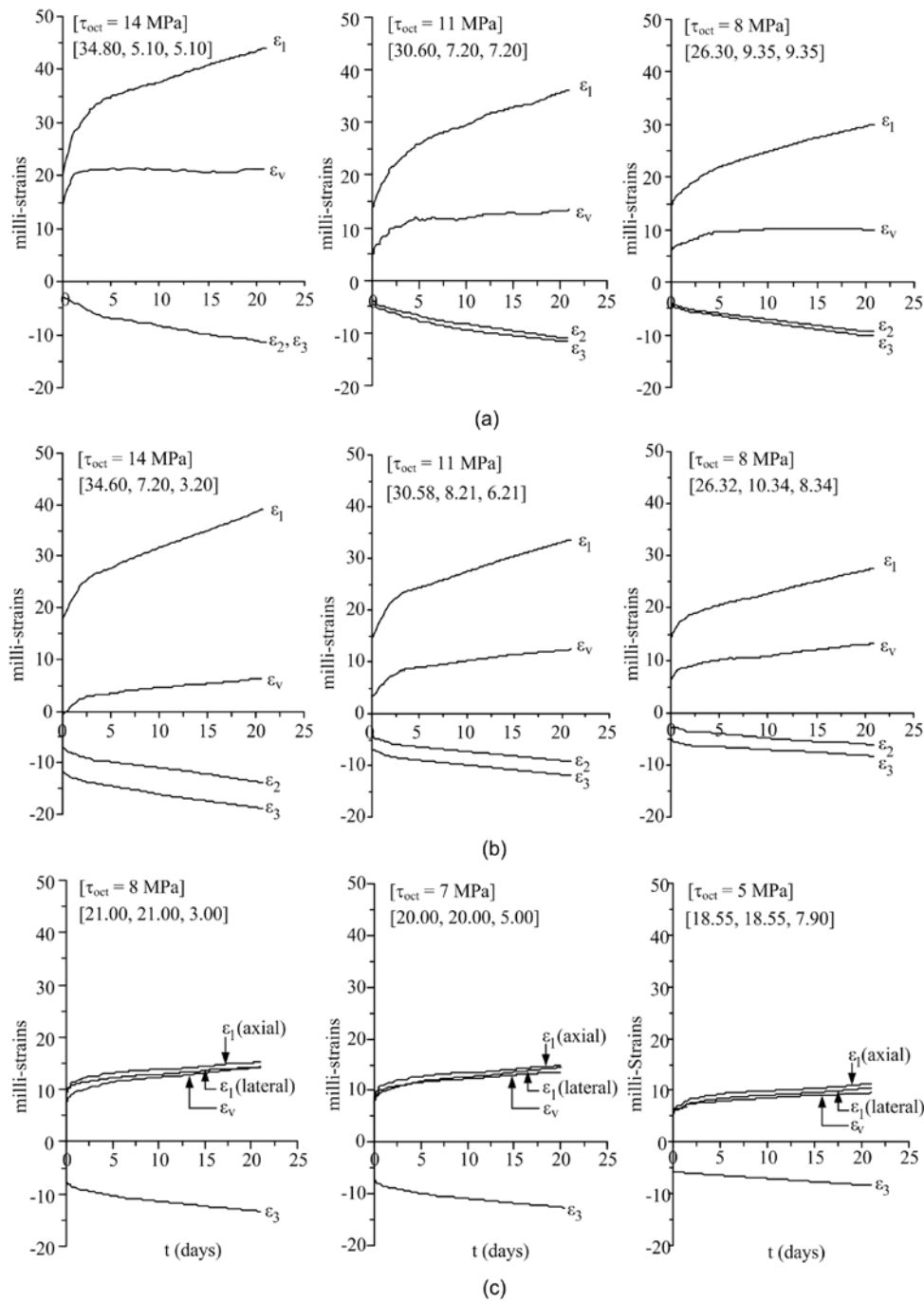


Figure1 Strain-time curves obtained from triaxial compression (a), polyaxial compression (b) and triaxial extension (c). Numbers in bracket indicate $[\sigma_1, \sigma_2, \sigma_3]$

where G is the shear modulus of the salt. Using the Laplace transformation a linear visco-elastic relation can be derived from the above equation by using time operator of the Burgers model, and hence the octahedral shear strain can be presented as a function of time [11]:

$$\gamma_{oct}(t) = \tau_{oct} [(t/\eta_1) + (1/E_1) + (1/E_2)(1 - \exp(-E_2 t/\eta_2))] \quad (2)$$

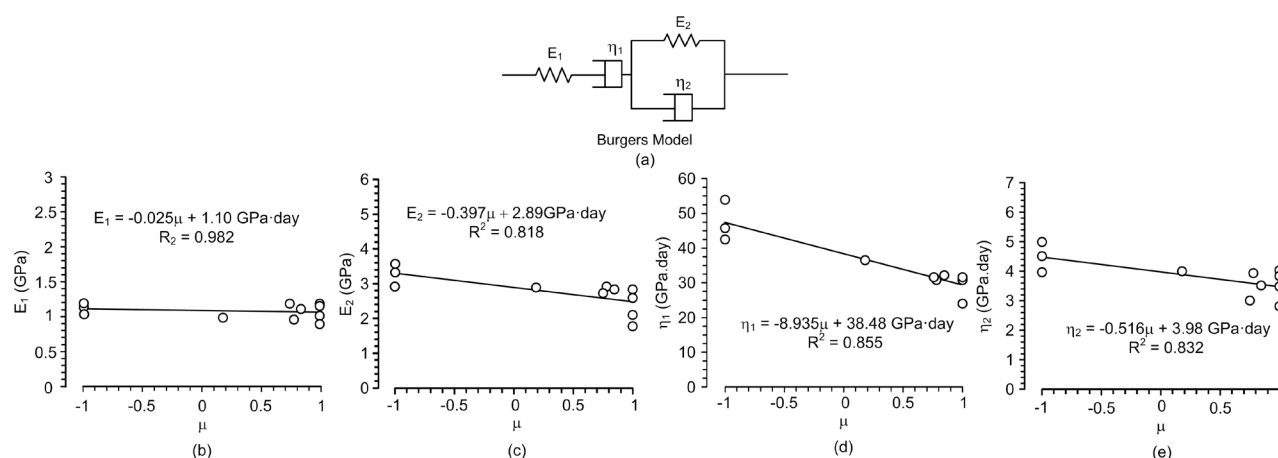


Figure 2 Modular components of the Burgers model (a) and Burgers parameters as a function of Lode parameter (b, c, d, e)

where τ_{oct} is the applied constant octahedral shear stresses (MPa), t is the testing time (day), E_1 is the elastic modulus (GPa), E_2 is the spring constant in visco-elastic phase (GPa), η_1 is the viscosity coefficient in steady-state phase (GPa·Day), and η_2 is the viscosity coefficient in transient phase (GPa·Day). Regression analyses on the octahedral shear strain-time curves based on equation (2) using the SPSS statistical software [12] are performed to determine the Burgers parameters for each salt specimen. Table 2 summarizes the calibration results. The Lode parameter (μ) [13] is used here to address the σ_2 effect on salt creep in three dimensions:

$$\mu = -(2\sigma_2 - \sigma_3 - \sigma_1) / (\sigma_1 - \sigma_3) \quad (3)$$

Table 2 Burgers parameters calibrated from each salt specimen

Loading conditions	μ	τ_{oct} (MPa)	Burgers Parameters			
			E_1 (GPa)	E_2 (GPa)	η_1 (GPa·day)	η_2 (GPa·day)
Triaxial Compression ($\sigma_1 \neq \sigma_2 = \sigma_3$)	1.00	14	1.15	2.80	32	4.0
	1.00	11	1.20	2.60	26	3.8
	1.00	8	1.03	2.10	23	3.5
	1.00	5	0.91	1.80	27	2.8
Polyaxial Compression ($\sigma_1 \neq \sigma_2 \neq \sigma_3$)	0.75	14	1.20	2.70	32	3.0
	0.84	11	1.12	2.80	32	3.5
	0.78	8	0.98	2.90	31	3.9
	0.18	5	1.00	2.90	42	4.0
Triaxial Extension ($\sigma_1 = \sigma_2 \neq \sigma_3$)	-1.00	8	1.20	3.55	53	4.0
	-1.00	7	1.05	2.30	48	4.5
	-1.00	5	1.15	2.90	44	5.0

The Lode parameter is equal to -1 for the triaxial extension testing, and equal to 1 for the triaxial compression testing. Figure 2 (b, c, d, e) shows the Burgers parameters as a function of the Lode parameter (μ). The parameters η_1 , E_2 and η_2 tend to decrease with increasing the Lode parameter. The spring constant, E_1 corresponding to the instantaneous deformation of salt, tend to be independent of the Lode parameter.

The parameters η_1 , E_2 and η_2 obtained from the triaxial extension ($\sigma_1 > \sigma_2 = \sigma_3$) are about 1–1.5 times greater than those obtained from the polyaxial loading conditions ($\sigma_1 > \sigma_2 > \sigma_3$). The triaxial compression condition yields in the lowest magnitudes for three parameters. Linear equations are used to describe the variation of η_1 , E_2 and η_2 with the Lode parameter, as follows:

$$\eta_1 \{\mu\} = -\alpha_1 \cdot \mu + \alpha_2 \quad (4)$$

$$E_2 \{\mu\} = -\beta_1 \cdot \mu + \beta_2 \quad (5)$$

$$\eta_2 \{\mu\} = -\gamma_1 \cdot \mu + \gamma_2 \quad (6)$$

where α_1 , β_1 and γ_1 are empirical constants equal to 8.935 GPa·day, 0.397 GPa and 0.516 GPa·day for the Maha Sarakham salt, and the constants α_2 , β_2 and γ_2 equal to 38.48 GPa·day, 2.89 GPa and 3.98 GPa·day. By substituting equations (4) through (6) into equation (2) the octahedral shear strain can be defined as a function of Lode parameter in the form of the Burgers model. It can be used to calculate the time-dependent deformation of rock salt while considering the effect of σ_2 .

5. Creep Closure of Storage Caverns

Sets of analytical solutions are derived here to calculate radial displacements around cylindrical and spherical gas or compressed-air caverns in an infinite salt mass. The salt is assumed to be time-independent under hydrostatic stress. The radial displacements (u_r) of cylindrical cavern are obtained from Laplace transformation using time operator of the Burgers model which can be expressed as [14]:

$$u_r = P_o [(A+B/9K) + (\alpha \cdot ((2A-B)/3))] - P_i r \alpha \quad (7)$$

$$A = [((1+k)/2) \cdot (r+(a^2/r))] + [((1-k)/2) \cdot (r-(a^4/r^3)+(4a^2/r))] \cos 2\theta \quad (8)$$

$$B = [((1+k)/2) \cdot (r-(a^2/r))] - [((1-k)/2) \cdot (r-(a^4/r^3))] \cos 2\theta \quad (9)$$

$$\alpha = (t/\eta_1) + (1/E_1) + (1/E_2) \cdot (1 - \exp(E_2 \cdot t/\eta_2)) \quad (10)$$

where P_i and P_o are an internal and external pressures, A and B are time-independent functions of position, K is bulk modulus, k is stress ratio, α is time-dependent function, θ is tangential coordinate, r is radius and a is inner boundary. For a spherical cavern under hydrostatic stresses the radial displacement (u_r) can be obtained from [15]:

$$u_r = P_o [(1/18K) + (\alpha/3)] \cdot (a^3/r^2) + P_o [-(1/18K) + (\alpha/6)] \cdot (a^3/r^2) - [(P_i/2) \cdot (a^3/r^2) \cdot \alpha] \quad (11)$$

The creep parameters defined in equations (4), (5) and (6) are used to determine the effect of intermediate principal stress on time-dependent closure of a salt cavern by incorporating them into equation (10). In general, the salt around a cylindrical cavern is under polyaxial stresses state ($\sigma_\theta > \sigma_z > \sigma_r$, $-1 < \mu < 1$). For the spherical cavern the surrounding salt is under triaxial extension stresses ($\sigma_\theta = \sigma_z > \sigma_r$, $\mu = -1$). For this demonstration, the cylindrical cavern is taken as an upright cylinder with a diameter of 50 m. The spherical cavern also has a diameter of 50 m. The external pressure is calculated from the in-situ stress of 10.9 MPa equivalents to the depth of about 500 m. The storage cavern model is assumed to subject to the internal pressures of 2.2 MPa or about 20% of the in-situ stress at the cavern shoe, representing the minimum storage pressure of salt cavern. This is mainly to demonstrate the effect of σ_z on the creep closure.

Figure 3 compares the radial closure of the cylindrical and spherical caverns calculated by equations (7) through (11) for 90 days. The radial closure obtained from the conventional compression creep test results is greater than that from the polyaxial and triaxial extension creep test results. In summary the conventional creep test results overestimate the actual closure of cylindrical and spherical caverns by as much as 16% and 35%, respectively.

6. Discussions and Conclusions

The true triaxial creep test results indicate that the intermediate principal stress affects both transient and steady-state creep phases of the Maha Sarakham salt. The creep strains decrease when σ_2 increases from σ_3 (triaxial compression) to σ_1 (triaxial extension). The elastic deformation of salt, E_1 , is not affected by the intermediate principal stress, σ_2 . The visco-plastic coefficient η_1 and visco-elastic parameters (E_2 and η_2) tend to decrease with increasing the Lode parameter. As demonstrated in Figure 3 the empirical relations of the Burgers parameters and the Lode parameter (equation (4)–(6)) can be effectively used to predict the time-dependent deformation (creep) of rock salt under various stress states where $\sigma_1 \neq \sigma_2 \neq \sigma_3$. Here they are substituted into equation (10) to calculate the creep closure of cylindrical and spherical caverns.

It should be noted that the calculation of cavern closure as demonstrated here is made under extreme loading condition, i.e., the internal pressure is left constant for long period (90 days). This is primarily to reveal the σ_2 effect on the creep closure of the storage caverns. In reality however the storage caverns would not be allowed to subject to the low minimum storage pressure to longer than few day.

Under the simplified test conditions used here (i.e. constant mean stress and temperature) the Burgers model sufficiently reveal the effect of σ_2 on the time-dependent deformation of the salt. The conventional creep test results clearly overestimate the actual closure of cylindrical and spherical caverns by as much as 16% and 35%, respectively. This finding imply that laboratory test results obtained from the conventional and commonly-used uniaxial and triaxial creep testing methods (e.g. ASTM standard practices [16]) may over predict the time-dependent deformation of the actual in-situ salt under the true triaxial stress conditions.

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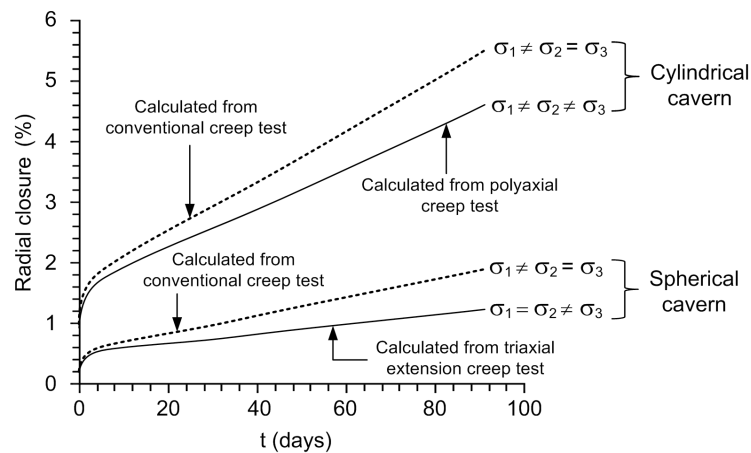


Figure 3 Closure of cavern wall as a function of time for cylindrical and spherical cavern shapes.

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