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TIME-DEPENDENT TENSILE STRENGTH OF MAHA SARAKHAM SALT

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บทคัดย่อ

การทดสอบการดัดงอแบบสี่จุดได้ดำเนินการโดยใช้ตัวอย่างเกลือหินรูปแท่งสี่เหลี่ยมขนาด 50×50×200 มิลลิเมตร ตัวอย่างแบ่งเป็นสองชุดสำหรับการทดสอบแบบอัตราแรงกดคงที่และแบบแรงกดคงที่เชิงเวลา วิธีการทดสอบได้ดำเนินตามมาตรฐาน ASTM ในระหว่างการทดสอบความเค้นดึงที่จุดแตกได้ถูกคำนวณในขณะที่ความเครียดดึงถูกวัดด้วยมาตรวัดความเครียด การทดสอบแบบให้แรงกดคงที่จะสอดคล้องกับค่าความเค้นดึงที่จุดแตกเท่ากับ 0.5 ถึง 1.25 เมกะปาสคาล ความเครียดดึงที่เกิดขึ้นถูกวัดเชิงเวลาถึง 21 วัน ซึ่งผลที่ได้สามารถอธิบายได้โดยกฎของความคืบแบบยกกำลัง ตัวอย่างที่ใช้สำหรับการทดสอบอัตราดึงคงที่มีค่าจาก 10^{-7} ถึง 10^{-2} เมกะปาสคาลต่อวินาที ผลที่ได้ระบุว่าภายใต้อัตราดึงสูงขึ้นส่งผลให้เกลือหินมีกำลังดึงและสัมประสิทธิ์ความยืดหยุ่นสูงขึ้น ผลการทดสอบทั้งสองแบบยืนยันว่าการเปลี่ยนรูปร่างของเกลือหินภายใต้แรงดึงจะขึ้นกับเวลา ซึ่งจะถูกควบคุมด้วยกลไกการเคลื่อนตัวระหว่างผลึกของเกลือ เมื่อรวมผลการทดสอบเข้ากับเกณฑ์การวิบัติเชิงพลังงานความเครียดจะสามารถคาดคะเนกำลังดึงของเกลือหินเชิงเวลาภายใต้ความเค้นดึงที่คงที่ได้

ABSTRACT

Four-point bending tests have been performed on prismatic specimens (50×50×200 mm) of rock salt. Two loading configurations are used on separate sets of the specimens: constant rate loading and static loading. The test procedure is in accordance with the ASTM standard practice. The tensile stresses at the crack initiation point are calculated and the tensile strains are measured with strain gage. The static loading test uses four loading magnitudes equivalent to the induced tensile stresses from 0.5 to 1.25 MPa. The tensile strains measured up to 21 days show the instantaneous and transient deformations which can be described by potential creep law. The constant loading rate specimens are subjected to the tensile stresses rates from 10^{-7} *to* 10^{-2} *MPa/s. Higher loading rates induce higher tensile strength and deformation modulus. Results from the two test series suggest that under tension rock salt exhibits elastic and time-dependent deformations. The tensile deformation modulus is low (less than 2 GPa). The creep deformation is governed by the dislocation climb mechanism and is non-recoverable. Combining the calibrated potential creep law and the strain energy at failure the time-dependent tensile strengths of salt under various constant tensile stresses can be predicted.*

KEYWORDS: Creep, Bending Test, Loading Rate, Tension, Dislocation Climb

1. Introduction

Tensile strength of rock dictates the maximum span and standup time of mine opening. The tensile strength can be obtained in the laboratory by various methods, including direct tension tests, Brazilian tension tests, ring tension tests, flexural tests, three- and four-point bending tests [1, 2]. For the analysis and design of mine roof span the bending test is more preferable than the others because the bending test specimen will subject to the stress configurations similar to those in the mine roof. The design of the roof span for brittle rocks normally considers the fracture characteristics (shear strength, spacing, water pressure, etc.) of the overlying rock. For soft and time-dependent rocks, such as rock salt and potash, the design considerations should also be placed on the time-dependent strength and deformation of the materials. The time-dependent behavior of rock salt under compression has long been recognized and investigated under variety of test parameters and boundary conditions (loading rate, temperature, stress paths, etc.). The significant of the time-dependent strength and deformability of rock salt under tension has however been recognized and examined.

The objective of this study is to determine the time-dependent tensile strength and deformation of rock salt. The four-point bending tests are performed on prismatic beams of rock salt specimens prepared from the Maha Sarakham formation. Two test series are performed: creep testing and loading rate testing. The creep tests are performed with the tensile stresses ranging between 0.5 and 1.25 MPa. The applied loading rates are varied which are equivalent to the tensile stress rates of 10^{-7} to 10^{-2} MPa/s at the crack initiation point. The specimen deformations are monitored with strain gages installed at the crack initiation point. The results are used to determine the maximum strain energy density of rock salt under tension, and hence the maximum unsupported span and standup time of the salt mine roof can be predicted.

2. Sample Preparation

The tested specimens have been obtained from underground openings of the ASEAN Potash Mining Co., Ltd. (APMC). They belong to the Lower Salt member of the Maha Sarakham formation. Warren [3] describes the origin and geological structures of the Maha Sarakham salt. The specimens used for the four-point bending and creep tests are prepared as prismatic beams with nominal dimensions of 50×50×200 mm^3. A strain gage (TML, PFL-20-11-1L, and 20 mm) is installed at the crack initiation point. The bedding planes are parallel to the specimen main axis and normal to the loading directions.

3. Test Method

The test method and calculation follow the ASTM standard practice [4]. Figure 1 shows the loading directions which are normal to the bedding plane. A data logger (TC-32K) connected with the switching box (Type B-2760) is used to monitor the induced tensile strains while loading. The creep specimens are subjected to the tensile stresses of 0.5, 0.75, 1.0 and 1.25 MPa. Each specimen is tested up to 21 days. The readings are made every one minute for the first hour. After that the reading interval are gradually increased to every hour. The induced tensile stress can be calculated by ASTM [4]:

$$\sigma_t = PL/bd^2 \tag{1}$$

where σ_t is tensile stresses, P is the applied load, L is support span (180 mm), b is specimen width (50 mm), and d is specimen thickness (50 mm).

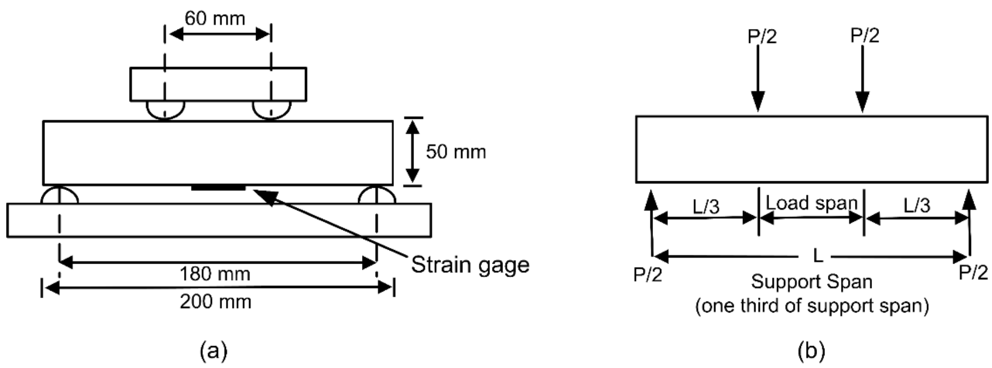

Figure 1 Test arrangement for four-point bending test (ASTM (D6272 – 10))

The loads for the rate-controlled testing are applied under six constant magnitudes which are equivalent to the induced stress rates from 4×10^{-2} MPa/s to 4×10^{-7} MPa/s at the center of the specimen. The specimen deformations are monitored and are used to calculate the principal strains during loading. The readings are recorded every 50 N of load increment until failure.

4. Test Results

To reveal the effects of loading rate on the tensile strength and deformability the applied tensile stresses are plotted as a function of tensile strain in Figure 2(a). The tensile stress-strain relations are nonlinear, particularly under low loading rates. Higher loading rates applied result in higher tensile stregths and lower tensile strains at failure. Table 1 shows the tensile stress and strain at failure and tensile deformation modulus. The tensile modulus is determined as a tangent at 40% of the failure stress. It is found that the tensile strengths and deformation moduli increase with loading rate. The tensile strains at failure however decrease with increasing loading rate for each specimen. This agrees with the ring tension test results obtained by Wisetsaen et al. [2] that the Maha Sarakham rock salt tensile strengths increase with the loading rate. Figure 2(b) shows the creep tensile strains as a function of time for 21 days. The curves show instantaneous and transient creep phases. Larger creep strains are obtained for the specimens under higher tensile stresses.

5. Time-Dependent Deformation

Due to the fact that there is no steady-state creep strain observed from the test results. The potential creep law is applied here to describe the time-dependent deformation of the creep specimens. The total tensile strain in salt can be divided into two parts, elastic tensile strain (linear and recoverable strain) and plastic tensile creep strain (time-dependent and non-recoverable strain):

$$\varepsilon_t = \varepsilon_t^e + \varepsilon_t^c \tag{2}$$

where ε_t is axial tensile strain, ε_t^e is elastic tensile strain and ε_t^c is plastic tensile creep strain.

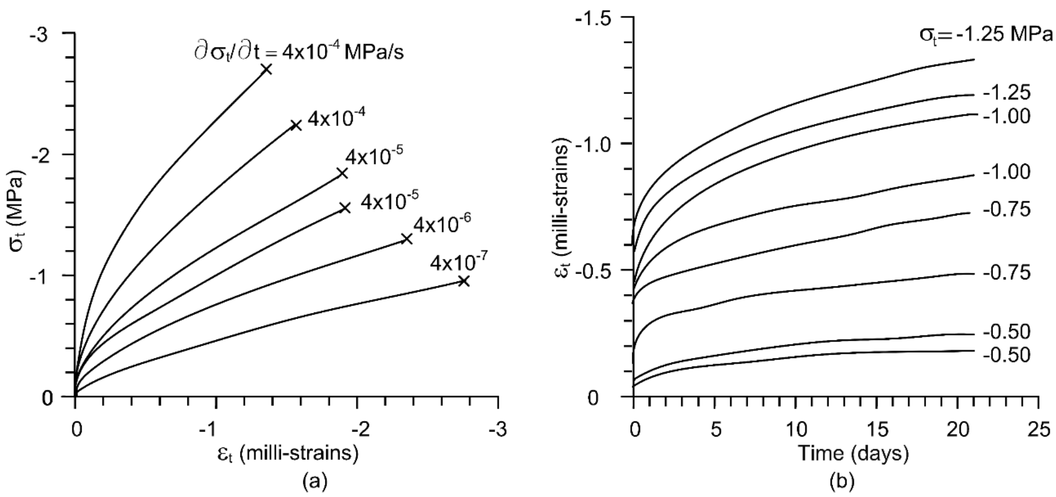

Figure 2 Tensile stresses (σ_t) as a function of tensile strains (ε_t) (a) and tensile strains (ε_t) as a function of time (b)

Table 1 Calculated Results of Strain Energy Density

Rate (MPa/s)	σ_t (MPa)	ε_t (milli-strains)	E (GPa)
$4\text{x}10^{-4}$	-2.72	-1.38	6.81
	-2.21	-1.52	4.19
$4\text{x}10^{-5}$	-1.53	-1.90	3.09
	-1.70	-1.91	2.35
$4\text{x}10^{-6}$	-1.23	-2.28	1.47
$4\text{x}10^{-7}$	-0.73	-2.78	0.53

The elastic tensile strain can be obtained from the generalized Hooke's law. The axial (principal) strain can be written as:

$$\varepsilon_t^e = \sigma_t / E \tag{3}$$

where σ_t is tensile stress and E is tensile deformation modulus.

For one-dimensional analysis the tensile creep strain (ε_t^c) can be presented in the form of the potential law as [5]:

$$\varepsilon_t^c = \kappa \cdot \sigma^{\beta} \cdot t^{\gamma} \tag{4}$$

where κ, β and γ are material parameters.

Regression analyses on the strain-time curves using the SPSS statistical software [6] are performed to determine the parameters in equations (3) and (4) for each specimen. Table 2 summarizes the calibration results. The parameters tend to be independent of the applied stresses.

Table 2 Calibration of Potential Law Parameters

σ_t (MPa)	E_0 (GPa)	κ (1/GPa·Day)	β	γ
-0.50	3.14	0.24	1.06	0.26
	3.11	0.29	1.01	0.28
-0.75	4.20	0.21	1.09	0.32
	4.40	0.26	1.05	0.30
-1.00	3.13	0.22	1.01	0.29
	2.82	0.23	1.07	0.31
-1.25	3.60	0.21	1.01	0.27
	3.02	0.29	1.00	0.30
Mean ± SD	3.41 ± 0.58	0.24 ± 0.03	1.03 ± 0.03	0.29 ± 0.02

6. Strength Criterion

The strain energy density principle is applied here to describe the salt strengths and deformability under different loading rates. The total strain energy density (W_T) can be calculated from the failure stress and strain for each salt specimen using the relations [7]:

$$W_T = \frac{1}{2} \sigma_T \cdot \varepsilon_T \tag{5}$$

where σ_T and ε_T are the tensile strength and strain at failure (as given in Table 1).

To develop a strength criterion based on the strain energy density principle, the total strain energy that the salt specimen can sustain before tensile failure occur can be presented as a function of the tensile stress at the crack initiation point. Figure 3 plots the W_T as a function of σ_T. A linear trend is obtained and can be described by:

$$W_T = 0.298\sigma_T + 0.905 \quad \text{(kPa)} \tag{6}$$

This equation can be used as a time-dependent strength criterion for salt under tension.

7. Time-dependent Tensile Strength

The time-dependent strength of rock salt under tension is an important factor governing the unsupported span and stand-up time of the mine roofs. Such knowledge can also be used for the planning of backfill installation or roof supports. This is mainly to ensure that the mine openings remain mechanically stable during operation while maximizing the extracted salt ore.

The salt strength in terms of the strain energy as shown in Figure 3 can be used as a tensile failure criterion. This approach has a particular advantage that both stresses and strains at failure are considered. The tensile strength can be correlated with time by using the potential creep law derived in section 5. For example if the constant tensile stresses at any point in salt is known (such as those in the middle of salt roof the corresponding time-dependent tensile strains can be predicted (equation 3 and 4)). The corresponding strain energy can then be calculated as a function of time. Figure 4(a) gives an example of the time-dependent strain energy curves for the constant tensile stresses from -1.0 to -2.5 MPa. The failure points represent the maximum tensile stress that the salt can sustain under each constant stress determined by the strain energy failure criterion.

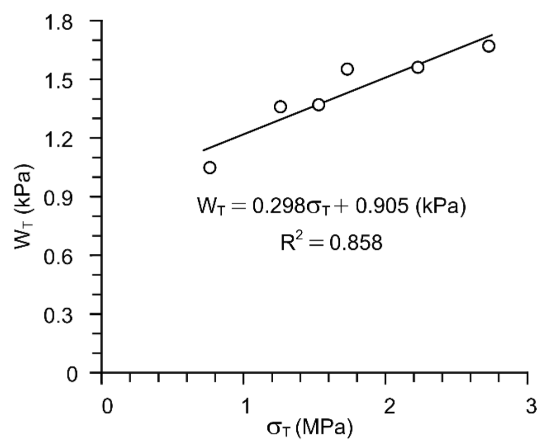

Figure 3 Total strain energy densities (W_T) as function of tensile strengths (σ_T)

Figure 4(b) shows the equivalent tensile strain until failure based on the same calculation above. The diagram in Figure 4(b) can be used to predict the time at failure for salt roof that is subjected to constant tensile stresses. The roof stresses can be obtained by any numerical modelling or by closed form solution, which also depend on depth and roof span.

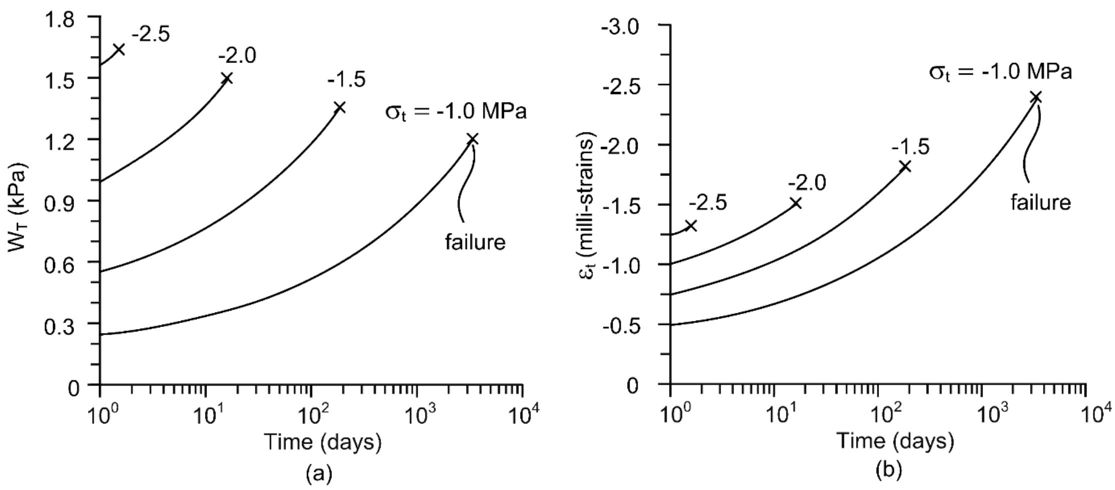

Figure 4 Total strain energy densities (W_T) (a) and tensile strains ($\mathcal{E}_t$) (b) as a function of time

8. Discussions and Conclusions

The four-point bending tests are performed on rock salt specimens under different loading rates and constant stress. The strength results are used to develop a strength criterion in the form of strain energy density as function of tensile strength. Obtaining the specimen strengths under a wide range of loading rates allows a rigorous calibration of the strain energy equation. The measured time-dependent strains are used to develop a governing equation based on the potential creep law. Results from the two test series suggest that under tension rock salt exhibits elastic and time-dependent deformations. The tensile elastic modulus is low (less than 2 GPa). The creep deformation is governed by the dislocation climb mechanism (sliding between crystals) and is non-recoverable. The findings obtained here can be used to predict the time-dependent tensile strength of salt to design the maximum unsupported span of salt opening, and to plan for the backfill operation.

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