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# TIME-DEPENDENT TENSILE STRENGTHS OF ROCK SALT AS AFFECTED BY CARNALLITE CONTENTS

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**บทคัดย่อ**

*การศึกษานี้มีวัตถุประสงค์เพื่อหากำลังดึงเชิงเวลาของเกลือหินที่มีผลกระทบจากการเจือปนของแร่คาร์นัลไลต์ ($C_{\%}$) การทดสอบการดัดงอแบบสี่จุดได้ดำเนินการโดยใช้แท่งตัวอย่างของโพแทชขนาด 50×50×200 มิลลิเมตร มีการผันแปรปริมาณแร่คาร์นัลไลต์จากร้อยละ 0 ถึง ร้อยละ 95 อัตราการให้แรงกดที่สอดคล้องกับการเพิ่มขึ้นของความเค้นดึงที่จุดแตกอยู่ในช่วงระหว่าง $10^{-6}$ ถึง $10^{-3}$ เมกะปาสคาลต่อวินาที ระหว่างการทดสอบมีการตรวจวัดความเครียดดึงอย่างต่อเนื่อง ณ จุดที่จะเกิดการแตกภายใต้แรงดึง ผลการทดสอบระบุว่าค่ากำลังดึง ($\sigma_t$) ของตัวอย่างหินมีค่าลดลงเมื่อมีการเพิ่มขึ้นของปริมาณแร่คาร์นัลไลต์และเมื่อมีการลดลงของอัตราการให้แรงดึง ($\sigma_R$) การผันแปรนี้สามารถอธิบายได้ด้วยสมการ $\sigma_t = 8.21 \cdot \exp [-0.02\ C_{\%}]\ (\sigma_R) \cdot 0.17$ เมกะปาสคาล ทั้งนี้การทดสอบได้มีการคำนวณค่าพลังงานความเครียดที่จุดแตก (W) และพัฒนาให้อยู่ในฟังก์ชั่นของ $C_{\%}$ โดย $W = 2.17 \cdot \exp [-0.03\ C_{\%}]$ กิโลปาสคาล แม็กเวลโมเดลถูกนำมาใช้เพื่ออธิบายการขึ้นกับเวลาของความเครียดดึงที่ตรวจวัดได้จากการทดสอบ ความยืดหยุ่นและความหนืดของตัวอย่างหินได้ถูกสอบเทียบจากค่าที่ได้จึงส่งผลให้สามารถร่างแผนภูมิของความเครียดดึงเชิงเวลาภายใต้ความเค้นดึงที่ผันแปร*

**ABSTRACT**

*This study aims at determining the time-dependent tensile strengths of rock salt under varying carnallite contents. Four-point bending tests are performed on prismatic beams (50×50×200 mm) of potash specimens with carnallite contents ranging from 0 to 95%. The applied loading rates are equivalent to the induced tensile stress rates at the crack initiation point ranging from $10^{-6}$ to $10^{-3}$ MPa/s. The tensile strains are monitored at the point where the incipient tensile crack is induced. The results indicate that tensile strengths ($\sigma_t$) decrease when the carnallite contents ($C_{\%}$) increase and the stress rates ($\sigma_R$) decrease, which can be best represented by an empirical equation: $\sigma_t = 8.21 \cdot \exp [-0.02\ C_{\%}]\ (\sigma_R) \cdot 0.17$ MPa. The strain energy at failure (W) has been calculated and derived as a function of $C_{\%}$, which can be described by: $W = 2.17 \cdot \exp [-0.03\ C_{\%}]$ kPa. The Maxwell model is used to describe the time-dependent tensile strain of the specimens. Its tensile elasticity and viscosity are calibrated by regression analysis of the test results, and hence series of tensile strain-time curves can be constructed for various applied tensile stresses.*

**KEYWORDS:** Bending Test, Stress Rate, Strain Energy, Viscosity

## 1. Introduction

Tensile strength of rock dictate the maximum span and standup time of the mine opening in stratified rock mass. 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 the 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 mine roof span for brittle rock will normally consider the fracture characteristics (shear strength, spacing, water pressure, etc.). 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. It has been found that carnallite content can decrease the compressive strength, elasticity and viscosity of rock salt [3]. The effect of the carnallite content on the bending tensile strength of the rock has however never been investigated.

The objective of this study is to determine the time-dependent tensile strengths of rock salt with various carnallite contents. The four-point bending tests are performed on prismatic beams (50×50×200 mm) of rock salt specimens with carnallite contents ranging from 0 to 95%. The applied loading rates are varied which are equivalent to the tensile stress rates of $10^{-6}$ to $10^{-3}$ MPa/s. They are loaded axially at a constant rate of 0.045 N/s to 45 N/s until failure occurs. The specimen deformations are monitored with strain gages to calculate the tensile strains. The tensile strains are monitored at the point where the incipient tensile crack is induced. The results can be used to determine the maximum unsupported span and standup time of potash mine roof.

## 2. Sample Preparation and Test Procedure

The tested samples have been obtained from underground openings of ASEAN Potash Mining Co., Ltd. (APMC). They belong to the Lower Salt member of the Maha Sarakham formation. Warren [4] describes the origin and geological structures of the Maha Sarakham salt. The samples mainly contain inter-beds of halite and carnallite. They are sometimes called carnallitite. The specimens used for four-point bending tests are prepared as prismatic blocks with nominal dimensions of 50×50×200 mm. Figure 1 shows examples of the specimens with different carnallite contents.

Chemical analyses by X-ray diffraction (XRD) performed on some specimens show that the primary mineral compositions of the specimens are halite and carnallite, which are of interest in this study (Table 1). The halite crystals are about 2-5 mm. The size of carnallite crystals varies greatly from 1 mm to 2 cm. Other minerals are relatively small and tend to appear about the same amounts in all specimens. Due to the difference of densities between halite and carnallite, the carnallite contents ($C_{\%}$) for each specimen can be estimated by:

$$C_{\%} = [(\rho_s - \rho) / (\rho_s - \rho_c)] \times 100 \quad (1)$$

where $\rho$ is specimen density, $\rho_s$ is density of halite (2.16 g/cc) and $\rho_c$ is density of carnallite (1.60 g/cc) [5]. The discrepancy between the carnallite contents obtained by the chemical analyses and by density ratio in equation (1) may be caused by the preparation procedure to obtain powder samples for the XRD analysis. Some hydroxyls may be lost during grinding of the rock

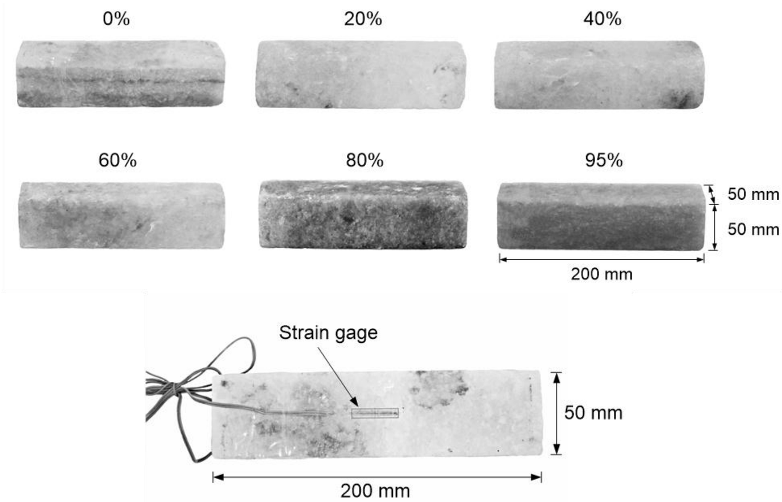


**Figure 1** Examples of prismatic specimens with strain gage position

**Table 1** Mineral compositions of samples

| Minerals | Sample (1) | Sample (2) | Sample (3) | Sample (4) |
|---|---|---|---|---|
| Carnallite ($KMgCl_3\ 6H_2O$) | 0.05 | 24.75 | 38.31 | 52.98 |
| Halite (NaCl) | 92.4 | 64.6 | 42.8 | 35.97 |
| $MgCl_2$ | 5.71 | 8.93 | 9.69 | 5.55 |
| Calcite ($CaCO_3$) | 0.00 | 0.21 | 0.48 | 1.92 |
| Anhydrite ($CaSO_4$) | 0.11 | 0.17 | 0.65 | 1.23 |
| Sylvite (KCl) | 0.09 | 0.19 | 6.10 | 1.01 |
| Hydrophilite ($CaCl_2$) | 0.00 | 0.00 | 1.64 | 0.56 |
| Wuestite (FeO) | 0.00 | 0.06 | 0.43 | 0.44 |
| Calcium Chloride (CaCl) | 1.65 | 1.08 | 0.89 | 0.33 |
| Density (g/cc) | 2.11 | 1.96 | 1.89 | 1.76 |
| $C_{\%}$ (determined by density ratio) | 8.56 | 36.12 | 49.01 | 71.08 |

fragments. Even through equation (1) considers only halite and carnallite contents, it seems reliable. This is because other trace minerals (those without Na, Mg, Cl and K) are less than 5% by weight.

## 3. Test Method

The test method and calculation follow the ASTM standard practice [6]. Figure 2 shows the positions of the loading for the upper and lower bearing plates. A data logger (TC-32K) connected with the switching box (Type B-2760) is used to monitor the induced tensile strains. The loads are applied under four constant rates from 0.045 N/s to 45 N/s, which are equivalent to the

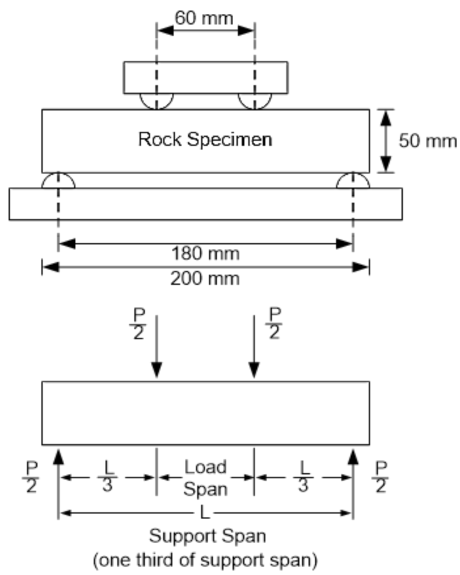


**Figure 2** Test arrangement for four-point bending test (ASTM (D6272 – 02))

induced tensile stress rates at the center of the specimen from $10^{-6}$ to $10^{-3}$ MPa/s. The load is applied until failure occurs. The induced tensile stress is calculated by:

$$\sigma_t = PL/bd^2 \quad (2)$$

where $\sigma_t$ 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). The tensile stress is defined here as positive values for a convenience of presentation.

## 4. Test Results

The tensile stress-strain curves can be plotted from the test results, as shown in Figure 3. It is obvious that the specimens with high carnallite content show lower tensile strengths and tensile strain at failure than those with lower carnallite. This holds true for all loading rates. Higher loading rates yield higher tensile strengths. The reduction of the tensile strengths with increasing carnallite content can be seen in Figure 4(a). The strength reduction under different stress rates ($\sigma_R$) can be represented by an exponential equation:

$$\sigma_t = \alpha \cdot \exp\left(-\beta \cdot C_{\%}\right) \cdot \sigma_R^{\chi} \tag{3}$$

where $\alpha \cdot$, $\beta$ and $\chi$ are empirical constants, equals to 8.21 MPa, 0.02, 0.17, respectively. Good correlation is obtained ($R^2$=0.997).

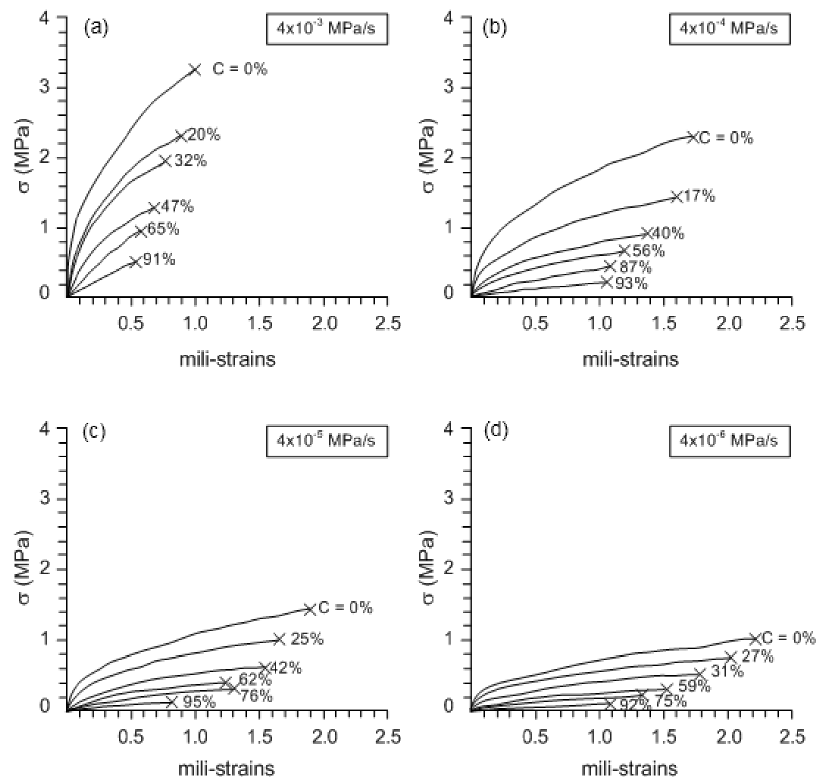


**Figure 3** Tensile stress-strain curves for various loading rate

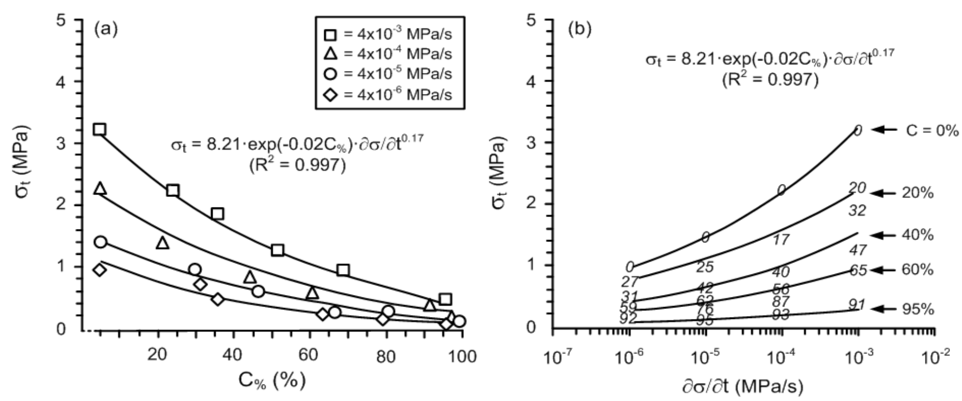


**Figure 4** Tensile strength as a function of carnallite content (a) and stress rate (b)

The diagrams in Figure 4(a) suggest also that the specimen tensile strengths become very low for the relatively pure carnallite specimens. The above equation can also present the tensile strengths as a function of induced stress rate in Figure 4(b). The diagrams suggest that the tensile strengths increase exponentially with the loading rates.

In order to link tensile stress, strain and time, the Maxwell model is used here to describe the time-dependent deformation of the specimens under different stress rates. Its elastic and viscosity parameters can be derived from the test results, and hence the series of tensile strain-time curves can be constructed for various applied tensile stresses.

Figure 5 shows the physical components arranged in the Maxwell model. It is postulated here that under tensile stress and unconfined condition the salt would exhibit the instantaneous (elastic) deformation and plastic flow due to the dislocation climb mechanism (sliding between grains). The governing equation for constant stress rate can present the tensile strain as a function of time as follows [7]:

$$\varepsilon_t = \sigma_R\,[(t / E) + (t^2 / 2\eta)] \tag{4}$$

where $\varepsilon_t$ is tensile strain at failure, $\sigma_R$ is constant stress rate, t is elapse time, E is spring constant, $\eta$ is viscosity. Regression analyses on the strain-time curves based using the SPSS statistical software [8] are performed to determine these parameters for each rock salt specimen. The results are shown in Figure 6, where exponential equations can be used to describe the variation of E and $\eta$ with carnallite contents ($C_{\%}$):

$$E = \delta \cdot \exp(-\delta' \cdot C_{\%}) \tag{5}$$

$$\eta = \omega \cdot \exp(-\omega' \cdot C_{\%}) \tag{6}$$

Where $\delta$, $\delta'$, $\omega$ and $\omega'$ are empirical constants, equals to 4.93 GPa, 0.03, 0.06 GPa·day, 0.04, respectively. The equations provide good correlation with the test data, with $R^2$ greater than 0.8.

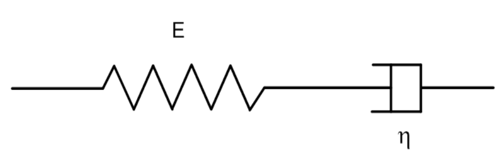


**Figure 5** Modular components of Maxwell model

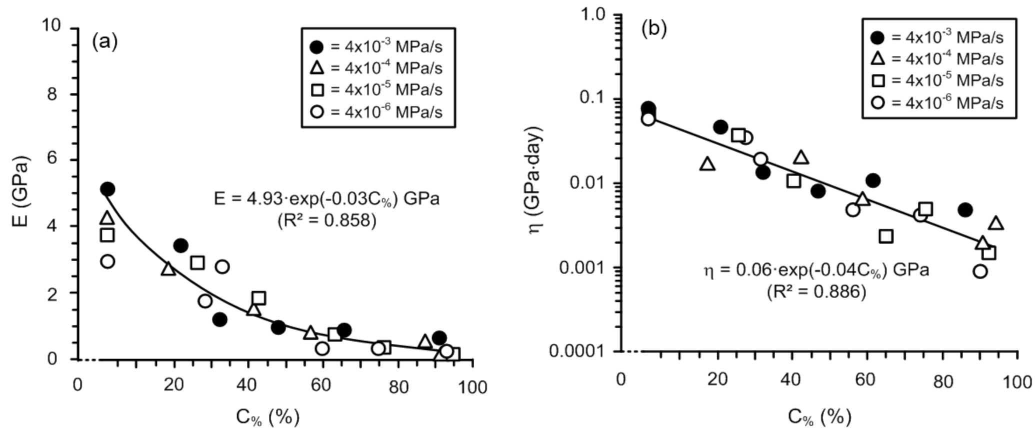


**Figure 6** Spring constant (a) and viscosity (b) of Maxwell model plotted as a function of $C_{\%}$

## 5. Strain Energy Density Criterion

The strain energy density principle is applied here to describe the specimen strengths and deformability with different carnallite contents. The strain energy density can be calculated by:

$$W_t = ½ \cdot \sigma_t \cdot \varepsilon_t \tag{7}$$

Figure 7 shows the results while they are plotted as a function of $C_{\%}$. The strain energy of the tested specimens decreases exponentially with increasing $C_{\%}$:

$$W_t = \lambda \cdot \exp(-\kappa \cdot C_{\%}) \tag{8}$$

where $\lambda$ and $\kappa$ are empirical constants, equals to 2.17 MPa, 0.03. The coefficient of correlation is 0.942. The above equation implies that the specimens with $C_{\%}$ toward 100% can sustain only small potential energy caused by the applied tensile stress and induced strain. It may be used as a strength criterion to determine the mine roof stability in the next section.

## 6. Prediction of Time-dependent Tensile Strength of Roofs

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 strain energy as shown in Figure 7 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 maxwell model.

For example if the constant tensile stresses at the middle of salt roof the corresponding time-dependent tensile strains can be predicted as follows [7]:

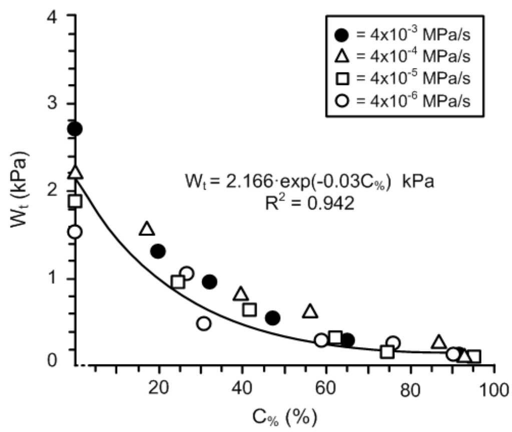


**Figure 7** Strain energy density as a function of $C_{\%}$

$$\varepsilon_t = \sigma_o [(1/E) + (t/\eta)] \quad (9)$$

where $\varepsilon_t$ is tensile strain, $\sigma_o$ is constant stress, t is elapse time, E is spring constant (Figure 5(a)), $\eta$ is viscosity(Figure 5(b)).

The corresponding tensile strain can then be calculated as a function of time. Figure 8 shows tensile strain curves for the constant tensile stresses from 0.5, 1.0, 1.5 to 2.0 MPa. The failure points represent the maximum tensile stress that the salt can sustain under each constant stress determined by the strain energy criterion.

## 7. Discussions and Conclusions

The maximum unsupported span and standup time of potash mine roof under varying carnallite contents may be determined based on laboratory testing and numerical analysis. The four-point bending tests are performed on rock salt specimens under different loading rates and carnallite contents. The strength results are used to develop a strength criterion in the form of the strain energy density as a function of the carnallite content. Obtaining the specimen strengths under a wide range of loading rates allows a rigorous calibration of the strain energy equation. By calibrating the Maxwell model against the test results, the roof horizontal strain under any horizontal stress can be described as a function of time. The roof distortional strain energy at failure can therefore be determined and used to calculate the corresponding strains and time after excavation.

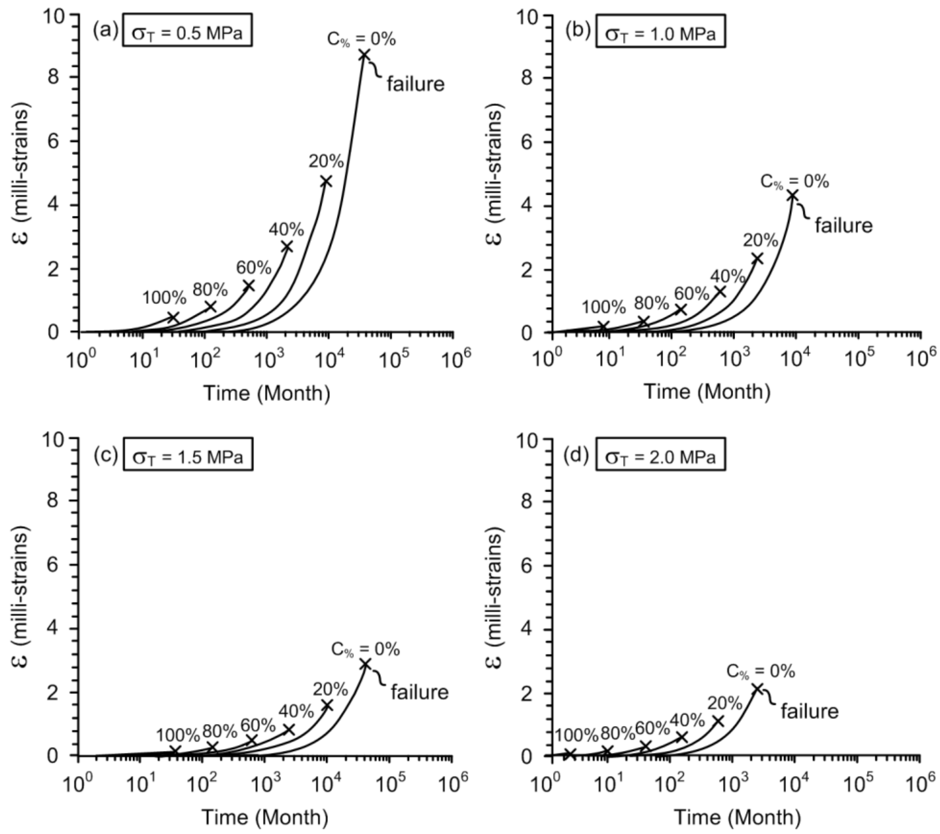


**Figure 8** Tensile strain as a function of time

The variation of the strength results is probably due to the high intrinsic variability of the test specimens. Even though halite and carnallite are the main mineral compositions, some trace inclusions (e.g., clay minerals and anhydrite) may cause the strength variation. It should be noted that different creep models can also be used to describe the time-dependency of the tensile deformations obtained from the bending testing. The Maxwell model is used here primarily because it can isolate the elastic (instantaneous) response from the visco-plastic deformation. More test specimens under a wider range of the loading rates would enhance the representativeness of the governing equation.

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