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HEALING EFFECTIVENESS OF FRACTURES IN ROCK SALT AND POTASH

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ABSTRACT

Long-term healing test under constant hydrostatic stresses (3-20 MPa) has been performed to assess the healing effectiveness of tension-induced fractures in rock salt and potash specimens. Gas flow testing has been conducted to monitor the changes of fracture permeability under constant stresses for up to 21 days. Line-loading on the healed fractures has been performed to assess the healing effectiveness. The results show that hydrostatic stresses and durations can decrease fracture permeability and increase healing effectiveness. Healing mechanism of rock salt fractures involves covalent bonding of cleavage planes, while that of potash fractures is related to recrystallization processes. The permeability and healing effectiveness of salt and potash fractures have been derived as a function of the applied mean strain energy, primarily to allow predicting their healing behavior under in-situ conditions (confining stresses). The findings imply that permeability of fractures at greater depths may be reduced quicker than those at shallower depths. Under the same mean strain energy, salt fractures can be healed better than potash fractures. This is because the bulk modulus of potash is much lower than that of rock salt, and hence it can absorb higher mean strain energy.

KEYWORDS: Permeability, Hydrostatic Stresses, Strain Energy, Recrystallization

บทคัดย่อ

ประสิทธิภาพการประสานตัวของรอยแตกแบบดึงบนตัวอย่างเกลือหินและโพแทชได้ถูกทดสอบภายใต้ความเค้นล้อมรอบคงที่ (3-20 เมกะปาสคาล) มีการตรวจวัดการเปลี่ยนแปลงค่าความซึมผ่านของรอยแตกภายใต้ความเค้นคงที่เป็นเวลา 21 วัน การให้แรงแบบเส้นบนรอยแตกที่มีการประสานตัวถูกดำเนินการเพื่อประเมินประสิทธิภาพการประสานตัว ผลการทดสอบระบุว่าความเค้นกดล้อมรอบและเวลาสามารถลดค่าความซึมผ่านของรอยแตกและเพิ่มประสิทธิภาพการประสานตัว กลไกการประสานตัวของรอยแตกในเกลือหินเกิดจากพันธะโคเวเลนต์บนระนาบรอยแตก ขณะที่รอยแตกในโพแทชเกิดจากกระบวนการการตกผลึก ความซึมผ่านและประสิทธิภาพการประสานตัวของรอยแตกในเกลือหินและโพแทชถูกนำมาสร้างความสัมพันธ์กับพลังงานความเครียดเฉลี่ยที่ได้รับ ผลดังกล่าวสามารถนำมาคาดคะเนพฤติกรรมการประสานตัวภายใต้สภาวะจริง (ความเค้นล้อมรอบ) ซึ่งสามารถสรุปได้ว่าค่าความซึมผ่านของรอยแตกที่อยู่ระดับลึกมีค่าลดลงอย่างรวดเร็วเมื่อเทียบกับรอยแตกระดับตื้น ภายใต้พลังงงานความเครียด

เฉลี่ยที่เท่ากัน รอยแตกของเกลือหินสามารถประสานตัวได้ดีกว่ารอยแตกในโพแทช เนื่องจากค่าสัมประสิทธิ์ก้อนของโพแทชมีค่าต่ำกว่าเกลือหินอย่างมาก ดังนั้นโพแทชจึงสามารถดูดซับพลังงานความเครียดเฉลี่ยได้มากกว่าเกลือหิน
คำสำคัญ: ความซึมผ่าน, ความเค้นอุทกสถิตย์, พลังงานความเครียด, การตกผลึกซ้ำ

1. Introduction

Micro-cracks or factures induced by excavation in salt formation can alter the structural stability and permeability of salt, affecting the integrity of openings [1]. Self-healing of the fractures may occur when subjected to sufficient stresses. When cracks are closed, permeability can be reduced by several orders of magnitude [2-3]. The healing behavior has been experimentally studied on crushed salt [4-5] and directly on fractures in salt [6-7] as affected by confinement, temperature, duration and humidity. Many techniques have been used to examine the healing of fractures: measuring the reduction of hydraulic conductivity, recovery of strength, and change of ultrasonic wave characteristics [8-9].

Fuenkajorn and Phueakphum [10] suggest that the primary factors governing the healing of salt fractures are the origin and purity of the fracture surface, and the magnitude and duration of the fracture pressurization. Inclusions or impurities significantly reduce the healing effectiveness. The hydraulic conductivity of fractures in pure salt can be reduced permanently by more than 4 orders of magnitude under the applied stress of 20 MPa for a relatively short period. For most cases the reduction of salt fracture permeability is due to the fracture closure which does not always lead to fracture healing. Charoenpiew [11] states that the fractures formed by separation of inter-crystalline boundaries or saw-cut fractures may remain unhealed. The fracture healing is more effective under hydrostatic stresses than under axial stresses. Elevated temperatures (up to 100 °C) slightly increase the healing effectiveness. Even though the effects of stresses and time on healing effectiveness and hydraulic behavior of salt fracture have been recognized and studied, long-term healing experiment is rare. This information is important in order to predict the healing behavior under in-situ condition. In addition, the healing characteristics of fracture in potash (carnallite) have never been investigated.

The objective of this study is to assess experimentally the healing effectiveness of fractures in salt and potash as affected by confinements for up to 21 days. The work involves healing test under various hydrostatic stresses, and gas flow permeability tests to monitor the behavior of the salt fractures. Line loading test is performed on the healed fractures to assess their mechanical performance after healing. The healing effectiveness is determined as a function of time and applied mean strain energy, and hence allows predicting the healing behavior of salt and potash fractures under in-situ conditions.

2. Sample Preparation

Salt and potash specimens used here are obtained from the Lower member of the Maha Sarakham formation in the Khorat basin, northeast of Thailand. Warren [12] gives detailed descriptions of the salt and geology of the basin. The nominal dimensions of rock specimens are 50×50×100 mm^3. Salt specimens are vitality pure halite. The carnallite content ($C_{\%}$) in potash specimens vary from 80 to 90%. These values are determined by the density correlation function [13]. The sample is drilled at the center to its mid-length. This pre-drilled hole (5-mm in diameter) is prepared for gas flow testing. The sample is subjected to line loading at the mid-length to create a tension-induced fracture (Figure 1). A total of six specimens are prepared form rock salt, and four specimens form potash.

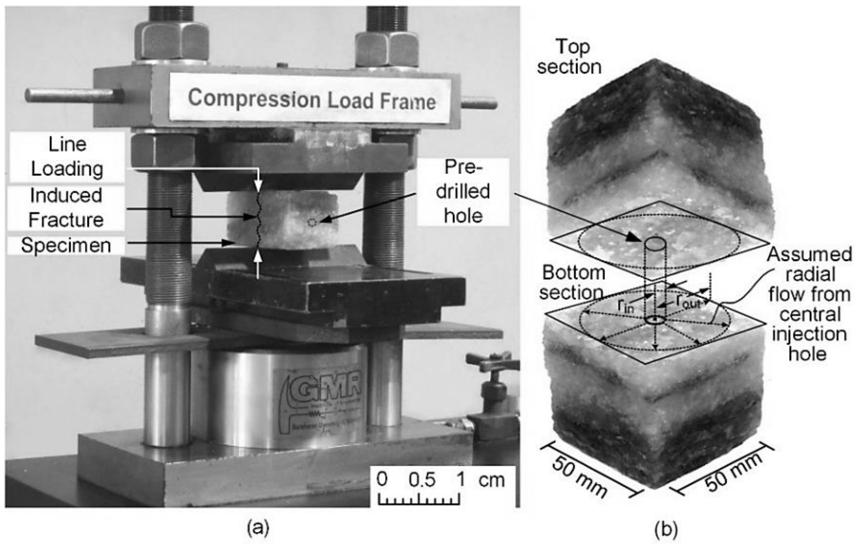

Figure 1 Tension-induced fracture for healing test (a). An access hole with diameter of 5 mm in top section of specimen (b).

3. Test Apparatus and Methods

A true triaxial loading device [14] is used to apply the constant and uniform axial and lateral stresses to the specimen (Figure 2a). Three pairs of 100-tons hydraulic pressure cylinders are set in three mutually perpendicular directions. The measurement system comprises pressure gages and displacement gages. The device can accommodate the cubic or rectangular specimens of different sizes by adjusting the distances between the opposite steel loading platens. Neoprene sheets are placed at all interfaces between the loading platens and specimen surfaces, except for near the fracture in order to allow the nitrogen gas to flow out freely from the fracture. All tests are conducted at ambient temperature (27 °C). The hydrostatic stresses range from 3, 5, 7, 10, 15 to 20 MPa for salt specimens, and from 5, 7, 10 to 15 MPa for potash specimens. The deformation along the axis perpendicular to the facture plane is monitored for every 2 hours, which is used to calculate the physical aperture of the fracture.

The nitrogen gas flow test is performed to measure the flow reduction of the fracture. The flow test system comprises nitrogen gas tank, flow meters and pressure regulator. Three gas flow meters used here are floating element type, which can measure the flow rates ranging from 10-100, 100-1000, and 1000-10,000 cm^3/minute. Nitrogen gas is injected under a constant pressure of 69 kPa through a high-pressure tube connected to the injection hole at the center of the loading platen (Figure 2b). Gas flow tests have been performed for every 12 hours throughout 21 days. The results are used to calculate the hydraulic aperture and intrinsic permeability of the fracture during healing. At the end of flow testing, the healed fracture is subjected to line-loading to assess the healing effectiveness.

The intrinsic fracture permeability (k_i) is calculated by [15]:

$$k_i = e_h^2/12 \quad (1)$$

The equivalent hydraulic aperture (e_h) for the radial flow path is calculated by [15]:

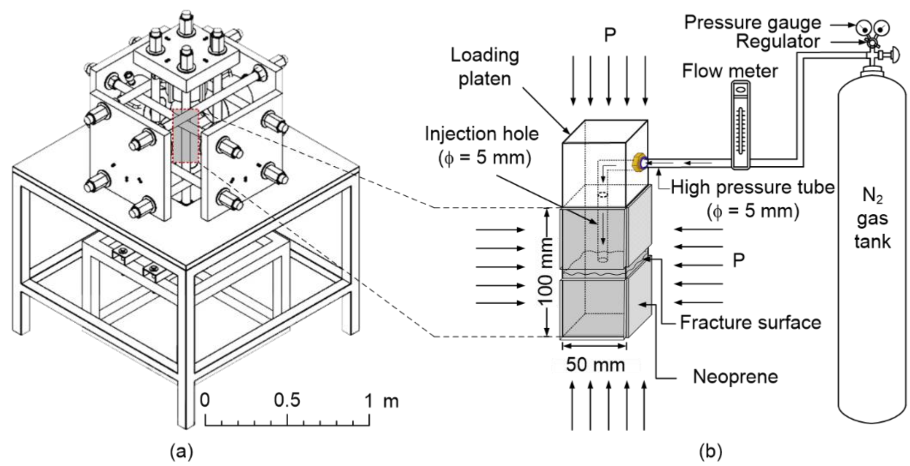

Figure 2 True triaxial load device (a) and test specimen with pre-drilled hole connected to nitrogen gas tank via high pressure tube (b).

$$e_h = [6\mu \cdot Q \cdot \ln(r_{out}/r_{in})/\pi\gamma(\Delta H)]^{1/3} \quad (2)$$

where γ is unit weight of nitrogen gas (11.428 N/m^3), μ is dynamic viscosity of nitrogen gas (1.759×10^{-5} N·s/m^2), Q is measured flow rate (m^3/s), ΔH is difference hydraulic head at the upstream and downstream points (m), r_{in} radius of the injection hole, and r_{out} is equivalent in the outflow boundary.

4. Test Result

4.1 Hydraulic Properties

Figure 3 shows the intrinsic fracture permeability obtained from fractures in salt and potash specimens. The permeability decreases with increasing hydrostatic stress and time. It rapidly decreases during the first few day and tends to steadily drop through the end of the test. Under the same stress, fractures in potash show lower permeability than those in rock salt. Under 15 MPa stress, the flow reaches the measurement limit within 13 days for salt fractures, and within 4 days for potash fractures.

4.2 Healing Effectiveness

The line load test results for intact and healed fractures are compared to assess the healing ability of the fractures. Here the healing effectiveness represents the percentage of the failure load of healed fracture (F_h) to failure load of intact specimen (F_i). It is found that healing has occurred in all fractures in salt and potash specimens after 21 days of pressurization. The fractures surface before and after the healing test has been observed by visual analysis. Recrystallization can be found only on the fractures in potash while the recrystallization in salt fracture is not noticeable. The relationship between the healing effectiveness and hydrostatic stresses can be represented by:

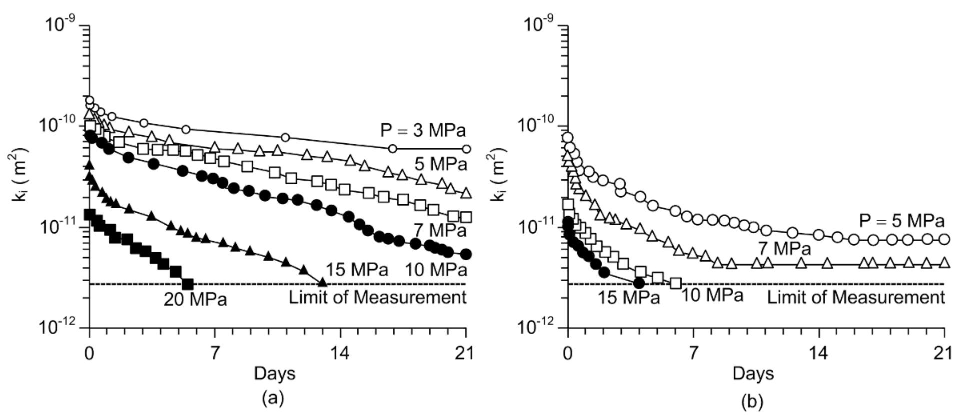

Figure 3 Intrinsic permeability (k_i) obtained for healing fractures in salt (a) and potash (b) specimens.

$$H_e = \tanh [P^{\beta} \cdot (\alpha/100)] \quad (3)$$

where H_e is the healing effectiveness (%), P is the hydrostatic stress (MPa), and α and β are empirical constants, which is equal to 4.94 for salt and 7.21 for potash, and β is equal to 1.13. Figure 4 shows the healing effectiveness as a function of hydrostatic stress. The results indicate that the healing increases with increasing stress. Under the same stresses fractures in potash specimens can heal quicker than those in salt specimens. This suggests that healing by recrystallization process maybe more effective than by covalent bonding between the two surfaces. The healing effectiveness of fractures in salt and potash can approach 100% after 21 days under the stresses of 19.9 and 15.3 MPa, respectively.

The healing effectiveness of fractures of salt obtained here and those obtained by Fuenkajorn and Phueakphum [10] can be used to establish an empirical equation:

$$H_e = \tanh [P^{\beta} \cdot (\kappa t^{\lambda_P^{\omega}})] \quad (\%) \quad (4)$$

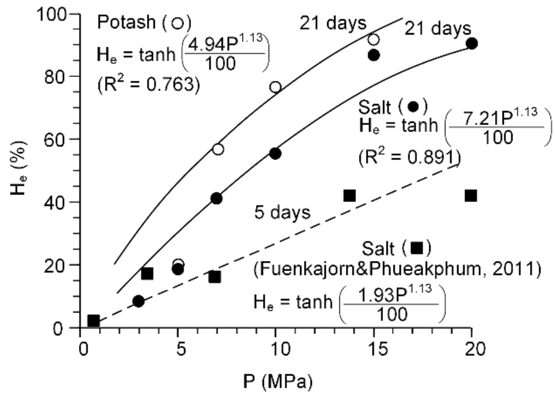

Figure 4 Healing effectiveness **(**H_e**)** as a function of applied hydrostatic stress **(**P**)** obtained for potash **(**○**)** and salt **(**●**).** Dash line is healing results of salt fractures for 5 days obtained by Fuenkajorn and Phueakphum **(**2011**).**

where κ, λ and ω are empirical constants, which are equal to 0.010, 0.264 and 0.311. The regression analysis with IBM SPSS Statistics 19 [16] is performed to determine the constant parameters. Figure 5 shows the healing effectiveness as a function of applied stress and time. The equation proposed above can be used to predict the mechanical properties of healed fracture around the salt openings under various stresses and durations.

5. Strain Energy Density Principle

The strain energy density principle is applied here to determine the energy required to heal the salt and potash fractures under different stresses and durations. It is postulated that the fractures can be healed by applying the mean strain energy (W_m). It can be calculating from the applied mean stresses (σ_m) [17]: $W_m = \sigma_m^2/2K$, where $\sigma_m = (\sigma_1+\sigma_2+\sigma_3)/3$, and K is the bulk modulus of the material. The bulk moduli of the rock salt and potash are obtained from Luangthip et al. [13], as shown in Table 1.

An attempt is made here to develop an empirical equation between the intrinsic permeability **(**k_i**)** as a function of the applied mean strain energy**.** The relation can be described by a power equation**:**

$$k_i = \chi W_m^{\eta} \tag{5}$$

where χ and η are empirical constants, which are equal to 8.94×10^{-12} (m^2/kPa) and -0.852 for rock salt and 1.33×10^{-11} (m^2/kPa) and -0.467 for potash. The constants are obtained by regression analyses using SPSS code. Good correlations are obtained (R^2 >0.8). Figure 6 plots curve fits comparing with the test data.

An empirical equation is also proposed to represent the healing effectiveness as a function of mean strain energy, as follows:

$$H_e = \tanh\left[P^{\beta}\cdot\{\psi P/100(2K)^{\beta}\}\right] \quad \% \tag{6}$$

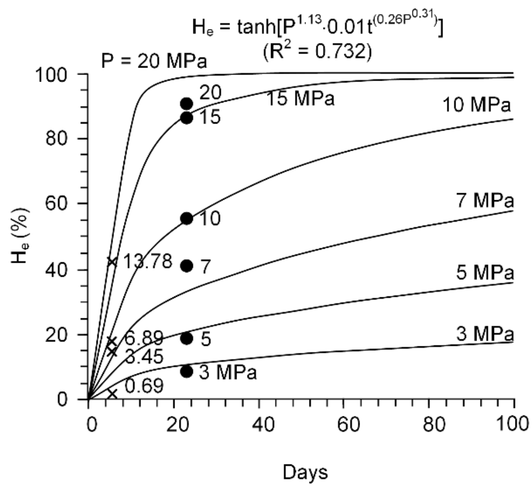

Figure 5 Healing effectiveness (H_e) as a function of applied hydrostatic stress (P) and time obtained for fracture in salt specimen.

Table 1 Strain energy applied to salt and potash specimens

Specimens	K (GPa)	σ_m (MPa)	W_m (kPa)
Salt	34.9	3	0.129
		5	0.358
		7	0.701
		10	1.431
		15	3.220
		20	5.724
Potash	2.7	5	4.682
		7	9.176
		10	18.727
		15	42.135

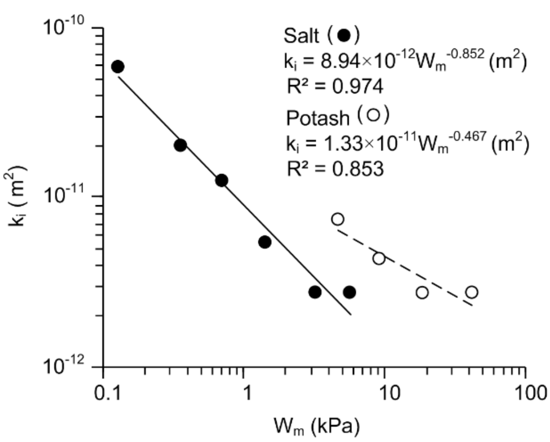

Figure 6 Intrinsic permeability (k_i) as a function of mean strain energy (W_m) calculated for fractures in salt and potash after 21 days of healing.

where ψ is empirical constants, which is equal to 52.5 for rock salt and 6.05 for potash (Figure 7). The correlation coefficients are greater than 0.8. The relations can be used to predict the hydraulic properties of rock salt and potash fractures around an opening under various external pressures. Note the pressures (P) is equal to mean stresses (σ_m) under isotropic stress conditions.

6. Discussions and Conclusions

True-triaxial load frame is used to apply constant hydrostatic stresses on fractures in salt and potash specimens to assess healing effectiveness for up to 21 days. These stresses conditions are equivalent to in-situ stresses at depths ranging from 100 to 740 m. Gas flow permeability tests are measured to determine the reduction of hydraulic properties of fractures as a function of time. The intrinsic permeability tends to decrease rapidly during the early state of the test as power functions with time, and slowly decrease after 7 days. The mechanical property of intact specimens and of healed fractures are compared to assess the healing effectiveness. All tests are conducted under ambient temperature.

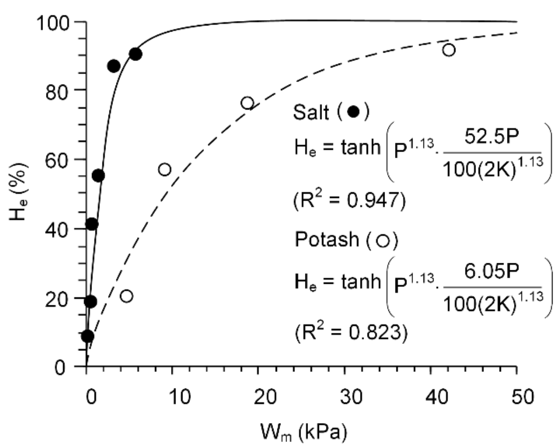

Figure 7 Healing effectiveness **(**H_e**)** as a function mean strain energy **(**W_m**)** calculated for salt and potash fractures after 21 days of healing**.**

The healing pressures and durations are important factors for the healing process of fracture in salt and potash. The intrinsic permeability of tension-induced fracture decreases with increasing stresses and healing durations. They can be used as index of fracture healing behavior. The healing effectiveness of tension-induced fractures also increases with increasing hydrostatic stresses. It is postulated that the fracture healing increases with increasing aperture closure, and hence promoting recrystallization within the boundaries of fractures. The results obtained here agree well with those of Fuenkajorn and Phueakphum [10].

The healing of rock salt and potash fractures depends on healing mechanisms (covalent bonding and recrystallation processes), pressurization and duration. The healing effectiveness of fractures in potash (recrystallation process) is higher than the fractures in salt (covalent bonding).

Fracture permeability obtained from the flow testing can be derived as a function of the applied mean strain energy. This allows predicting of the salt and potash fractures around openings, providing that the mean stress and bulk modulus of the materials are known. The mean stress is related to the depth where the fractures are developed. This suggests that fractures at greater depth may have lower permeability quicker than those at shallower depth. Similarly, the healing effectiveness also increases with mean strain energy, as suggested by the diagram in Figure 7. Under the same mean strain energy, the salt fractures tend to be healed better than the potash fractures. This is because intact potash poses much lower bulk modulus than does intact rock salt, and hence it can absorb higher strain energy. This means that under the same depth the strain energy contributes to rock salt fractures is higher than that of the potash fractures.

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