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Creep Healing of Fractures in Rock Salt

Laurence S. Costin, Wolfgang R. Wawersik

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ABSTRACT

Fracture and healing experiments were performed on specimens of bedded salt from the Salado formation, Southeastern New Mexico. Short rod specimens (100 mm in diameter) were loaded to failure in tension. During each test, a crack was initiated along the axis of the specimen. The fracture toughness of the salt was determined from the resulting load-crack opening displacement record. After the test, each specimen was pieced back together, jacketed and placed in a pressure vessel under hydrostatic pressure for several days. The confining pressure (10-35 MPa), temperature (22-100°C) and healing time (4-8 days) were varied to determine the effect of each on the healing process. Upon removal from the pressure vessel, each sample was retested and the toughness of the healed fracture was determined. Results show that the salt specimens regained 70-80% of their original strength under all conditions except at the lowest temperature and pressure where specimens regained only 20-30% of their original strength. It is suspected that the primary mechanism involved is creep of asperities along the fracture surface which forms an interlocking network. Thus, the healing pressure is probably the most significant variable.

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INTRODUCTION

Rock salt formations are being considered for use as storage repositories for crude oil, nuclear waste and compressed gases. In each of these cases it is important to determine whether fractures, formed during the mining phase of the site development, will cause permanent damage to the integrity of the storage medium. In order to assess the permanent damage resulting from the introduction of a large fracture into the boundary of a storage cavity, it is necessary to determine whether such fractures will heal as a result of the time dependent deformation of the host material. It is well known that rock salt has a relatively large rate of creep under non-hydrostatic compressive loading, even at low temperatures (22°C) [1,2]. Thus, in salt, tensile stresses that created the fracture will relax rapidly allowing the in situ compressive stresses to close the cracks. Should the cavity once again be pressurized, either by the introduction of oil or brine or by the production of gases by nuclear wastes [3], the permeability and strength of the surrounding material will depend heavily on the extent of healing that has occurred in the existing fracture network.

In this report, we examine the fracture toughness and healing characteristics of rock salt. Our approach to this problem is through the use of linear elastic fracture mechanics (LEFM) concepts. Unfortunately, under in situ compressive stresses, salt exhibits a non-linear, inelastic, time dependent stress-strain behavior. However, in the vicinity of an advancing crack tip, tensile stresses are responsible for the majority of the damage process that leads to the creation of new crack surfaces. In laboratory tests, unconfined samples of rock salt exhibit a nearly linear elastic behavior when subjected to uniaxial tensile loading [4]. Thus, it is expected, that for the purposes of the fracture mechanics analysis of the

stability of cracks under tensile loading, the LEFM approach will provide an adequate solution. In any case, the experimental technique employed here to determine the fracture and healing toughness of salt core samples, while based on LEFM, can be adapted where necessary to yield reliable data in the elastic-plastic regime under small scale yielding.

In the elastic regime, a material's resistance to fracture is characterized by its fracture toughness, K_{Ic} . This material property is the critical value of the crack-tip stress intensity factor, K_I , at which a crack in the given material will begin to grow. The value of K_I for any given crack in a material depends on the particular geometry and loading. However, when K_I reaches a value of K_{Ic} , the crack begins to grow. It is the purpose of this investigation to determine the toughness or resistance to growth of a crack running along a healed fracture plane relative to that of a crack propagating through virgin material.

EXPERIMENTAL DESCRIPTION

The fracture toughness and healing tests were conducted using the Terra Tek short rod specimen configuration. A complete description of the short rod specimen and its associated fracture mechanics analysis is given in references 5 and 6. This specimen is cylindrical in shape with a notch machined parallel to the axis so that the remaining ligament is V-shaped as shown in Figure 1. The short rod is designed so that the initial portion of crack growth takes place under increasing load. When the crack length reaches a critical value, a_c , (near the point of maximum load) the stress intensity factor becomes equal to K_{Ic} . The primary advantage of this specimen configuration is that a_c depends only on the geometry of the specimen. Thus, there is no need to measure the crack length, which eliminates one major source of error in testing rocks. The details of the

specimen geometry used in the present tests are shown in Figure 1.

Seven fracture and healing experiments were conducted on rock salt from the Southeastern New Mexico WIPP site. The specimens used were machined from core taken from the WIPP-12 corehole at various depths in the interval from 628 to 641 m. The specimens consisted principally of halite with some polyhalite and clay inclusions. A brief description of the composition of each specimen is given in Table 1. All specimens had a nominal grain size of 5 to 15 mm with only a few grains as large as 20 mm. It is thought that at the point of maximum load (the load at which K_{Ic} is determined) the crack front (b, in Figure 1) extends approximately 50-70 mm. Thus, at the critical load the crack front covers nearly half of the specimen diameter (Dia = 100 mm) and intersects four to five grains.

Each virgin specimen was loaded to failure in a closed loop servo-controlled load frame. The load transfer to the specimen was accomplished through a set of aluminum plates cemented to the ends of the specimen. This loading arrangement replaces the crack face grips described in references 5 and 6. Eyebolts attached to the end plates allowed for easy insertion of the specimen into the load train of the test machine. Bending stresses due to slight misalignments were minimized by including several lengths of hardened steel chain in the load train. During the test both load and crack mouth displacement (CMD) were recorded. The CMD was measured by a linear variable differential transducer (LVDT) attached to the loading plates. Loading was accomplished by increasing the CMD at a fixed rate of 10^{-3} mm/s. Figure 2 shows a specimen with end grips attached ready for testing.

Figure 3 shows an idealized load versus CMD curve from an initial fracture test. At several points along the curve, the specimen was unloaded

slightly and then reloaded in order to obtain an unloading compliance. Barker [6] has shown that when the specimen stiffness is reduced to one-half the original stiffness, the crack length has reached a_c . Normally this occurs at or near the peak load (see Figure 3). The apparent fracture toughness is computed from the expression derived by Barker [5].

$$K_Q = 22 P_Q D^{-3/2} \quad (1)$$

where P_Q is the load at crack length a_c and D is the diameter of the specimen. In some tests unloading compliances were not taken. In these tests, P_Q was taken to be the peak load [5].

The measured K_Q can be corrected to yield a better estimate of K_{Ic} by applying a plasticity correction. The plasticity factor, P , is determined from successive unloading compliance curves by [6]

$$P = \frac{\Delta X_o}{\Delta X} \quad (2)$$

where ΔX_o and ΔX are the distances shown in Figure 3. A value of $P = 0$ indicates perfectly elastic crack growth whereas a value of $P = 1$ would imply that no crack growth took place and that ΔX is due entirely to plasticity. The corrected fracture toughness, then, is given by [6]

$$K_{Ic} = \left(\frac{1 + P}{1 - P} \right)^{\frac{1}{2}} K_Q \quad (3)$$

After testing, the end grips from each specimen were carefully removed and the specimen was prepared for the healing phase of the experiment. In order to keep the pressurizing fluid from invading the crack, each specimen was encased in several layers of jacketing material.

First, an aluminum template having the shape and thickness of the sawed notch (Figure 1) was inserted into the notch, as shown in Figure 4a, to prevent it from collapsing under pressure. Aluminum end caps were then placed on the specimen and the salt surface was sealed with a coating of silicon rubber. Next a thin copper jacket was placed around the specimen (Figure 4b). This jacket was thin enough (0.08 mm) to transmit the external pressure to the salt yet strong enough to prevent the pressurizing fluid from puncturing through in places where there were small voids near the surface. Finally, two layers of heat resistant rubber jacketing were placed over the copper. The ends were sealed by a thin bead of silicon rubber sealant. Stainless steel lock wire was used to clamp the outer jacket to the end caps as a final seal. The completely jacketed specimen is shown in Figure 4c.

After jacketing, the specimen was placed in the pressure vessel of one of the Sandia load frames used for creep testing of salt at elevated temperature. This apparatus is described in reference 7. The confining pressure (10-35 MPa), the temperature (22-100°C) and the healing time (4-8 days) were varied from test to test to determine the effect of each on the healing process (see Table 2).

Upon completion of the healing phase of the experiment, each specimen was again tested for fracture strength. The load and CMD were recorded as before so that the fracture toughness of the healed cracks could be determined.

RESULTS AND DISCUSSION

Figure 5 shows a typical load versus CMD history for a single specimen. The load-CMD record for the first loading of the specimen shows an initial elastic response followed by the initiation of crack growth at

point A (Figure 5). At point B, the unloading compliance is approximately one-half of the initial compliance, indicating the crack length has reached a_c . This also corresponds to the point of maximum load. Twice, at points C and D, the specimen was unloaded all the way to demonstrate that upon reloading, the crack begins to grow at the same load that was applied just prior to unloading. The plasticity factor, P , for the specimen in Figure 5, which was computed from successive unloading compliances, ranged from 0.81 to 0.94; values which are typical of the results from all the tests. The final unloading began at point E, after which the specimen was put through the healing process.

The load-CMD record of the fracture test of the healed specimen begins at point F in Figure 5. Note that the CMD scale is not necessarily continuous from unloading at E to reloading at F since a change in CMD could have occurred during healing. It is obvious that the healing process has had a pronounced effect on the residual strength of the specimen. The peak load achieved at G is much greater than the previous load at E and is approximately 85% of the maximum load achieved by the virgin specimen. Furthermore, the loading stiffness at F is the same as that at A indicating the crack has been reduced or healed back to its original length.

Table 2 summarizes the results of all seven tests. All specimens showed some degree of healing. In order to quantify the degree of healing, we have defined a healing index, H_I , as follows:

$$H_I = \frac{P_{2max} - P_{1F}}{P_{1max} - P_{1F}} \quad (4)$$

where the symbols used are as defined in Table 2. If $H_I = 0$, no healing has taken place whereas if $H_I = 1$, the fracture plane is as tough as in the

virgin material. The healing index was defined in terms of well defined loads on the load-CMD curve instead of in terms of K_Q or K_{Ic} because the plasticity factor computed for all of the tests was so large. It is doubtful whether the fracture toughnesses computed from equations (1) and (3) are valid when P is greater than 0.2 to 0.3. This is because the assumptions of small scale yielding at the crack tip are violated. However, the maximum load achieved during a test is still a significant quantity in that it gives a relative measure of the strength of the specimen along the crack plane. Note that for two of the specimens listed in Table 2, $H_I > 1.0$, implying that the healed specimen is stronger than was the noncracked virgin specimen. This is probably due to the virgin specimen containing some major flaw which weakened it substantially.

Because of the limited number of tests, it is difficult to assess the relative importance of temperature, time, and pressure on the healing process. From the data presented here, it appears that healing is more sensitive to temperature and pressure than to time. Most of the healing occurs in less than four days which is short compared to estimated excavation and storage times. The results, as far as the relative importance of temperature and pressure, are inconclusive.

In the next phase of the program, the healed specimens will be sectioned and examined in order to identify the mechanisms involved in the healing process. A preliminary analysis shows that the most probable mechanism is one which involves the creep of asperity contacts along the crack interface. When the crack surfaces are brought into contact under large normal forces, the contacting asperities are subjected to large stresses which result in very rapid but localized creep flow of material. These asperities flow to form an interlocking network which holds the

crack surfaces together when the normal forces are relaxed. There is no evidence that, at the temperatures and pressures used here, any recrystallization takes place. Thus, the healed crack should be slightly weaker than the virgin material. A similar mechanism of healing by creep of asperity contacts has been demonstrated to occur during creep deformation along joints in several different rocks [8]. After a small amount of displacement has occurred along the joint, it appears to "lock up" and no further slip takes place. Subsequently, the jointed region has nearly the same strength properties as the unjointed material. Thus the creep of asperities appears to be an important mechanism in the healing of fracture surfaces in rock.

SUMMARY AND CONCLUSIONS

Experiments were conducted to determine the extent to which fractures in rock salt heal under various conditions of temperature and pressure.

From the results presented here, the following can be concluded:

1. Tensile fractures in salt will heal, when subjected to nominal overburden pressures (10-35 MPa), to the extent that the resistance to crack propagation along the pre-existing fracture plane is approximately 70-80% of that through virgin material.
2. The healing process takes place rapidly compared to the time scale over which mining or storage in salt occurs.
3. The principal mechanism in healing appears to be creep of contact asperities along the fracture surface.

At present, additional work is underway in which the micromechanisms of healing will be examined. Sections of healed fractures will be examined with both optical and scanning electron microscopy to determine the nature of the bonding which occurs at the healed interface. Of equal importance to the recouping of mechanical strength due to healing, is the change in permeability which occurs during healing. If healed fractures retain their

permeability, they would provide paths for stored material to be conducted away from the storage cavern. Thus, it is recommended that this question be examined in parallel with the ongoing research.

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Table 1. Material Description of Each Specimen

<u>Specimen Hole-Depth (ft), (m)</u>	<u>Description</u>
12-2066, 629.7	50% gray halite 50% pink polyhalite
12-2062, 628.5	Pink halite with clay blebs
12-2064, 629.1	Pink halite with clay blebs
12-2102, 640.7	Pink halite with polyhalite inclusions (2-3%)
12-2063, 628.8	Pink halite
12-2095, 638.6	Halite with trace of polyhalite
12-2094, 638.3	Halite with trace of polyhalite

Table 2. Summary of Results

(Hole-Depth)	P_{lmax} (N)	P_Q (N)	P_{lf} (N)	$K_{Q \frac{1}{2}}$ (MPa-m ^{3/2})	T_h (°C)	P_h (MPa)	t_h (hrs)	P_{2max} (N)	H_I	Comment
12-2066	1370	1270	489	0.84	100	34.5	91	604	0.13	jacket leaked
12-2062	863	863	409	0.57	100	34.5	92	747	0.74	
12-2064	974	-----	169	-----	100	10.3	168	979	1.01	
12-2102	1220	-----	289	-----	100	34.5	168	765	0.51	
12-2063	752	729	0	0.49	22	10.3	167	147	0.20	spec. completely severed
12-2095	792	712	467	0.48	100	34.5	96	676	0.64	
12-2094	369	-----	214	-----	100	34.5	144	783	3.67	
				(apparent fracture toughness from Equation (1))	(healing temperature)	(healing pressure)	(healing time)	(maximum load achieved during loading of healed specimen)	(healing index, Equation 4)	
	(maximum load achieved by virgin specimen)	(load at which $a = a_c$, determined by unloading compliance)	(final load achieved during first loading, point E in Figure 5)							
(depth in feet from surface)

Figure 1: Short Rod Specimen

Figure 2: Photograph of salt specimen in load frame just prior to testing. String around specimen is used to support the specimen until the load is applied.

Figure 3: Idealized load versus CMD record for a short rod test.

Figure 4: a) Salt specimen with aluminum template inserted into notch.

Figure 4: b) Salt specimen with copper jacket.

Figure 4: c) Fully jacketed specimen ready for healing phase of experiment.

Figure 5: Complete load versus CMD history for a salt specimen.

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