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Thermomechanical Damage Recovery Parameters for Rocksalt from the Waste Isolation Pilot Plant

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THERMOMECHANICAL DAMAGE RECOVERY PARAMETERS FOR ROCKSALT FROM THE WASTE ISOLATION PILOT PLANT

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ABSTRACT

Laboratory tests were conducted in which intact WIPP salt specimens were damaged by testing under constant strain-rate triaxial conditions at low confining pressure (0.5 MPa) and near room temperature (25°C) until 1.5 percent axial strain was reached. Introduction of dilatant damage caused specimen volume to increase and compressional wave velocities and amplitudes to decrease. Specimens were then subjected to hydrostatic loads of 15 MPa at a temperature of either 20°C, 46°C, or 70°C. Under these conditions damage was partially recovered and specimen volume and compressional wave characteristics approached the values of the undamaged state.

The data from each test were fitted using a first order kinetics law to determine characteristic time constants for the damage recovery process at each temperature. The mean time constant associated with recovery of ultrasonic amplitudes decreased as temperature increased, as expected for a thermally activated process. Time constants associated with ultrasonic velocities and with volumetric strains showed no systematic change with temperature. The modeling results show that time constants are very short compared with time scales required for creep closure of rooms and shafts, implying that the rate of healing under confining pressure will be extremely rapid.

The rates of volumetric strain recovery determined at different temperatures were fitted to an Arrhenius plot to determine an activation energy for the recovery process. The data were fitted using linear least squares to calculate an activation energy of 10.5 kJ · mole⁻¹.

MASTER

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1.0 INTRODUCTION

1.1 Background

The Waste Isolation Pilot Plant (WIPP) is a research and development facility sited in a bedded salt formation in southeastern New Mexico. The purpose of the facility is to aid in the development of the technology necessary for the safe disposal of radioactive transuranic waste from the defense programs of the U.S. Excavation of rooms and shafts at the WIPP will induce deviatoric stresses in the surrounding rock, resulting in inward creep deformation which may also produce a microcracked zone (Holcomb, 1988) referred to as the Damaged Rock Zone (DRZ). Formation of a DRZ has the potential to increase the permeability of the salt adjacent to the excavations and to degrade the effectiveness of the seal system. Although initial deformation is expected to form the DRZ, emplaced seals are expected to take up the load so that further creep of the surrounding salt will stop. Repressurization of the surrounding salt will close void spaces in the DRZ. This is especially important for the design and performance of seal systems because an increase in permeability will degrade performance. In evaluating seal design and performance it is necessary to predict the behavior of the DRZ and the kinetics of the healing of the repressurized fractures initially formed in the DRZ. The mechanics of this damage recovery process have not been studied in detail and the work described here is a preliminary attempt to define some of the thermomechanical quantities that control recovery.

Very few studies have documented the process of void closure or crack healing. Costin and Wawersik (1980) measured fracture toughness by inducing damage in short rod specimens of salt. Specimens were pieced back together, and fracture toughness was remeasured after subjecting specimens to hydrostatic pressures for varied lengths of time at two temperatures. Typically, specimens subjected to 10 to 35 MPa regained 70 to 80 percent of their original fracture toughness. Ultrasonic wave velocities and attenuation have been used extensively to indicate crack opening and closure in geologic materials (Birch, 1960, 1961; Simmons, 1964; Gupta, 1973; Hadley, 1975; Soga et al., 1978; Sobolev et al., 1978; Spetzler et al., 1981; Granryd et al., 1983; Shea and Hanson, 1988). This technique was applied qualitatively to the study of crack closure and healing in salt by Brodsky (1990). In that study, compressional wave ultrasonic data were used to assess the extent of crack closure during hydrostatic compression of damaged WIPP salt specimens at 20°C. The two test variables studied were damage level and the hydrostatic pressure used for damage recovery. It was found that the recovery of ultrasonic velocities depended on pressure. As expected, the higher the pressure, the greater the velocity recovery during crack closure and healing. Ultrasonic velocities and amplitude recoveries also depended

on damage level. Recovery was more complete in specimens with the least damage and it was concluded that recovery is slower when damage is sufficient to cause changes in the geometry of the crack walls. This report extends the work of Brodsky (1990) to the elevated temperature regime. All tests described here were taken to a single level of damage and healed at a single value of hydrostatic pressure; however, tests were conducted at temperatures up to 70°C.

1.2 Scope

A laboratory experiment was designed to measure damage recovery quantitatively in the form of crack closure and healing. Specimens were damaged by testing under constant strain-rate triaxial conditions at low (0.5 MPa) confining pressure and near room temperature (25°C) until 1.5 percent axial strain was reached. Damage recovery, as indicated by the recovery of strains and of ultrasonic compressional wave velocities and amplitudes, was measured as a function of time at a hydrostatic stress of 15 MPa and at temperatures of 20°C, 46°C, or 70°C. Introduction of dilatant damage caused specimen volume to increase and compressional wave velocities and amplitudes to decrease. During damage recovery under confining pressure, these trends reversed and specimen volume and compressional wave characteristics approached the values of the initial undamaged state. The data from each test were fitted using a first order kinetics law to determine characteristic time constants for damage recovery at each temperature. The rates of damage recovery determined at different temperatures were fitted to an Arrhenius plot to determine an activation energy for the recovery process.

1.3 Report Organization

This report contains seven chapters including this introductory chapter. Chapter 2.0 provides information on sample origins and specimen preparation. The experimental methods including system shakedown and verification procedures are given in Chapter 3.0. Results are given in Chapter 4.0 and discussion and analysis of results are given in Chapter 5.0. A summary is contained in Chapter 6.0 and cited references are given in Chapter 7.0.

2.0 SPECIMENS

2.1 Sample Acquisition

Specimens were prepared from two separate sample stocks, both obtained from the same stratigraphic layer in the WIPP underground facility. Most specimens were taken from the east rib of Room M and made into specimens having identification numbers beginning with "MCE." These samples were horizontally oriented 1-m-diameter cores that were vertically subcored normal to the plane of the bedded formation to provide samples 0.4 m in diameter. Data from one test, reported previously by Brodsky (1990), will be discussed in this report. That specimen was taken from one of the ribs of experimental room C and its specimen identification number begins with C1X01. The locations from which the two sample batches were obtained were less than 38 m apart. All samples were packed in plastic wrap, sealed with duct tape, placed in padded wooden crates, and shipped to the RE/SPEC Inc. Laboratory in Rapid City, South Dakota. The C1X01 samples were shipped via a temperature-controlled truck to prevent freezing. The "MCE" samples were shipped in a non-temperature-controlled vehicle during the warmer months (arrived in October of 1980).

2.2 Specimen Preparation

The 0.4-m-diameter subcores were further subcored using saturated brine to obtain 101.6-mm-diameter (4-in), 203.2-mm-long (8-in) specimens with axes normal to bedding. The specimen ends were machined flat and parallel to within 0.015 mm (0.0006 in) by placing the specimen in a collet and mounting the collet in the jaws of a lathe. After facing one end, the collet was turned end-for-end and the other end was faced. After finishing, each specimen was assigned an identification number according to WIPP Procedure No. 092 and logged into the RE/SPEC Inc. specimen inventory along with its dimensions.

3.0 EXPERIMENTAL TECHNIQUE

3.1 Apparatus and Instrumentation

3.1.1 Load Frame and Pressure Vessel

Tests were performed in a computer-controlled, servohydraulic test system comprising a pressure vessel and an MTS 312.41 load frame as shown in Figure 3-1. A hydraulic actuator located in the base of the load frame was capable of applying an axial force of 500 kN. A load cell bolted to the movable crosshead was used to measure axial force. Pressure was measured by a strain-gage-type pressure transducer in the hydraulic line between the intensifier and pressure vessel. A control console housed signal conditioning for the deformation transducers, as well as feedback and valve driver modules for the hydraulics. A controller was used for the actuator servoloop, and a servocontroller was used for maintaining confining pressure. This console interfaced with a DEC LSI-11/73 microprocessor to provide data acquisition and programmable control.

3.1.2 Strain Measurements

Specimens were instrumented with direct contact extensometers as illustrated in Figure 3-1. The axial extensometer, an MTS 632.90C-04 strain-gage-type, consisted of two sensing arms, each 100 mm long and mounted 180° apart. The circumferential extensometer, an MTS 632.92C-05 strain-gage-type, comprised a roller-link chain wrapped around the specimen and a sensor that monitored the relative displacement of the ends of the chain as the specimen circumference changed. The relationship between circumferential extensometer output and change in circumference is nonlinear but is related by simple geometry and accounted for during data reduction. During testing, the axial extensometer and the chain of the circumferential extensometer were centered with respect to the specimen midheight. The influence of changes in pressure on the outputs of the strain extensometers was measured before testing. Changes in the transducer outputs were determined by calibration using a specimen of fused quartz as described by Senseny (1987). For the pressure range used in this study pressure effects were shown to be negligible.

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Figure 3-1. Load frame, pressure vessel, and strain extensometry used for crack healing tests.

Thin 0.127 mm (0.005 in) teflon sheets that adhered to the platens were placed at both ends of the specimen to minimize end effects. Uniformity of deformation was checked by comparing post-test diameter measurements in two perpendicular directions made at equally spaced intervals along the specimen length. For all tests the post-test diameter measurements were uniform to within 0.6 percent of one another.

3.1.3 Ultrasonic Velocity Measurement System

The ultrasonic velocity measurement system is shown schematically in Figure 3-2 and includes two pairs of compressional wave velocity transducers, a switching box, a pulser/receiver, a preamplifier with power supply, and a digital oscilloscope. One set of velocity transducers was mounted in the platens above and below the specimen for measurements parallel to the specimen axis, and a second set of transducers was held by springs against the sides of the specimen for measurements perpendicular to the axis. The second set of transducers was located just above the specimen midheight to allow room for the circumferential extensometer. All transducers had a 500 kHz resonant frequency. Although the contact area between the flat transducers and the cylindrical sides of the specimen was small, sufficient energy was transmitted across the interface to conduct the tests.

During velocity measurements, a 250-V main pulse generated by the pulser/receiver was sent through a switching box to one of the pulsing transducers. Simultaneously, the pulser/receiver sent a 1-V signal to the external trigger of the oscilloscope. The main pulse traversed the specimen, and the received signal was preamplified before it was sent to the pulser/receiver. The preamplifier contained a high pass filter of 0.3 MHz to eliminate noise. All signals were amplified between 20 and 50 dB to bring the maximum expected amplitudes to within ± 1.0 V. The combined RF output of the pulser/receiver (containing both the trigger pulse and amplified received signal) was sent to a digital oscilloscope. Voltage resolution was ± 0.4 percent of full scale or ± 4 -mV. Each waveform was digitized into 2^{13} (8,192) points with a precision of 20 ns. Thirty repeated signals were averaged (except where noted in the procedure) to increase the signal-to-noise ratio. The averaged signal was recorded on diskette.

3.1.4 Jacketing

Ported jackets were used to shield the specimen from the silicon oil confining fluid. In this ported jacket design, holes were cut out of the Viton jackets at the velocity transducer locations

RSI-124-89-006

Figure 3-2. Schematic diagram of ultrasonic velocity measurement system.

and the locations required for the circumferential extensometer. The Viton was replaced with 0.051-mm-thick (0.002 in.) steel shims that were bonded to the remaining Viton with adhesive and held tightly against the specimen by the confining pressure. All ultrasonic transducers were immersed in confining fluid. A thin film of this fluid acted as a couplant between the transducers and platens for transducers mounted in the platens, and between the transducers and metal shims of the ported jacket for transducers mounted on the sides of the specimen. For waves traveling parallel to the specimen axis, a thin film of P-wave couplant (glycerine) was placed between the flat ends of the specimen and the teflon sheets used to minimize end effects.

3.2 Procedures

3.2.1 Calibration Procedures for Force, Pressure, and Displacement

All force, pressure, and displacement sensing elements were calibrated in their normal operating orientations on the test system, and outputs were observed at normal data collection points. By using this approach, the signal conditioners, filters, and analog-to-digital converters were all included within the "end-to-end" calibration. Calibrations for force, pressure, and displacement were performed by determining the best straight-line fit to indicated readings versus standard input, after applying the standard input in 20 equal steps. The calibration constants were then verified by applying the standard input in ten equal steps over the calibrated range. The transducer response at each step was predicted using the calibration constants. The process of calibration/verification was repeated until the predicted values fell within acceptance limits of: 1.0 percent of reading for load and pressure calibrations, and 2.0 percent of reading for displacement.

At the conclusion of the testing program, the verification steps were repeated and the results are given in Table 3-1. The calibration constants for lateral strain and pressure reverified to within the acceptance limits given above for all tests. Axial force reverified successfully for Tests LDR003 through LDR006. For Tests LDR001 and LDR002, axial force did not consistently reverify for loads below 10 MPa; however, the errors were less than 0.2 MPa. Axial strain reverified to within the acceptance limits for the latter portion of the constant strain rate segment and for the damage recovery segment.

Table 3-1. Post-Test Transducer Reverification Status

Transducer	Range	Error (Given as a Percent of Reading)
Axial Strain	0 - 0.25 percent strain	No Data
	0.25 - 0.50 percent strain	7.6 percent
	0.5 - 0.75 percent strain	4.1 percent
	0.75 - 1.0 percent strain	2.5 percent
	1.0 - 2 percent strain	< 2.0 percent
Lateral Strain	0 - 0.05 percent strain	No Data
	0.05 - 2.0 percent strain	< 2.0 percent
Confining Pressure	0 - 3.4 MPa	No Data
	3.4 - 34 MPa	< 1.0 percent
Axial Force ^(a)	0 - 5 kN	No Data
	5 - 10 kN	5 percent
	10 - 15 kN	2.5 percent
	15 - 30 kN	< 2.0 percent
	30 - 40 kN	< 1.0 percent
	40 - 80 kN	< 2.0 percent
Axial Force ^(b)	80 - 250 kN	< 1.0 percent
	0 - 15 kN	No Data
	15 - 250 kN	< 1 percent

(a) Applicable to Tests LDR001 - LDR002.

(b) Applicable to Tests LDR003 - LDR006.

3.2.2 Measurements of Time Delays for Ultrasonic System

To determine the time required for an acoustic signal to traverse a specimen accurately, one must first measure the time required for the signal to travel through the external portions of the transducer, the platens, and the teflon sheets that were used in the experimental assembly to

minimize end effects. Any time delay between the main pulse and the pulse to the oscilloscope trigger must also be measured. A standard method of calibration was used in which transducers were configured in their normal operating positions and travel times were measured through metal specimens of different lengths. A straight line was then fitted to the travel time versus specimen size data and the travel time intercept corresponding to a specimen length of zero provided the required correction. Aluminum specimens 0.05 m (2 in), 0.077 m (3 in), 0.127 m (5 in), and 0.1526 m (6 in) in length were used. Three sets of measurements were made: one in which the transducers were mounted in platens as in the axial measurement configuration, and two (one replicate set) in which metal shims were placed between the specimen and the transducers, as in the configuration for measurements perpendicular to the specimen axis. The appropriate couplants and teflon sheets were used in each setup to correctly emulate the test assembly. The travel time versus specimen size data are shown for the three sets of measurements in Figures 3-3 through 3-5. The delay time for signals parallel to the specimen axis is given by the Y-intercept in Figure 3-3 (2.76 μ s). The average of the Y-intercepts given in Figures 3-4 and 3-5 (0.49 μ s) was used for signals perpendicular to the axis.

3.2.3 Validation Tests for Ultrasonic System

Ultrasonic measurements were made on an aluminum specimen at elevated pressures and temperatures to measure the reproducibility of transducer output before and after pressure cycles and to evaluate the stability of the transducers over time. Shakedown test conditions are summarized in Table 3-2. The first two test conditions were used to measure compressional (P) wave travel times and amplitudes parallel ($P_{||}$) and perpendicular ($P_{\perp}$) to the specimen axis during pressure cycling at constant temperature. These tests were performed to ensure that the necessary pressure changes during testing did not cause unexpected hysteresis in ultrasonic transducer output. The remaining test conditions were imposed to ensure that transducer output did not drift significantly over long periods of time at elevated temperatures and pressures.

Shakedown test results are summarized in Table 3-3. Travel time data appear to be stable as a function of time and as a function of pressure cycling at both room and elevated temperatures. Amplitude data recorded during pressure cycling show hysteresis; however, test data obtained during depressurization cycles was of insufficient quantity to be used, thus hysteresis was not critical. Amplitude data at room temperature show no systematic drift over time but some drift at elevated temperature and pressure is indicated.

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Figure 3-3. Travel time versus specimen length for compressional waves traveling through a suite of aluminum specimens. Transducers are configured for measurement of time delay parallel to the specimen axis.

RSI-208-93-027

Figure 3-4. Travel time versus specimen length for compressional waves traveling through a suite of aluminum specimens. Transducers are configured for measurement of time delay perpendicular to the specimen axis. Data set 1.

RSI-208-93-028

Figure 3-5. Travel time versus specimen length for compressional waves traveling through a suite of aluminum specimens. Transducers are configured for measurement of time delay perpendicular to the specimen axis. Data set 2.

Table 3-2. Test Matrix for Transducer Stability Shakedown Tests

Test	Temperature (°C)	Pressure (MPa)	Test Type
1	20	0.5 - 15	Test stability during pressure cycling
2	70	0.5 - 15	Test stability during pressure cycling
3	20	15	Test stability over time
4	70	15	Test stability over time
5	70	0.5	Test stability over time

Table 3-3. Results of Transducer Evaluation Shakedown Tests

	Travel Time		Amplitude	
	P	P _⊥	P	P _⊥
Room Temperature				
Pressure Cycling	±20 ns ^(a)	±10 ns ^(a,b)	±1.5-5% ^(a)	±1.25-5% ^(a)
Stability (15 MPa)	±10 ns ^(a,b)	±20 ns ^(a)	±1.5% ^(a)	±0.5% ^(a)
Elevated Temperature (70°C)				
Pressure Cycling	±50ns ^(a)	±10 ns ^(a,b)	±2.5-6% ^(a)	±1% ^(a)
Stability (0.5 MPa)	±25 ns ^(a)	±10 ns ^(a,b)	-0.01% ^(c)	-0.1% ^(c)
Stability (15 MPa)	±20 ns ^(a)	± 0	-0.7% ^(c)	-0.2% ^(c)
(a) Width of scatter band.				
(b) Resolution of measurement.				
(c) Change per day.				

3.2.4 Experiments

The test matrix is given in Table 3-4. All tests conducted as part of this study have test identification numbers beginning with LDR (Loading and Damage Recovery) and were conducted

on specimens with identification numbers beginning with MCE. Test LCH015 (Loading and Crack Healing) was conducted in a previous study (Brodsky, 1990) and was conducted on a specimen with a C1X01 specimen identification designation. Test identification numbers are abbreviated in some figures by omitting the zeros; i.e., LDR001 is abbreviated as LDR1.

Table 3-4. Test Matrix

Test	Specimen ID	Closure/Healing Segment		
		Pressure (MPa)	Temperature (°C)	Duration
LCH015	C1X01-2/1-4/2-2	15	20	2.4 days
LDR001	MCE36-1/2-1/2-7/2	15	70	45 min
LDR002	MCE36-1/2-1/2-6/2	15	70	12 days
LDR003	MCE36-1/2-1/2-2/2	15	46	mechanical failure no data
LDR004	MCE36-1/1-1/2-4/2	15	46	mechanical failure no data
LDR005	MCE36-1/2-1/2-1/2	15	46	7 days
LDR006	MCE36-1/1-1/2-7/2	15	46	15 min

All specimens were preconsolidated at a hydrostatic stress of 20 MPa for 2 weeks before testing in an effort to heal any preexisting fractures formed during coring and machining. The load histories followed during testing are shown in Figures 3-6 and 3-7 for C1X01 and MCE specimens, respectively. Test segments shown in Figure 3-7 are described in Table 3-5. Preliminary pressure and temperature cycles were performed so that the ultrasonic wave velocities and amplitudes characteristic of the undamaged material at particular pressures and temperatures could be measured and used as reference readings for normalization of data obtained in the damaged state. The same preliminary temperature and pressure cycles were applied to all MCE specimens to eliminate introduction of variations in specimen history. Temperatures were changed at $0.2^{\circ}\text{C} \cdot \text{min}^{-1}$ and then allowed to stabilize for at least 2 hours before initiating the next test next test segment. The test on the C1X01 specimen was subjected to a much simpler preliminary cycling sequence which consisted of only one pressure cycle to 15 MPa at 20°C

After completion of preliminary cycling, a constant strain-rate triaxial compression test was conducted at 25°C and 0.5 MPa confining pressure to introduce damage into the specimen

RSI-208-93-29

Figure 3-6. Load history for damage recovery tests on C1X01 specimens.

RSI-208-93-025

Figure 3-7. Load history for damage recovery tests on MCE specimens. "S" values refer to test segments.

Table 3-5. Conditions for Each Segment of Crack Closure and Healing Test

Segment	Stress Difference (MPa)	Pressure (MPa)	Temperature (°C)
S1	Maintain at 0.25	Raise to 15	Raise to 70, stabilize
S2	Maintain at 0.25	Lower to 0.5	Maintain at 70
S3	Maintain at 0.25	Maintain at 0.5	Lower to 46
S4	Maintain at 0.25	Raise to 15	Maintain at 46
S5	Maintain at 0.25	Lower to 0.5	Maintain at 46
S6	Maintain at 0.25	Maintain at 0.5	Lower to 25
S7	Maintain at 0.25	Raise to 15	Maintain at 25
S8	Maintain at 0.25	Lower to 0.5	Maintain at 25
S9	Raise for Constant Strain Rate Test	Maintain at 0.5	Maintain at 25
S10	Decrease to 0.25	Maintain at 0.5	Maintain at 25
S11	Maintain at 0.25	Maintain at 0.5	Raise to test value
S12	Maintain at 0.25	Raise to test value of 15	Maintain at test value

microstructure. Load was applied at an axial strain rate of approximately 10^{-6}s^{-1} until axial strain reached approximately 1.5 percent. Specimens were unloaded quickly at constant stress rate to a stress difference of 0.25 MPa. This small amount of stress difference was maintained to provide good axial coupling. Specimens were then heated to the damage recovery temperature, either 25°C, 46°C, or 70°C as shown in Figure 3-7. Once temperature had stabilized they were loaded hydrostatically to begin the crack closure and healing phase of the test. Several unload/reload cycles were conducted during testing so that strain and ultrasonic data could be recorded when damaged surfaces were not held together by high hydrostatic stresses.

3.3 Data Acquisition and Reduction

Time, axial force, axial strain, circumferential strain, temperature, and pressure were read and recorded at timed intervals for each test using a computerized data acquisition system. The ultrasonic data were recorded by manual triggering at regular intervals. During the constant strain rate segment of the test, automated data were recorded every 50 seconds. Ultrasonic data were recorded every 250 seconds (approximately every 4.2 minutes or 225 μe at the test strain

rate) for the first 16.7 minutes, every 8.3 minutes until the segment time reached 33 minutes, and every 16.7 minutes thereafter.

During the crack closure and healing segment, automated data were recorded every 100 seconds for the first hour, every 5 minutes until the segment duration reached 3 hours, every 10 minutes until segment duration reached 6 hours, and every 30 minutes thereafter. Ultrasonic data were recorded by manual triggering every 500 seconds during the initial 33 minutes of the test segment, every 16.7 minutes until the segment duration reached 83 minutes, and every 33 minutes until segment duration reached 3 hours. At this point the rapid changes associated with pressurization were completed and the data acquisition rate was slowed. Generally up to 5 readings per day were taken during the work week and one reading per day on other days.

Arrival times and amplitudes for the first peak and first trough were read from the digital oscilloscope for each recorded waveform. Typical waveforms obtained at reference conditions, at the start of crack closure and healing, and after 10 days are shown in Figures 3-8, 3-9, and 3-10, respectively, for Test LDR005. Compressional waves traveling perpendicular and parallel to the specimen axis are given in each figure. Initial velocities were determined using the arrival times at which the signals emerged from the noise. Changes in velocities were then tracked using the arrival times of the first peaks. In calculating velocities from travel time data, corrections were made for the transducer delay times (see Section 3.2.2) and for specimen strain. Amplitudes given are the difference between the first peak and first trough. Ultrasonic velocity and amplitude data acquired during the constant strain-rate segments were normalized to the data obtained just before the initiation of loading. Data acquired during the crack closure and healing phase of the test were normalized to reference data obtained during the preliminary pressurization, as discussed in Section 3.2.4.

Reference Waveforms : LDR005

RSI-208-93-030

Figure 3-8. Received waveforms for compressional (P) waves traveling parallel and perpendicular to the specimen axis for Test LDR005. These waveforms were obtained during preliminary cycling at the reference conditions and characterize the undamaged material.

Waveforms : Begin Healing for LDR005

RSI-208-93-031

Figure 3-9. Received waveforms for compressional (P) waves traveling parallel and perpendicular to the specimen axis for Test LDR005. These waveforms were obtained at the start of the damage recovery segment and characterize the highly damaged material.

Waveforms : End Healing for LDR005

FSI-208-93-032

Figure 3-10. Received waveforms for compressional (P) waves traveling parallel and perpendicular to the specimen axis for Test LDR005. These waveforms were obtained at the end of the damage recovery segment and characterize the recovered material.

4.0 RESULTS

4.1 Constant Strain-Rate Triaxial Loading Data

The stress-strain curves obtained during the constant strain-rate triaxial loading test segments are shown in Figure 4-1. Recall that all LDR tests were conducted on MCE specimens taken from a rib of Room M at the WIPP site while the LCH test was conducted on a C1X01 specimen taken from a rib of Room C. Through the end of this test segment all LDR tests were treated identically. As noted previously, Test LCH015 was subjected to a much simpler preliminary cycling sequence. The LDR tests show very good reproducibility and show much higher strains at a given stress level than the LCH test.

4.1.1 Velocity and Amplitude Data During Loading

Compressional wave velocities determined during the constant strain rate test segment are shown in Figure 4-2 for waves traveling perpendicular and parallel to the specimen axis. Velocities are normalized to the values obtained just prior to loading. Several values increase upon initial application of stress difference, but all velocities eventually decay for both wave directions as strain increases. These data are consistent with results presented in Brodsky (1990).

The normalized amplitude values obtained during the constant strain-rate segment are given in Figure 4-3 for waves traveling perpendicular and parallel to the specimen axis. Again, values are normalized to amplitudes obtained just prior to loading. There are no data for LDR002 in Figure 4-3b due to mechanical problems associated with the test system. All $P_{||}$ values initially increase as do most $P_{\perp}$ amplitudes. Both waveforms decay as strain increases. Again, these data are consistent with results presented in Brodsky (1990).

DAMAGE RECOVERY TESTS

RSI-208-93-033

Figure 4-1. Stress difference versus strain for constant strain-rate triaxial compression test segments at 0.5 MPa confining pressure. Stress difference is the axial stress minus the confining pressure.

RSI-208-93-034

Figure 4-2. Normalized compressional wave velocities as a function of axial strain for constant strain-rate triaxial compression test segments. Test identification numbers are abbreviated.

RSI-208-93-035

Figure 4-3. Normalized peak-to-trough amplitudes as a function of axial strain for constant strain-rate triaxial compression test segments. Test identification numbers are abbreviated.

4.2 Crack Closure and Healing Phase

4.2.1 Strain-Time Data

The axial and lateral strains are given as a function of time during damage recovery in Figure 4-4. Tests LDR001 and LDR006 had mechanical failures during the first hour of this test segment and so the data are not shown. Compression is positive, thus a reduction in the lateral dimension and slight axial extension are indicated. The lateral reduction is as expected because damage volume is greatest in this direction and therefore the damage reduction is expected to be greatest. The axial strain results are similar to those given in Brodsky (1990). Axial strains initially decrease, showing specimen extension. For the longest duration test at 70°C, the axial strain goes through a minimum between 5 and 9 days and the specimen then begins to axially compress. The sudden decrease in axial strain for LDR002 at approximately 1.2 days corresponds to a small change in stress. Unload/reload cycles are evident at 4 days for Test LDR005 and at 5 and 9 days for Test LDR002. It was hoped that data obtained at low pressure during these cycles could be used to differentiate between the closure of damage under load and the permanent rejoining of surfaces. However, because jacket leaks terminated many of these tests prematurely, insufficient data were obtained to be used for this purpose.

Changes in volumetric strain occurring during damage recovery are plotted versus time in Figure 4-5. All strains show compression or closure of void volume. The initial rates of damage recovery increase with temperature.

4.2.2 Velocity Changes During Damage Recovery

Normalized velocity data for damage recovery are given in Figure 4-6 for waves traveling perpendicular and parallel to the specimen axis. Velocities are normalized to values obtained on the undamaged specimen during preliminary cycling at the temperature and pressure conditions used for the damage recovery segment. Unlike the volumetric strain data, the velocity data do not show a clear correlation between temperature and the rate and magnitude of recovery. Data for tests at 20°C and 46°C are essentially indistinguishable.

RSI-208-93-036

Figure 4-4. Changes in axial and lateral strains as a function of time during damage recovery for all tests.

RSI-208-93-037

Figure 4-5. Changes in volumetric strain as a function of time during damage recovery for all tests.

RSI-208-93-038

Figure 4-6. Normalized compressional wave velocities versus time during damage recovery for tests at three temperatures. Test identification numbers are abbreviated.

4.2.3 Amplitude Changes During Damage Recovery

Normalized amplitude data for the crack closure and healing phase are given in Figure 4-7 for waves traveling perpendicular and parallel to the specimen axis. Amplitudes were also normalized using data from the preliminary cycles. The unloading cycles are very evident in these data. These data show that recovery proceeds faster for tests at higher temperatures. The absence of P_{11} data for Test LDR002 is due to a mechanical problem during testing.

RSI-208-93-039

Figure 4-7. Normalized compressional wave amplitudes versus time during damage recovery for tests at three temperatures. Test identification numbers are abbreviated.

5.0 DISCUSSION AND DATA ANALYSIS

A discussion of the mechanisms responsible for wave attenuation and velocity changes at these test conditions is given in Brodsky (1990) and will not be repeated here. Similarly, ultrasonic velocity and amplitude changes seen during loadup are consistent with the observations and discussion already given in Brodsky (1990).

5.1 Time Constant for the Damage Recovery Process

Time constants for the recovery process were calculated using a first-order kinetics law given in differential form as

$$\frac{dV}{dt} = -\lambda * (V_{\infty} - V) \quad (5-1)$$

where dV/dt is the rate of recovery of a measured value (e.g., volumetric strain, ultrasonic velocities, or amplitudes), V_{∞} is the parameter value at infinite time, V is the value at time t , and λ is the inverse of the time constant for the recovery process. This equation describes an exponential decay of the difference between the measured value and its postrecovery value. This equation was integrated as follows

$$V = V_{\infty} - (V_{\infty} - V_0)e^{(-t/\tau)} \quad (5-2)$$

where

- V = Measured value (measured strain or ultrasonic value)
- V_{∞} = Value after damage recovery
- V_0 = Initial value, at start of recovery
- t = Time
- τ = Time constant.

Equation (5-2) was fitted separately for each test and for each of five experimentally determined values: ultrasonic compressional wave velocities parallel and perpendicular to the specimen axis, compressional wave amplitudes parallel and perpendicular to the specimen axis, and volumetric strain. The fitting was performed under the constraint that post-damage-recovery experimental values (V_{∞}) asymptotically approached those of the undamaged state. The fits to the data are shown in Figures 5-1 to 5-5. Each plot contains data from tests at each test temperature, and

RSI-208-93-040

Figure 5-1. Normalized velocities for ultrasonic compressional waves traveling perpendicular to the specimen axis during the damage recovery segment of the test. Symbols: data; Lines: fits to data.

RSI-208-93-041

Figure 5-2. Normalized compressional wave velocities for waves traveling parallel to the specimen axis during the damage recovery segment. Symbols: data; Lines: fits to data.

RSI-208-93-042

Figure 5-3. Normalized amplitudes for ultrasonic compressional waves traveling perpendicular to the specimen axis during the damage recovery segment. Symbols: data; Lines: fits to data.

RSI-208-93-043

Figure 5-4. Normalized amplitudes for ultrasonic compressional waves traveling parallel to the specimen axis during the damage recovery segment. Symbols: data; Lines: fits to data.

RSI-208-93-044

Figure 5-5. Measured volumetric strain during the damage recovery segment. Symbols: data; Lines: fits to data.

separate plots are given for each of the five experimentally measured values. For the volumetric strains, the data provided very little constraint on the fits (Figure 5-5) and so the fits were forced to the same starting point (a strain of 0.0005) and asymptote (a strain of 0.0022). This new fit is shown in Figure 5-6. Despite this, fits to the volumetric strain data (Figures 5-5 and 5-6) are substantially affected by the end constraints and therefore do not represent the data well. The end constraints were chosen because they represent a reasonable physical model; however, the data may be better represented by fitting to two separate healing regimes. The time constants and fitted values of V_0 are summarized in Table 5-1 and 5-2. Time constants calculated from amplitude and volumetric strain data decrease as temperature increases as expected for a thermally activated process; however, time constants determined from velocity data show no systematic change with temperature. In fact, the data given in Figure 5-1 show more rapid recovery at 20°C than at 46°C. All time constants are very short compared with times required for creep closure of rooms and shafts.

5.2 Activation Energy for Damage Recovery

The initial volumetric strain data obtained at each temperature were fitted to the following simple model so that an activation energy for the recovery process could be approximated:

$$\dot{\epsilon}_v = Ae^{\left(-\frac{Q}{RT}\right)} \quad (5-3)$$

where $\dot{\epsilon}_v$ is the time rate of change of volumetric strain, Q is the activation energy, R is the gas constant, and T is temperature. Initial strain rates were used because specimen microstructures were most equivalent at the start of damage recovery. Rearranging Equation (5-3) gives

$$\ln(\dot{\epsilon}_v) = \ln(A) - \frac{Q}{R} * \frac{1}{T} \quad (5-4)$$

which can be fitted linearly on a $\ln(\dot{\epsilon}_v)$ -versus-inverse temperature plot (Arrhenius plot) to obtain the slope, Q/R . Data from Tests LDR001, LDR002, LDR005, and LCH015 are plotted in Figure 5-7. (Only these tests were of sufficient duration to provide initial strain rates.) Linear least squares fitting provided an activation energy of $10.5 \text{ kJ} \cdot \text{mole}^{-1}$. This is considerably less than the range of creep values: $105 \text{ kJ} \cdot \text{mole}^{-1}$ for dislocation climb and $41.8 \text{ kJ} \cdot \text{mole}^{-1}$ for the undefined mechanism of creep expected to be active under repository conditions (Munson and Dawson, 1979). Although thermally activated healing may be related to a surface process, no specific process could be established at this time.

Figure 5-7. Arrhenius plot for volumetric strain rate.

6.0 SUMMARY AND CONCLUSIONS

Laboratory experiments were conducted in which introduction of damage and damage recovery were observed in intact WIPP salt specimens. Damage was introduced during constant strain-rate tests at low confining pressure and damage recovery occurred during subsequent hydrostatic pressurization at elevated temperature. During both the introduction of damage and damage recovery, axial and lateral strains were monitored as were ultrasonic compressional waves traveling both perpendicular and parallel to the direction of maximum principal stress. Tests were performed in a computer-controlled, servohydraulic test system. A load path test control program was used to apply the load path and acquire stress and strain data.

Data were modeled using a first-order kinetics law and applying fitting constraints. Ultrasonic data obtained at 70°C recovered to values characteristic of the undamaged state within days. Based on the modeling results, time constants associated with the recovery process at all temperatures are short, implying that the rate of void closure of the DRZ under confining pressure will be rapid. Rates of recovery obtained at different temperatures were used to determine an activation energy for the recovery process of $10.5 \text{ kJ} \cdot \text{mole}^{-1}$. This is considerably less than the range of creep values: $105 \text{ kJ} \cdot \text{mole}^{-1}$ for dislocation climb and $41.8 \text{ kJ} \cdot \text{mole}^{-1}$ for the undefined mechanism of creep expected to be active under repository conditions.

The implications of the rapid recovery of the damaged specimens under confining pressure are significant to seal performance evaluation. Clearly these results indicate that once the seal system is repressurized by the creeping salt, the DRZ will reclose and heal quite rapidly; i.e., on a short time frame compared to the creep closure process.

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