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Swelling Pressure, Water Uptake, and Permeability of 70/30 Crushed Salt/Bentonite

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ABSTRACT

Two experiments were conducted on specimens consisting of 70 percent by dry weight crushed salt and 30 percent by dry weight bentonite. The experiments included fifteen tests and were designed to measure the swell pressures induced by the introduction of saturated Brine A, a high magnesium-content brine, and to measure permeability. Specimens of three dry densities were used: 1,600 kg·m$^{-3}$, 1,800 kg·m$^{-3}$, and 2,100 kg·m$^{-3}$. Experiments were conducted in an oedometer which is a stiff pressure vessel designed to maintain specimens at constant volume. Test durations ranged from 3 to 112 days.

When specimens were put into contact with brine, their swelling was inhibited by the oedometer, and the pressures that were required to restrict swelling were recorded. The mean peak pressures increased with density and were 0.5 MPa, 1.1 MPa, and 6.5 MPa for densities of 1,600 kg·m$^{-3}$, 1,800 kg·m$^{-3}$, and 2,100 kg·m$^{-3}$, respectively. For tests at 1,600 kg·m$^{-3}$ and 1,800 kg·m$^{-3}$, the pressures peaked and then decayed to residual values. These residual values also increased with density and had mean values of 0.15 MPa and 0.37 MPa for densities of 1,600 kg·m$^{-3}$ and 1,800 kg·m$^{-3}$, respectively. The pressure never decayed for tests at 2,100 kg·m$^{-3}$ even though one test ran for 112 days.

Permeability measurements were made on specimens with densities of 1,600 kg·m$^{-3}$ and 1,800 kg·m$^{-3}$ using the constant hydraulic head, steady-state flow method. Flow was never established for the 2,100 kg·m$^{-3}$ specimens. Including recent data, permeability changed approximately two orders of magnitude (from $1 \times 10^{-15}$ m$^2$ to $1 \times 10^{-17}$ m$^2$) as density increased from 1,600 kg·m$^{-3}$ to 1,950 kg·m$^{-3}$. Moisture content and distribution measurements were made on all specimens post-test. On the average, all specimens reached saturation; however, moisture content distributions were nonuniform in many specimens.

$^1$Performed Under Contract No. 05-3605 For Disposal Rooms Systems Department (6345), Sandia National Laboratories
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1.0 INTRODUCTION

1.1 BACKGROUND

The U.S. Department of Energy (DOE) is responsible for providing for the safe disposal of transuranic (TRU) waste generated from defense-related activities. As such, DOE is developing the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico to assess the viability of long-term waste storage in a bedded salt formation located at a depth of approximately 660 m. If the assessment conducted by DOE proves favorable, the WIPP will be licensed and developed as a permanent facility for the storage of TRU wastes.

Salt is attractive because when subjected to a shear stress, it readily deforms with time or creeps. As a result of this time-dependent behavior, waste that is emplaced in storage rooms excavated from the salt will eventually be encapsulated as the salt pillars and walls flow into the room. Also, microcracks that are created in the salt during excavation can close and eventually heal as the rooms close [Costin and Wawersik, 1980; Brodsky, 1990]. Closure and healing of microcracks are important because it is expected that permeability will be reduced; therefore, the potential for radionuclide transport will also be reduced.

After the waste is emplaced in the storage rooms but before the rooms have closed to encapsulate the waste, radionuclide transport could be high if waste containers are breached, because of the significant void volume existing in the salt near the waste. To reduce the void volume during this time, backfill materials will be placed around the wastes and in the storage rooms. The backfill is expected to lower the effective permeability in the rooms and reduce the total time required for complete encapsulation of the waste. In addition, the backfill may be engineered so that it actually adsorbs radionuclides, thereby providing an additional barrier around the waste.

A primary requirement of the backfill is that it be compatible with the host rock. Obviously, one candidate material receiving considerable attention is crushed salt. Crushed salt is attractive because of its compatibility with the host rock and because it will be available in large quantities as storage rooms are excavated. It has also been shown that crushed salt consolidates relatively quickly when subjected to a hydrostatic stress [Holcomb and Hannum, 1982; Pfeifle and Senseny, 1985; and Stroup and Senseny, 1987]. Unfortunately, crushed salt remains relatively permeable before it completely consolidates and has little ability to adsorb radionuclides.

To improve the properties of pure crushed salt, additional candidate backfill materials have been proposed. These candidate materials are primarily composite materials such as mixtures of crushed salt and varying amounts of bentonite, a montmorillonite-rich clay. It is widely accepted that the addition of bentonite reduces permeability and increases the adsorbing ability of mixtures. The addition of bentonite may have its drawbacks, however. Preliminary results from consolidation
tests suggest that the rate of consolidation for crushed salt/bentonite backfills is lower than for pure crushed salt [Pfeifle, 1990; Stroup and Senseney, 1987]. This result implies that the time required for complete encapsulation of the waste is longer for the crushed salt/bentonite backfills. Another disadvantage of bentonite is that it swells in the presence of water or brine. If swelling is prevented, as may be the case in a storage room, swelling pressure develops instead. This swelling pressure may be large and could add significantly to the time required for complete encapsulation of the waste as it resists the natural tendency of the intact rock to deform into the room.

Two laboratory experiments have been performed on a mixture of 70 percent by dry weight crushed salt and 30 percent by dry weight bentonite. The objectives of these experiments were (1) to measure the swelling pressures that develop in specimens of 70/30 crushed salt/bentonite during brine uptake at constant volume, and (2) to estimate the permeability of the mixture. Testing additional salt/bentonite ratios is outside the scope of this study. The experiments were performed on specimens prepared at three levels of dry density, 1,600 kg·m⁻³, 1,800 kg·m⁻³, and 2,100 kg·m⁻³. This report presents the results of the two experiments.

1.2 SCOPE

Two experiments were performed on specimens of 70/30 crushed salt/bentonite to determine the relationships between swelling pressure and density and permeability and density. The experiments were conducted using two oedometers that were designed especially for performing swelling pressure tests at constant volume. Specimens were prepared at densities of 1,600 kg·m⁻³, 1,800 kg·m⁻³, and 2,100 kg·m⁻³ by combining crushed salt and bentonite so that the resulting mixture was 70 percent by dry weight crushed salt and 30 percent by dry weight bentonite. All tests were performed at room temperature (20°C) and had durations that varied in length from 3 to 112 days.

Table 1-1 gives the test matrix for the swelling pressure experiment. As shown, seven tests were performed at unique combinations of density and test duration. Table 1-2 gives the test matrix for the permeability experiment. Eight tests were performed at various combinations of density and initial moisture condition. Three density levels (1,600 kg·m⁻³, 1,800 kg·m⁻³, and 2,100 kg·m⁻³) and two initial moisture conditions were investigated. Because flow was never established for 2,100 kg·m⁻³ specimens, permeability results will be given only for specimen densities of 1,600 kg·m⁻³ and 1,800 kg·m⁻³. The initial moisture conditions were termed either (1) as-received, or (2) saturated. The “as-received” specimens were prepared by mixing as-received crushed salt and bentonite in the proper proportions accounting for the initial water content of the two materials and then compacting the specimens to the required density. The final specimen volume in the oedometer was fixed, and so different densities were achieved by adjusting the amounts of salt and bentonite used. The loads required to achieve specimen densities of 1,600 kg·m⁻³,
Table 1-1. Test Matrix for Swelling Pressure Experiment

<table>
<thead>
<tr>
<th>Density ( (\text{kg.m}^{-3}) )</th>
<th>Time (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,600</td>
<td>SWP003</td>
</tr>
<tr>
<td>1,800</td>
<td>SWP005</td>
</tr>
<tr>
<td>2,100</td>
<td>SWP010</td>
</tr>
</tbody>
</table>

Table 1-2. Test Matrix for Permeability Experiment

<table>
<thead>
<tr>
<th>Density ( (\text{kg.m}^{-3}) )</th>
<th>Initial Moisture Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,600</td>
<td>SWP012, SWP013, SWP014, SWP015</td>
</tr>
<tr>
<td>1,800</td>
<td>SWP016, SWP017</td>
</tr>
<tr>
<td>2,100</td>
<td>SWP018</td>
</tr>
</tbody>
</table>

(a) Steady state flow was not established after 42 days.

(b) Steady state flow was not established after 112 days.
1,800 kg·m$^{-3}$, and 2,100 kg·m$^{-3}$ were approximately 40 kN, 160 kN, and 1 MN, respectively. All specimens were loaded to the required force in less than 1 minute and were held at load for approximately 3–4 minutes. Specimens were saturated by allowing brine to enter the lower end of the specimen and exit the upper end of the specimen. The saturation was performed while the specimens were housed inside an oedometer, which prevented any volume change during the saturation process. The saturated specimen was prepared by mixing crushed salt, bentonite, and enough brine so that when the specimen was compacted it was fully saturated with brine. Again, the final specimen volume was fixed, and so enough brine was added to completely fill the calculated void space. The volumes required by the salt and bentonite were determined based on their measured dry masses and intact densities of 2,140 kg·m$^{-3}$ and 2,700 kg·m$^{-3}$, respectively. The permeability tests were performed using a constant head, steady-state flow technique in which brine was used as the permeant. In some cases, steady-state flow could not be established even after 112 days at a constant head of greater than 305 mm. At the end of each test, the specimens were sectioned so that the post-test water content and water content distribution could be determined for each specimen.

1.3 REPORT ORGANIZATION

In addition to this introduction, this report contains six chapters and one appendix. Chapter 2 describes the materials that were used in the experiments. Chapter 3 describes the experimental apparatus and is followed by Chapter 4, which describes the experimental procedures. The results of the experiments are given in Chapter 5. Chapter 6 provides a summary and conclusions from the study. References cited in the report are given in Chapter 7. Appendix A contains flow-versus-time curves for each of the permeability tests.
2.0 MATERIALS

The materials used in the experiments were crushed salt, bentonite, and brine. Crushed salt and bentonite were combined in proportions so that the resulting mixture contained 70 percent crushed salt and 30 percent bentonite (by dry weight). This mixture was then used to prepare specimens having dry densities of 1,600 kg·m⁻³, 1,800 kg·m⁻³, and 2,100 kg·m⁻³. The procedure used to mix the materials and prepare the specimens is described in Chapter 4. During the swelling pressure experiment, brine was permitted to contact each specimen so that swelling pressure could be measured as a function of time. Brine was also used as the permeant during the permeability experiment. The remainder of this chapter describes each of the three materials in more detail.

2.1 CRUSHED SALT

The crushed salt used in the samples was provided by Sandia National Laboratories and was produced by a continuous miner during development of the WIPP test facility. The mine-run salt contains particles that range in size up to several centimeters. Because the test specimens have a nominal length of only 50 mm, the mine-run salt was sieved to remove particles larger than 3.35 mm to produce a maximum particle size to minimum specimen dimension of about 0.07. The water content of the crushed salt was 0.38 percent as determined from three 100-g samples dried for 2 days at 110°C. (Samples were dried until the mass was constant to within less than 0.1 percent over a 24-hour period.) This water content does not represent the as-mined water content because no special measures had been taken to preserve the water content either in shipping or during storage. The assumed solid density of the salt is 2,140 kg·m⁻³.

2.2 BENTONITE

The bentonite used in the samples was a granular MX-80 Volclay bentonite commercially available from the American Colloid Company of Belle Fourche, South Dakota, and is described in greater detail elsewhere [Pfeifle, 1986]. This product is identical to the material used in the backfill studies at the WIPP. The as-received water content of the bentonite was 5.27 percent as determined from the method described above. The assumed solid density of the dry bentonite is 2,700 kg·m⁻³.

2.3 BRINE

The brine used in the study was a synthetic brine prepared by Twin Cities Testing, Rapid City, South Dakota. The brine had a final composition that simulated
Brine A, a naturally occurring WIPP brine that is high in magnesium. Small amounts of finely crushed WIPP salt were added to this brine to ensure that the solution was fully saturated with salt. The brine contains 69 percent by weight water and 31 percent by weight dissolved solids.
3.0 EXPERIMENTAL APPARATUS

Swelling pressure measurements require that specimens be constrained to prevent volume changes during brine (or water) uptake. One experimental apparatus that has been used to measure swelling pressures in bentonites is the LuH swelling pressure oedometer [Pusch, 1980]. In this apparatus, a cylindrical specimen is constrained in the radial direction by a thick-walled tube and in the axial direction by locking the piston into position with a steel ring. Swelling pressure is measured periodically during the test by axially loading the piston until the strain gauge on the steel ring is free of strain. Swelling pressure is then defined as the stress required to unload the steel ring.

In the current study, an apparatus similar to the LuH oedometer was used. The oedometer used at RE/SPEC Inc., however, was equipped with active control of the axial stress so that swelling pressure was monitored continuously during each test. The RE/SPEC oedometer was also equipped with ports to provide access to both ends of the specimens so that permeability measurements could be made. Pore pressure varies through the specimen when brine is introduced; however, resolution of the effects produced by pore pressure variations are beyond the scope of this study. This chapter provides a detailed description of the experimental apparatus used for both the swelling pressure and permeability experiments.

3.1 SWELLING PRESSURE OEDOMETER

The swelling pressure oedometer used in the experiments is depicted schematically in Figure 3-1. The oedometer is self-contained within an outer steel shell that includes a cylindrical steel tube or vessel and two steel end plates. The vessel provides the radial constraint for the specimen and has dimensions of 203 mm and 254 mm for the outside diameter and length, respectively. The end plates are removable and provide access to the vessel interior for test setup. The upper end plate is equipped with an opening through which an axial loading piston can be installed. The piston can be used to apply additional axial stress if the specimen volume is to be changed during the test. In the current study, the piston was installed but external loads were not applied because the tests were to be performed at constant volume. Therefore, the piston was in direct contact with the upper end plate throughout both experiments.

The oedometer vessel contains two chambers. The upper chamber houses the specimen, two porous stones, and the loading piston. The inside diameter of this chamber, and therefore the diameter of the specimen, is 102 mm. The chamber has an overall height of 114 mm so that the length of the specimen is 51 mm accounting for the thicknesses of the porous stones (each are 12.7 mm thick) and the piston (38 mm). The ends of the specimen are vented through two ports. The lower port extends radially outward from the upper chamber to the outer surface of the vessel.
Figure 3-1. Schematic of swelling pressure oedometer.
The upper port extends vertically through the loading piston. The ports are used either to introduce brine to the specimen during brine uptake or to provide access to the specimen for permeability measurements.

The lower chamber is filled with silicon oil, which is pressurized (to the swell pressure value) during the test to prevent axial expansion of the specimen. This chamber is 133 mm in diameter and 64 mm in height. This chamber is also equipped with a port that extends radially outward from the chamber to the outer surface of the vessel.

The two chambers of the vessel are physically separated by a Viton seal and clamp ring so that the silicon oil of the lower chamber cannot intrude into the specimen and porous stone assembly of the upper chamber. A Linear Variable Differential Transformer (LVDT) is mounted in the clamp ring and provides both a measure of the axial displacement of the specimens during testing and the feedback control for the intensifier or dilatometer that is used to pressurize the lower chamber. To eliminate the compliance of the Viton seal at the point of contact between the LVDT and the specimen assembly, a small portion of the Viton seal (2.4 mm in diameter) is cut away at the location of the LVDT and is replaced by a steel shim that attaches to the LVDT and is bonded directly to the Viton seal.

3.2 PERMEABILITY APPARATUS

The permeability apparatus is shown schematically in Figure 3-2. Brine flowed from an upper reservoir into a funnel. An overflow tube leading from the funnel to a lower reservoir maintained the brine level in the funnel at a constant value. Brine was channeled from the funnel to the inflow port of the oedometer and also into a measurement tube that was used to measure the actual hydraulic level of the inflow. Brine exited the oedometer at the outflow port and was collected in a graduated cylinder. A second measurement tube gave the hydraulic level of the outflow. A caliper was used to read the difference in hydraulic levels, which was the hydraulic head across the specimen.

3.3 DATA ACQUISITION AND CONTROL

During both the swelling pressure and permeability experiments, the swelling pressure and axial displacement of the specimen were measured continuously once brine was introduced into the specimen through the bottom port of the upper chamber. The swelling pressure was assumed to be equal to the pressure in the lower chamber required to prevent axial displacement of the specimen and was measured by a pressure transducer located in the hydraulic line connected to the pressure port of the lower chamber. The axial deformation was measured by the control LVDT described in Section 3.1. The range and accuracy of the pressure transducer and LVDT are shown in Table 3-1. The analog outputs of both transducers
Figure 3-2. Permeability apparatus.
Table 3-1. Range and Accuracy of Transducers

<table>
<thead>
<tr>
<th>Transducer Type</th>
<th>Range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (MPa)</td>
<td>0-14 MPa</td>
<td>0.014</td>
</tr>
<tr>
<td>LVDT (mm)</td>
<td>± 1.29 mm</td>
<td>2.6 μm</td>
</tr>
</tbody>
</table>

were amplified through MTS 450-series controllers and digitized by an LSI 11/23 microprocessor equipped with a 14-bit analog-to-digital converter.

In theory, the position of the LVDT should remain in the null or starting position throughout a test if the original volume of the specimen is to be preserved. In fact, however, the position of the LVDT must change as swelling pressure increases to account for the compliance of the porous stones and interfaces of the upper chamber. The compliance correction to the LVDT measurement was determined through calibration using a metal specimen of known mechanical properties. The calibration also accounted for any pressure sensitivity of the LVDT.

Two systems were used to control the volume of the specimen during the experiments. The first system included the control LVDT and a high-speed, MTS-supplied pressure intensifier. This system was required because of the high rate of change of swelling pressures during the early periods of the tests. The second system included the control LVDT and a standard dilatometer pressure system. The second system was used once the rate of change of swelling pressures had slowed. This system offered long-term test reliability since it is static and does not lose pressure during electrical power outages. Both systems were controlled using software written in MTS BASIC that was installed on an LSI-11/23 microprocessor. While the intensifier controlled the specimen volume, the LVDT output could be kept constant to within ±1 mV, which corresponded to ±1 micron; however, corrections could not be made for system compliance. Once control was switched to the dilatometer system, the software would check the position of the LVDT approximately every 2 seconds. If the output of the LVDT corrected for compliance fell outside of the control window of ±10 microns, a command was given to the dilatometer to increase or decrease the lower chamber pressure so that the new LVDT position was inside the control window, thereby preserving the original volume of the specimen. An example of the control provided by the intensifier system is shown in Figure 3-3. The trough and peak occurring at approximately 10 to 15 minutes coincides with the introduction of brine and initiation of system response.
Figure 3-3. Typical control for axial displacement during swelling pressure tests.

SWP005
Density = 1,800 kg/m³
70% Crushed Salt
30% Bentonite
4.0 EXPERIMENTAL PROCEDURE

Experimental procedures were developed for each of the two experiments performed in this study. In addition, several supplemental procedures were required. The procedures used in this study include:

- Transducer Calibration/Verification
- Equipment Shakedown
- Specimen Preparation
- Swelling Pressure
- Moisture Content
- Permeability

This chapter describes in detail the experimental and supplemental procedures required to complete the current study.

4.1 TRANSDUCER CALIBRATION/VERIFICATION

All 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. Known input levels to the calibration system were provided by NIST traceable standards maintained in the RE/SPEC Inc. metrology laboratory. Calibrations for pressure and displacement were performed by determining the best straight-line fits to indicated readings versus standard input, after applying the standard input in twenty 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 acceptable levels of error: 1.0 percent of reading for pressure calibrations and 2.0 percent of reading for displacement calibrations. These levels of error determine the accuracies given in Table 3-1.

4.2 EQUIPMENT SHAKEDOWN

To verify that the control system and equipment were performing as anticipated, a shakedown test was performed on a specimen composed entirely of bentonite. The specimen was prepared so that its dry density was 1,800 kg·m⁻³ and its diameter
and length were 101.7 mm and 19.1 mm, respectively. The liquid used during uptake was tap water. Figure 4-1 presents the swelling pressures that developed with time for this specimen. The curve shown in Figure 4-1 is similar to those presented by Pusch [1980] in that the pressure slowly builds to a peak and then levels off or decreases slightly after the peak. The response differs from that reported by Pusch in that the magnitude of the peak swelling pressure is about three times higher than in the tests performed by Pusch, i.e., 3.3 MPa versus 0.6 to 1.0 MPa for specimens of comparable density. One explanation for the difference may be the difference in specimen size. Pusch tested specimens having diameters and lengths of 50 mm and 20 mm, respectively.

4.3 SPECIMEN PREPARATION

The specimen materials were prepared by weighing out the proper amounts of crushed salt and bentonite to give the correct ratio and density when compacted to the specified volume. A porous stone was placed in the oedometer and then the thoroughly mixed materials were poured in. The piston was placed on top of the specimen and load was applied using a loading frame until the mixture compacted to the predetermined volume. A porous stone was then placed on top of the specimen. For higher density specimens, a steel plate having the same dimensions as a porous stone was used in the bottom of the oedometer during specimen compaction because the high forces (up to 1 MN) required to compact these specimens would break a porous stone. After compaction was completed, the lower end plate was removed and the steel plate was replaced with a porous stone.

4.4 SWELLING PRESSURE

After the specimen was compacted, the oedometer was completely assembled and a test control and data acquisition computer program was initialized. The specimen was preloaded to 0.25 MPa and the system allowed to stabilize for several hours. Stabilization was complete when the output of the pressure transducer was constant to within ±0.003 MPa for 1 hour. The displacement reading taken at the end of this stabilization period was used as the reference for maintaining constant specimen volume. A brine reservoir was connected to the inflow port of the oedometer (lower port of upper chamber), and brine was allowed to contact the specimen. An MTS pressure intensifier kept the displacement reading constant as the specimen swelled. After the rate of change of swelling pressure slowed, the control was shifted to a standard dilatometer pressure system. A buret was used as the brine inflow reservoir for the earlier tests (SWP001 to SWP013). When it became evident that the high hydraulic head in the buret caused brine to channel along the specimen/oedometer interface, the buret was replaced with a wide diameter (203 mm) reservoir. The reservoir was filled so that the upper brine level was 76 mm above the center of the
Figure 4-1. Swelling pressure as a function of time for a bentonite specimen with a density 1,800 kg·m\(^{-3}\).
inflow port. The reservoir level was raised 38 mm every 2 days until the brine level in the reservoir was 305 mm above the outflow port of the oedometer.

4.5 MOISTURE CONTENT

Each test was maintained for the time durations shown in Table 5-1. When a test was completed, the specimen was removed from the oedometer while keeping track of specimen orientation. The specimen was divided in half, cutting along the specimen axis as shown in Figure 4-2. One half was placed in a weighed aluminum tray, and the other half was divided into four equal sections, cutting along planes perpendicular to the specimen axis. The four sections were (1) 0-12.5 mm, the section located adjacent to the brine entrance; (2) 12.5-25 mm, the section immediately below the specimen midheight; (3) 25-37.5 mm, the section immediately above the specimen midheight; and (4) 37.5-50 mm, the section adjacent to the brine exit. Each section was placed in a weighed tray. The moisture content of each section was measured by placing the trays in an oven at 110±5°C until the weights stabilized (i.e., they were constant to within 0.1 percent over a 24-hour period).

4.6 PERMEABILITY

Measurements of permeability were made using the constant-head, steady-state flow method once specimens reached full saturation. A specimen was considered fully saturated when brine emerged from the outflow port (upper port of upper chamber). The permeability apparatus was set up as shown in Figure 3-2. The outflow tubes were filled and the heights of the graduated cylinder and funnel were adjusted to provide the correct hydraulic head. Values of hydraulic head ranged from 38 mm to 371 mm with 75 mm being a typical value. Exact values are given in Appendix A. Brine was allowed to flow through the specimen until approximately 20 ml of brine had collected in the graduated cylinder. For 1,600 kg·m⁻³ specimens, this typically required 20 hours; for 1,800 kg·m⁻³ specimens, approximately 20 days were required. Brine flow was never established for 2,100 kg·m⁻³ specimens although one test lasted 112 days.
Figure 4-2. Specimen sectioning for moisture content measurements.
5.0 EXPERIMENTAL RESULTS

5.1 SWELLING PRESSURE

As shown in Table 1-1, seven swelling pressure tests were performed on specimens having dry densities of either 1,600 kg·m\(^{-3}\), 1,800 kg·m\(^{-3}\), or 2,100 kg·m\(^{-3}\). The durations of the tests ranged from 3 days to 12 days. The permeability tests (Table 1-2) also provided swelling pressure information. Therefore, swelling pressure results were obtained from 15 independent tests.

The initial swelling pressure responses (times < 60 minutes) are shown in Figures 5-1 through 5-3 for the three dry densities, respectively. Although the initial control of the volume, and therefore pressure, is not always good, it can be readily seen that swelling pressures develop rapidly as brine is introduced to the specimens. For the two lower densities, i.e., 1,600 kg·m\(^{-3}\) and 1,800 kg·m\(^{-3}\), the swelling pressures reach a peak and begin to decay. At a density of 2,100 kg·m\(^{-3}\), however, the swelling pressures are still increasing after 60 minutes. (The somewhat anomalous results for Test SWP019 will be discussed later in greater detail.)

The swelling pressure responses over the first 24 hours are shown in Figures 5-4 through 5-6 for the three dry densities, respectively. Figures 5-4 and 5-5 show that the swelling pressures at the two lower densities are continuing to decay with time. Figure 5-6 shows that the pressures are still increasing after 24 hours for the tests performed at a density of 2,100 kg·m\(^{-3}\).

The long-term swelling pressure responses (up to 30 days) are shown in Figures 5-7 through 5-9 for the three dry densities, respectively. (The anomalous result for Test SWP014 will be discussed later.) It appears from Figures 5-7 and 5-8 that the swelling pressures are decaying to some residual pressure for the two lowest densities. Figure 5-9 shows that even at 30 days, the swelling pressure has not reached a peak for a density of 2,100 kg·m\(^{-3}\). To determine the time required to reach the peak swelling pressure at this density, Test SWP018 was continued for 112 days. The swelling pressure data for this test is shown in Figure 5-10 and indicates that a peak pressure is reached at about 75 days. The swelling pressure does not appear to be decaying after this time; however, the test duration may still be too short to support this conclusion. Discontinuities in the data, such as those seen for test SWP016 in Figure 5-8 and SWP018 in Figure 5-10, were due to power outages.

The results of the 15 swelling pressure tests are summarized in Table 5-1. Both the peak and residual swelling pressures recorded for each test are shown in the table. No residual swelling pressure information was obtained at a density of 2,100 kg·m\(^{-3}\). The peak swelling pressures measured in the tests are ordered with respect to density. The peak pressures for densities of 1,600 kg·m\(^{-3}\), 1,800 kg·m\(^{-3}\), and 2,100 kg·m\(^{-3}\) are 0.5 MPa, 1.1 MPa, and 6.5 MPa, respectively. These values
Figure 5-1. Initial swelling pressure response for 70/30 crushed salt/bentonite at a density of 1,600 kg·m⁻³.
Figure 5-2. Initial swelling pressure response for 70/30 crushed salt/bentonite at a density of 1,800 kg·m⁻³.
Figure 5-3. Initial swelling pressure response for 70/30 crushed salt/bentonite at a density of 2,100 kg·m$^{-3}$. 

Density = 2,100 kg/m$^3$

70% Crushed Salt
30% Bentonite

Pressure (MPa)

Time (Minutes)
Figure 5-4. First day swelling pressure history for 70/30 crushed salt/bentonite at a density of 1,600 kg·m⁻³.
Figure 5-5. First day swelling pressure history for 70/30 crushed salt/bentonite at a density of 1,800 kg·m⁻³.
Figure 5-6. First day swelling pressure history for 70/30 crushed salt/bentonite at a density of 2,100 kg·m⁻³.
Figure 5-7. Long-term swelling pressure history for 70/30 crushed salt/bentonite at a density of 1,600 kg·m$^{-3}$. 

Density = 1,600 kg/m$^3$

70% Crushed Salt
30% Bentonite
Figure 5-8. Long-term swelling pressure history for 70/30 crushed salt/bentonite at a density of 1,800 kg·m⁻³.
Density = 2,100 kg/m³
70% Crushed Salt
30% Bentonite

Figure 5-9. Long-term swelling pressure history for 70/30 crushed salt/bentonite at a density of 2,100 kg·m⁻³.
Figure 5-10. Swelling pressure history for test SWP018 at a density of 2,100 kg·m\(^{-3}\).
Table 5-1. Peak and Residual Swelling Pressures

<table>
<thead>
<tr>
<th>Density (kg/m³)</th>
<th>Test I.D.</th>
<th>Test Duration (Days)</th>
<th>Peak Swell Pressure (MPa)</th>
<th>Residual Swell Pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1600</td>
<td>SWP003</td>
<td>3</td>
<td>0.45</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>SWP012</td>
<td>3</td>
<td>0.40</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>SWP013</td>
<td>3</td>
<td>0.52</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>SWP008</td>
<td>10</td>
<td>0.41</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>SWP015(a)</td>
<td>10</td>
<td>0.71</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>SWP014(a,b)</td>
<td>32</td>
<td>0.48</td>
<td>0.25</td>
</tr>
<tr>
<td>1800</td>
<td>SWP005</td>
<td>3</td>
<td>1.33</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>SWP004</td>
<td>10</td>
<td>1.03</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>SWP016(a)</td>
<td>30</td>
<td>1.22</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>SWP017(a)</td>
<td>75</td>
<td>1.00</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>SWP019(a,c)</td>
<td>42</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>2100</td>
<td>SWP010</td>
<td>3</td>
<td>2.58</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SWP011</td>
<td>10</td>
<td>4.18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SWP009</td>
<td>12</td>
<td>5.50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SWP018(a)</td>
<td>112</td>
<td>6.50</td>
<td></td>
</tr>
</tbody>
</table>

(a) Low hydraulic head was maintained.
(b) Caulking was used in specimen/oedometer interface. Cross-sectional area was corrected to account for intrusion of caulking into the specimen.
(c) Brine added during specimen fabrication.

are the means of all the peak swelling pressures shown in Table 5-1 for densities of 1,600 kg·m⁻³ and 1,800 kg·m⁻³ (except Test SWP019) and the actual peak value recorded for Test SWP018. The relationship between peak swelling pressure and dry density appears to be highly nonlinear as shown in Figure 5-11. The mean residual swelling pressures are 0.15 MPa and 0.37 MPa for densities of 1,600 kg·m⁻³ and 1,800 kg·m⁻³, respectively. These values are again ordered with respect to density and are also plotted in Figure 5-11. The data in Figure 5-11 are plotted with error bars that show ±1 standard deviation. Since the peak value for only one test is plotted at 2,100 kg·m⁻³, no standard deviation is given.

The ordering of the swelling pressures with density was expected. The decay of the peak swelling pressures was not expected, however, based on previous work on pure bentonite. One explanation for the swelling pressure decay is that the
Figure 5-11. Mean peak and residual swelling pressures as functions of dry density for 70/30 crushed salt/bentonite. Standard deviations are given for tests at 1,600 kg·m⁻³ and 1,800 kg·m⁻³; the data point at 2,100 kg·m⁻³ represents an individual test.
swelling pressure that developed in the bentonite may actually stress the crushed salt particles causing them to deform into the remaining free void space, i.e., voids that contain only brine. This deformation would allow the bentonite to expand, which would then relieve some of the swelling pressure. However, if free void space is present in the specimen, the bentonite, when wetted, could simply expand into these free voids, and thus, no swelling pressure would develop. This hypothesis is therefore considered to be unlikely. A second explanation for the decay is that the bentonite is chemically altered by the brine. The brine used in the tests has a relatively high magnesium content. From clay chemistry [Mitchell, 1976], it is known that magnesium can readily replace sodium, which reduces the swelling potential of the clay. Since bentonite is rich in sodium, a replacement of the sodium by magnesium or some other similar action may result in the observed swelling pressure decay.

Although most of the test results follow the general trends described above, the results for two tests, SWP0014 and SWP019, are quite different. The differences are attributable to the differences in procedures used for these tests. The primary purpose for performing SWP014 and SWP019 was to measure permeability rather than swelling pressure. Based on results obtained in SWP012 and SWP013, it was concluded that brine was channeling (and perhaps eroding salt and bentonite) at the specimen-oedometer wall interface for low density specimens. Therefore, SWP014 was performed by placing a caulking material in the specimen-wall interface and using low hydraulic heads during brine uptake to prevent channeling. Although the swelling pressure reached approximately the same peak and residual swelling pressures as determined from other tests at this density (see Figure 5-7), the time required to reach the peak and residual pressures was longer. The peak and residual pressures recorded for Test SWP019, as shown in Table 5-1, are identical and are considerably lower than for the other pressures recorded at density of 1,800 kg·m⁻³. This difference is explained by the method in which the specimen for SWP019 was prepared. Unlike all the other specimens tested, this specimen was prepared by adding sufficient amounts of brine to saturate the specimen during preparation, and therefore before testing. By adding the brine before testing, the chemical changes that may control the drop in pressure from a peak to a residual have already occurred, and thus, no pressure changes are observed.

5.2 PERMEABILITY

Permeability measurements were made on seven specimens having densities that varied from 1,600 kg·m⁻³ to 1,800 kg·m⁻³. The technique used to make the measurements was a constant hydraulic head, steady-state flow technique that used brine as the permeant. For the lower density specimens, redundant measurements were made on a single specimen at different hydraulic heads. The heads ranged from 38 mm to about 371 mm of brine, or one order of magnitude. At low densities and high hydraulic heads, flow channeling and erosion was a problem. Some channeling also occurred in the low density specimens, even at relatively low hydraulic heads.
especially along the specimen-vessel interface, as discussed previously. The results of the permeability tests are given below.

In the calculation of permeability, it was assumed that Darcy’s law for flow through porous media was valid. Therefore, permeability was calculated from

\[ k = \frac{\mu}{\rho g} \cdot \frac{QL}{b.hA} \]  

(5-1)

where

- \( k \) = Intrinsic permeability, \( m^2 \)
- \( \mu \) = Dynamic viscosity of brine = \( 1.26 \times 10^{-3} \) kg·m\(^{-1}\)·s\(^{-1} \)
- \( \rho \) = Density of brine = \( 1,200 \) kg·m\(^{-3} \)
- \( g \) = Acceleration of gravity = \( 9.8 \) m·s\(^{-2} \)
- \( Q \) = Flow rate, m\(^3\)·s\(^{-1} \)
- \( L \) = Length of specimen, m
- \( \Delta h \) = Hydraulic head of brine, m
- \( A \) = Cross-sectional area of specimen, \( m^2 \)

The hydraulic head varied from about 38 mm to 371 mm of brine. The flow data for each test are shown in Appendix A. The permeabilities calculated from Equation 5-1 are summarized in Table 5-2 for each of the densities tested. At a density of \( 1,600 \) kg·m\(^{-3} \), channeling was a problem in two tests (SWP012 and SWP013), and therefore, permeability calculations were not made. Although channelling is expected in situ, accounting for the effects of channelling is beyond the scope of this study. At a density of \( 2,100 \) kg·m\(^{-3} \), flow rates could not be established even after 112 days of testing.

The results of the permeability testing are shown in Figure 5-12, which plots permeability as a function of dry density. Included in this figure are two other results reported by Pfeifle [1990]. The figure shows that permeability changes by about two orders of magnitude (i.e., from \( 1 \times 10^{-15} \) m\(^2\) to \( 1 \times 10^{-17} \) m\(^2\)) for changes in density from \( 1,600 \) kg·m\(^{-3} \) to about \( 1,950 \) kg·m\(^{-3} \), respectively. If the data plotted are used to extrapolate to \( 2,100 \) kg·m\(^{-3} \), the permeability would further decrease to less than \( 1 \times 10^{-18} \) m\(^2\).

### 5.3 BRINE UPTAKE AND WATER CONTENT DISTRIBUTION

After each test was completed, the specimens were sectioned to obtain four samples for determining water content and the distribution of water content throughout the specimen. The samples were obtained by making cuts perpendicular to the specimen axis at the quarter points (see Figure 4-2). The water content of each sample, defined as the ratio of the mass of water to the dry mass of solids expressed as a percent, was determined by drying the samples in an oven at 110±5°C until a
Table 5-2. Summary of Permeability Measurements

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Density kg·m⁻³</th>
<th>Q (m³/s)</th>
<th>H (m)</th>
<th>k (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWP012</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run 1</td>
<td>1,600</td>
<td>4.20×10⁻⁶</td>
<td>.371</td>
<td>(a)</td>
</tr>
<tr>
<td>Run 2</td>
<td>1,600</td>
<td>5.38×10⁻⁶</td>
<td>.371</td>
<td>(a)</td>
</tr>
<tr>
<td>Run 3</td>
<td>1,600</td>
<td>5.41×10⁻⁶</td>
<td>.371</td>
<td>(a)</td>
</tr>
<tr>
<td>Run 4</td>
<td>1,600</td>
<td>5.59×10⁻⁶</td>
<td>.371</td>
<td>(a)</td>
</tr>
<tr>
<td>SWP013</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run 1</td>
<td>1,600</td>
<td>7.06×10⁻⁷</td>
<td>.132</td>
<td>(a)</td>
</tr>
<tr>
<td>Run 2</td>
<td>1,600</td>
<td>3.96×10⁻⁷</td>
<td>.072</td>
<td>(a)</td>
</tr>
<tr>
<td>Run 3</td>
<td>1,600</td>
<td>2.23×10⁻⁷</td>
<td>.038</td>
<td>(a)</td>
</tr>
<tr>
<td>Run 4</td>
<td>1,600</td>
<td>4.77×10⁻⁷</td>
<td>.076</td>
<td>(a)</td>
</tr>
<tr>
<td>SWP014</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run 1</td>
<td>1,600</td>
<td>2.06×10⁻¹⁰</td>
<td>.152</td>
<td>9.16×10⁻¹⁶</td>
</tr>
<tr>
<td>Run 1</td>
<td>1,600</td>
<td>4.52×10⁻¹⁰</td>
<td>.305</td>
<td>10.05×10⁻¹⁶</td>
</tr>
<tr>
<td>Run 2</td>
<td>1,600</td>
<td>3.38×10⁻¹⁰</td>
<td>.305</td>
<td>7.52×10⁻¹⁶</td>
</tr>
<tr>
<td>SWP015</td>
<td>1,600</td>
<td>No permeability data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SWP016</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run 1</td>
<td>1,800</td>
<td>1.23×10⁻¹⁰</td>
<td>.076</td>
<td>10.94×10⁻¹⁶</td>
</tr>
<tr>
<td>Run 2</td>
<td>1,800</td>
<td>1.05×10⁻¹⁰</td>
<td>.076</td>
<td>9.34×10⁻¹⁶</td>
</tr>
<tr>
<td>Run 3</td>
<td>1,800</td>
<td>1.68×10⁻¹⁰</td>
<td>.152</td>
<td>7.47×10⁻¹⁶</td>
</tr>
<tr>
<td>Run 4</td>
<td>1,800</td>
<td>1.61×10⁻¹⁰</td>
<td>.152</td>
<td>7.16×10⁻¹⁶</td>
</tr>
<tr>
<td>Run 5</td>
<td>1,800</td>
<td>1.74×10⁻¹⁰</td>
<td>.152</td>
<td>7.74×10⁻¹⁶</td>
</tr>
<tr>
<td>Run 6</td>
<td>1,800</td>
<td>0.93×10⁻¹⁰</td>
<td>.076</td>
<td>8.27×10⁻¹⁶</td>
</tr>
<tr>
<td>SWP017</td>
<td>1,800</td>
<td>1.07×10⁻¹⁰</td>
<td>.152</td>
<td>0.48×10⁻¹⁶</td>
</tr>
<tr>
<td>SWP018</td>
<td>2,100</td>
<td>Flow not established</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SWP019</td>
<td>1,800</td>
<td>Flow not established</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) Permeability was not calculated because brine channeled through the specimen-oedometer wall interface.

(b) Permeability calculated based on an effective area to account for caulking.
Figure 5-12. Permeability as a function of dry density for 70/30 crushed salt/bentonite.
constant mass was recorded. This section presents the results of the water content tests.

In the swelling pressure tests, the durations of the tests at a constant density were varied so that swelling pressure could be correlated with brine uptake, i.e., the mass of brine taken in by the specimen. The brine uptake was so rapid, however, that the specimens essentially saturated before even the shortest test was completed. Therefore, water contents of the samples should be near the theoretical saturated water content. In the permeability tests, the water content determinations were performed to verify that the samples were fully saturated. In these tests, the water contents should again be near the saturated water content. Table 5-3 provides the water contents for each specimen.

The data given in Table 5-3 is summarized in Figures 5-13 through 5-15 for densities of 1,600 kg·m⁻³, 1,800 kg·m⁻³, and 2,100 kg·m⁻³, respectively. Each figure gives water contents as functions of four regions within the respective specimens (see Figure 4-2) and assumes that for any one region the water content is uniform. The water contents of each specimen are denoted by different line types. The theoretical water content for a fully saturated specimen is also shown in the figures and was calculated assuming that all voids were completely filled with brine.

An examination of Figures 5-13 and 5-14 shows that the water contents of specimens having densities of 1,600 kg·m⁻³ and 1,800 kg·m⁻³ are approximately equal to the theoretical saturated water contents; however, near the ends of the specimens, the water content is higher than near the midheights of the specimens. This difference is probably attributable to small differences in density produced during preparation of the specimens. At a density of 2,100 kg·m⁻³, the water content data, as shown in Figure 5-15, show an interesting result. As expected, the water contents of the samples nearest the brine entrance are higher than at any other location. A somewhat surprising result, however, is that the water contents in this region are considerably higher than the theoretical saturated water content. This result implies that more voids are located in this region and that the density is actually much lower than 2,100 kg·m⁻³. This low density region could be a result of specimen preparation or could be a region where volume expansion is occurring as brine is being wicked in by the bentonite. If this were the case, the density at other locations in the specimen would be increasing because the overall specimen volume is held constant.

Figure 5-16 plots the average water content measured for each specimen as a function of the theoretical saturated water content. The dotted line represents where the data should plot if the specimens were fully saturated. As shown, the measured water content data fall very near this theoretical line indicating that the specimens are saturated. These results can be misleading, however, because no account is made of the water content distribution. As was shown for the specimens at a density of 2,100 kg·m⁻³, the water content in one region of the specimen could be much higher than the theoretical saturated water content, which masks the fact that the greatest portion of the specimen is not fully saturated.
Table 5-3. Moisture Content as a Percent of Dry Weight for Individual Specimen Regions

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Average(^{(b)}) Moisture Content (%)</th>
<th>Moisture Content by Region (%)(^{(a)})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Region 1</td>
</tr>
<tr>
<td>SWP003</td>
<td>13.76</td>
<td>15.10</td>
</tr>
<tr>
<td>SWP004</td>
<td>11.76</td>
<td>9.56</td>
</tr>
<tr>
<td>SWP005</td>
<td>10.20</td>
<td>10.19</td>
</tr>
<tr>
<td>SWP009</td>
<td>3.04</td>
<td>5.79</td>
</tr>
<tr>
<td>SWP010</td>
<td>4.29</td>
<td>9.00</td>
</tr>
<tr>
<td>SWP011</td>
<td>3.74</td>
<td>6.70</td>
</tr>
<tr>
<td>SWP012</td>
<td>13.93</td>
<td>15.72</td>
</tr>
<tr>
<td>SWP013</td>
<td>15.59</td>
<td>14.08</td>
</tr>
<tr>
<td>SWP016</td>
<td>10.15</td>
<td>10.98</td>
</tr>
<tr>
<td>SWP017</td>
<td>10.25</td>
<td>11.44</td>
</tr>
<tr>
<td>SWP018</td>
<td>3.79</td>
<td>5.51</td>
</tr>
<tr>
<td>SWP019</td>
<td>9.74</td>
<td>10.10</td>
</tr>
</tbody>
</table>

\(^{(a)}\) Specimen regions are defined in Figure 4-2.

\(^{(b)}\) The average moisture content was measured using a different section of the specimen (see Figure 4-2) and is therefore different than the average of the four regions.
Figure 5-13. Water content as a function of specimen location for 70/30 crushed salt/bentonite at a density of 1,600 kg·m$^{-3}$. 

Figure 5-13. Water content as a function of specimen location for 70/30 crushed salt/bentonite at a density of 1,600 kg·m$^{-3}$. 

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Figure 5-14. Water content as a function of specimen location for 70/30 crushed salt/bentonite at a density of 1,800 kg·m⁻³.
Figure 5-15. Water content as a function of specimen location for 70/30 crushed salt/bentonite at a density of 2,100 kg·m$^{-3}$. 
Figure 5-16. Measured water content as a function of theoretical water content at saturation for 70/30 crushed salt/bentonite.
6.0 SUMMARY AND CONCLUSIONS

Two experiments were conducted on specimens of 70/30 crushed salt/bentonite. In the first experiment, composed of seven tests, swelling pressure was measured as a function of specimen density. The second experiment, composed of eight tests, also provided swell pressure information; however, the purpose of that experiment was to measure permeability as a function of density. Specimens were prepared at densities of 1,600 kg·m⁻³, 1,800 kg·m⁻³, and 2,100 kg·m⁻³ by combining crushed salt and bentonite so that the resulting mixture was 70 percent by dry weight crushed salt and 30 percent by dry weight bentonite. Tests were conducted in two oedometers that maintained the specimens at constant volume when they were put into contact with simulated Brine A, a high magnesium-content brine. When specimens were put into contact with brine, their swelling was restricted by the building swell pressure in the oedometer. For the lower density specimens, the pressure reached a peak and then decayed to a residual value. At the end of each test, the specimens were sectioned to determine their actual moisture contents and moisture distributions.

The peak swelling pressures increased with density. The mean peak pressures for densities of 1,600 kg·m⁻³, 1,800 kg·m⁻³, and 2,100 kg·m⁻³ were 0.5 MPa, 1.1 MPa, and 6.5 MPa, respectively. The residual pressures also increased with density and had mean values of 0.15 MPa and 0.37 MPa for densities of 1,600 kg·m⁻³ and 1,800 kg·m⁻³. Tests at the highest density showed no decay of swell pressure. The most likely explanation for the decay of swell pressure in the lower density specimens is that the magnesium in the brine replaced sodium in the bentonite, reducing the swelling potential of the bentonite. This is a hypothesis and needs to be tested.

Permeability measurements were made on seven specimens having densities of 1,600 kg·m⁻³ and 1,800 kg·m⁻³. The constant hydraulic head, steady-state flow method was used, and saturated brine was used as the permeant. Including data from Pfeifle [1990], permeability changed approximately two orders of magnitude (from 1 × 10⁻¹⁵ m² to 1 × 10⁻¹⁷ m²) for changes in density from 1,600 kg·m⁻³ to 1,950 kg·m⁻³, respectively.

Moisture content and moisture distribution were measured in all specimens post-test. The water contents of all specimens were approximately equal to their theoretical moisture contents at saturation. Specimens with densities of 1,600 kg·m⁻³ and 1,800 kg·m⁻³ had higher moisture contents near the ends of the specimens, a distribution attributed to small differences in density produced during specimen preparation. Specimens with densities of 2,100 kg·m⁻³ showed high moisture contents at the brine inlet and low moisture contents at the brine outlet. The average moisture contents of these specimens, however, were at the saturation level. These data imply that for the high density specimens, the region close to the brine inlet was at a lower density than the specimen average. This could be an artifact of heterogeneity developed during specimen preparation, or the density of the region may have changed as brine moved into the specimen. If heterogeneity is significant, then
it remains to be determined what the effects of heterogeneities developed during backfill implacement would be.
7.0 REFERENCES


Pusch, R., 1980. Swelling Pressure of Highly Compacted Bentonite, 80-13, Division of Soil Mechanics, University of Luleå, Luleå.

APPENDIX A

FLOW DATA FOR PERMEABILITY TESTS
APPENDIX A
LIST OF FIGURES

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BRINE FLOW IN CRUSHED SALT/BENTONITE MIXTURES

Flow Rates:
- Run 1: 4.20 ml/s
- Run 2: 5.38 ml/s
- Run 3: 5.41 ml/s
- Run 4: 5.59 ml/s

Hydraulic Head = 371 mm

Figure A-1. Flow-versus-time for Test SWP012. Flow rates were established during four separate runs.
Figure A-2. Flow-versus-time for Test SWP013. Flow rates were established during four separate runs.
Figure A-3. Flow-versus-time for Test SWP014 at a hydraulic head of 152 mm.
Figure A-4. Flow-versus-time for Test SWP014. Flow rates were established for two runs at a hydraulic head of 305 mm.
Figure A-5. Flow-versus-time for Test SWP016. Flow rates were established for six runs conducted at two hydraulic heads. Runs are labeled in the order in which they were performed.
Figure A-6. Flow-versus-time for Test SWP017 at a hydraulic head of 152 mm.
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