

Assessment of preconsolidation to achieve high fractional densities

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Executive Summary

This report describes a study in which consolidation tests were conducted with a separate and distinct initial consolidation stage (i.e., preconsolidation). Preconsolidation is defined as application of elevated stresses and/or temperatures to achieve high fractional densities over relatively short times. In the context of consolidation testing, preconsolidation can be used to establish initial conditions for subsequent tests that are focused on investigation the behavior of granular salt in the relatively high fractional density range.

Procedures for an initial consolidation stage were developed and implemented. The initial consolidation involves rapid, unheated loading. Sample dimensions are measured before and after the initial consolidation; deformation is not monitored during this stage. Other changes to the test procedures included modest compaction of the sample during construction and applying the hydrostatic stress during both the initial consolidation and the subsequent creep consolidation strictly with confining fluid. The development of the methods and procedures for the initial consolidation stage improve the consolidation testing in that there is more confidence in the measured creep data and there is more control over sample loading.

With the initial consolidation stage, samples can be prepared with a fractional density in the range of 0.8 to nearly 0.9 using hydrostatic stresses between 20 and 38 MPa. The initial consolidation is consistent with a range of compacted in place densities, depending on the particular placement method. Thus, the initial consolidation stage serves as a reasonable method for preparing samples for subsequent consolidation testing to evaluate as placed granular salt.

Creep consolidation data was obtained for six samples that had an initial consolidation stage. These samples were consolidated at temperatures up to 175 °C, hydrostatic stresses of 20 to 38 MPa, and with and without added water. The samples were consolidated to fractional densities greater than 0.94, and the data and trends were consistent with previous expectations. Post-consolidation testing of porosity, thermal properties and permeability provide data sets that are being used to understand how consolidation affects thermal and hydrologic properties.

1. Introduction

Preconsolidation is defined as application of elevated stresses and/or temperatures to achieve high fractional densities over relatively short times. In the context of consolidation testing, preconsolidation can be used to establish initial conditions for subsequent tests that are focused on investigation the behavior of granular salt in the relatively high fractional density range.

Loose granular salt has a fractional density of less than 0.70. The important range for granular salt is generally considered to be at fractional densities greater than 0.90 because at the higher fractional densities, (1) the permeability decreases dramatically and (2) the salt offers more resistance to continued densification and plastic deformation mechanisms dominate. The deformation that occurs from a loose state to a fractional density of 0.90 is therefore of less interest.

Initiating a consolidation test at a greater initial fractional density is advantageous as a practical matter simply because there is less deformation to measure. The amount of deformation going from a fractional density 0.70 to nearly 1 is relatively large; this amount of deformation can be difficult to properly measure as it may exceed the range of a measurement technique (e.g., an LVDT). In addition, the deformation at the lower fractional density occurs rapidly as it is principally due to particle re-arrangement and cataclastic processes. The test and measurement system may have difficulty in monitoring and responding with this rapid deformation.

Preconsolidation is relevant to initial conditions achieved by field emplacement methods. Dynamic impact and brick-forming presses have been shown to achieve fractional densities on the order of 0.90 (e.g., Hansen and Ahrens, 1996). Preconsolidation in the laboratory may produce a resulting structure that is consistent with a construction technique such as dynamic compaction; in this case, the preconsolidated samples would be consistent with those expected for some construction techniques.

This report describes a study in which consolidation tests were conducted with a separate and distinct initial consolidation stage (i.e., preconsolidation). The principal objective of developing this testing approach is to improve data quality. In order to implement this testing approach, many changes and modifications were made to the consolidation testing procedures and conduct.

Results from consolidation tests and subsequent post-consolidation tests are provided to evaluate the effectiveness of the preconsolidation and how it may relate to field placed granular salt.

2. Methods and materials

2.1 Consolidation testing

The consolidation test procedures and conduct has been described in previous reports (Stormont et al., 2015). Here, we identify important changes and modifications that were made in order to obtain higher quality data.

A principal issue that arose in previous testing is that large volume strains are very difficult to monitor during a consolidation test. The previous sample preparation involved pouring the granular salt into the jacket without any compaction or densification; this resulted in an initial fractional density of less than 0.70. As the tests are intended to achieve fractional densities in excess of 0.95, the amount of deformation that had to be measured during consolidation was large. Further, some of the initial densification happens very quickly upon initial loading and was difficult to accurately monitor, especially if it occurred concurrent with initial heating of the sample.

Another issue was control of the axial load during the hydrostatic tests. The tests were conducted with independent confining pressure and axial loading. The axial load was applied through an axial piston, which had to continue to advance in response to sample consolidation. The control of the piston was via metering valves which were sometimes difficult and problematic to adjust. This lack of control could result in an overload of the sample (which deviated from hydrostatic conditions) or a loss of contact with the bottom of the sample. In the case of losing contact with the sample, the axial LVDTs (used to interpret volume strain) were no longer measuring sample deformation. However, it was not always obvious whether the loading piston was in contact with the sample.

With loose samples, there was a concern that settling during handling the sample prior to testing would result in segregation of particle sizes and the formation of a gap at the top of the jacketed sample. A gap would result very little resistance to deformation and would be difficult for the axial piston to keep up with. Further, this would result in ambiguity in data reduction and

interpretation as the initial sample dimensions are used to estimate fractional density during the test.

In order to reduce ambiguities in data from the above mentioned issues, we made the following changes in the hydrostatic stress consolidation tests:

- Samples were constructed at a greater initial fractional density by modest compaction during sample construction. The relative density of the sample was measured by fluid immersion after construction.
- Samples were pre-consolidated during an initial rapid, unheated loading stage to remove some of the deformation. The relative density of the sample was measured by fluid immersion after this pre-consolidation.
- Confining fluid was brought to temperature while vented under no confining pressure prior to applying the target stress level.
- Samples were hydrostatically loaded with the confining fluid only so that axial load did not have to be applied separately. The confining pressure was controlled by a programmable pump.
- At the conclusion of the test, the entire sample was weighed and its volume was measured with the fluid immersion method.

These modifications are described subsequently.

2.1.1 Sample preparation

The modified test method includes modest compaction of the granular salt as it is being emplaced in the jacket system. Samples are constructed with four lifts of salt, each receiving ten blows from a 1.54 kg hammer. Each blow is nominally 12 to 30 cm of fall with the 1.54 kg hammer. This compaction gives a sample with an average initial fractional density of 0.70.

All tests using an initial consolidation stage must be constructed with lead jackets. Viton cannot be used for tests that have to be removed from the test frame after pre-consolidation as it loses continuous contact with the sample (Figure 1). It appears advisable to use an inner lead sheet to prevent excessive deformation and tearing of the outer lead jacket.



Figure 1 - Viton jacket after initial consolidation showing how it wrinkled and lost complete contact with the sides of the granular salt sample.

A test of a blank lead jacket assembly revealed that the lead jacket readily deformed at ambient temperature under as little as 35 kPa. It is concluded that the lead provides no significant resistance to consolidation and can be used for all tests if desired.

A standard data collection sheet was created and refined over this period of testing. As the testing progressed more information was collected and recorded on the samples including multiple mass measurements at different stages of testing to ensure that the sample had not gained oil, multiple height and diameter measurements to allow for separate volume calculations, and the labeling of each component that is used (endcaps and chamfered disks) on multiple tests.

2.1.2 Fluid immersion volume measurement

A measurement system was developed for determining the volume of the sample using a fluid immersion technique. The volume of the jacketed samples were measured after preconsolidation (described subsequently) and after termination of the consolidation test. This data provides a measure of volume changes (and hence volume strain and fractional density and porosity changes) during the conduct of the test.

The fluid immersion vessel consists of a length of 15 cm diameter PVC pipe which acts as the reservoir to immerse sample components as well as fully assembled samples (Figure 2). A burette is plumbed into the bottom of the reservoir to allow for an accurate reading of the change in the height of the fluid. The system was calibrated by adding a small volume of water to the reservoir incrementally and recording the change of the reading on the burette. The resolution to the immersion vessel was determined to be 11.45 mL, which is between 1-2% of the final volume of the sample.



Figure 2 – Photograph of fluid immersion vessel.

2.1.3 Initial consolidation stage

The initial phase of the hydrostatic testing was performed to reduce the porosity or increase the fractional density of the sample prior to the hydrostatic creep test. The jacketed sample was suspended from the top of the frame, and did not contact the axial piston at all. The confining fluid was silicone oil. In subsequent testing not included in this study, nitrogen was used. The hydrostatic stress varied from 19 to 38 MPa. No deformation was measured during this stage, and the temperature was the ambient temperature (nominally 27 °C). The loading was accomplished in 5-10 minutes time, after which the sample was rapidly unloaded. The sample was removed from the test frame, and its volume was obtained by fluid immersion. An example of a sample shown before and after the initial consolidation stage is given in Figure 3.



Figure 3 - Sample UNM-WP-HY-175-03 before (left) and after (right) initial consolidation.

2.1.4 Hydrostatic creep test

The hydrostatic creep test was considered to start after the preconsolidation stage. The test sample was again suspended from the top of the frame, and did not contact the axial piston at all. In order to accomplish this and allow for optional gas flow testing during consolidation, a long nipple arrangement connected to the sample's bottom end piece was fabricated and used. The long nipple is 24 cm long and allows the sample to travel with deformation while still maintaining the seal at the bottom of the frame. Schuler gages were applied to the sample to measure lateral deformation during creep.

The confining fluid (silicone oil) was first brought to temperature while the pressure vessel was vented to avoid applying a stress to the sample during this step. Next, the vessel was shut-in and the confining pressure was increased to the target pressure by means of a pump. The volume of oil necessary to reach and maintain the confining pressure was recorded, along with the response of the Schuler gages along with the confining fluid temperature.

2.1.5 Data reduction

The data reduction has evolved to be consistent with the change in the test method and conduct. The principal parameter of interest is the sample's fractional density or porosity. The porosity and fractional density are related one-to-one as shown below:

$$\phi = 1 - \rho_f$$

where ϕ is the porosity and ρ_f is the fractional density of the specimen.

We determined the as-built sample fractional density from external measurements of the sample. The mass and volume of all non-salt components used to encase the specimen was determined prior to sample construction. After construction, the mass was measured and the height and width of the sample was measured. The net as-built fractional density was determined by subtracting the known contribution of the non-salt components to the mass and volume. After the initial consolidation stage, we determined the fractional density from the fluid immersion technique and in some cases from external measurements as well.

During consolidation, we tracked the fractional density or porosity from the volumetric deformation of the sample. Because the volume change of non-salt components was negligible, all volume changes were that of the salt specimen. Additionally, the deformation of granular (or intact) salt under a hydrostatic stress is isotropic, therefore the same deformation occurred in all three spatial dimensions. Based on these principles, the volumetric deformation was calculated from the measured radial deformation. Radial deformation was determined using a pair of Schüler gages on two orthogonal planes at the sample's mid-height. All volumetric deformation measured by the Schüler gages was attributed to changes in pore volume, and from this a change in pore volume along with the initial porosity, the porosity was determined throughout the test. Additionally, because the salt was consolidated under constant stress, no elastic deformation occurred once at the desired confining pressure (e.g., compressibility of the load frame, confining fluid, non-salt components, or salt). As the sample consolidated, its volume decreased and additional confining fluid was metered into the test frame to maintain the confining pressure. The volume of metered fluid was equivalent to the volume change of the sample at constant

pressure and therefore equivalent to the change in pore volume. Then, the volume of fluid needed to maintain a constant confining pressure equaled the change in pore volume, and from this a change in porosity was also calculated. This second method of porosity calculation provided quality assurance for the transient salt porosity measurement.

After the consolidation test, fluid immersion and external measurements were made on the sample to obtain estimates of fractional density of the entire sample.

With some tests, the interpreted fractional density history during the consolidation test was adjusted in order to be consistent with fractional densities found on the samples post-test. The adjustment was accomplished by small changes in sample dimensions and/or in the fluid compressibility.

2.2 Post-consolidation testing

After the consolidation test was completed, the consolidated salt was removed from the jacket assembly. Two discs, each approximately 25 mm thick, were cut from the top and bottom of the consolidated specimen using a diamond wire saw. The discs were used in the thermal properties testing and for microscopic observations. Subsequently, one of the discs was further cored to obtain 25.4 and 38.0 mm diameter sub-samples for porosity measurements. The center portion of the cores was used for permeability and porosity testing.

2.2.1 Porosity

Porosity was measured in a number of different ways. On the discs sliced from the ends of the consolidated samples, porosity was measured with a gas porosimeter. Porosity was also estimated from the mass and volume of these sub-samples using an assumed grain density of 2.16 g/cc. Point counting on thin-sections produced from the discs also produced porosity estimates. Porosity measurements were made on the center core portion of the core using a differential pressure permeameter. Essentially, the permeameter is used as a gas porosimeter. Porosity was estimated for the entire or bulk sample based on the deformation the sample experienced during consolidation. The deformation was determined two different ways: from

the strain interpreted during the consolidation testing, and from fluid immersion (volume) measurements made on the prepared samples before and after consolidation testing.

2.2.2 Thermal properties

Thermal properties measurements were made using the transient plane source method with a Hot Disk® TPS 1500. In this method, a heat pulse is applied with a thin plane sensor that is sandwiched between two pieces of the material of interest. Thermal properties are interpreted numerically from the dissipation of the heat pulse with a time. The thermal properties that are obtained are thermal conductivity, diffusivity, and specific heat.

2.2.3 Microstructural observations

Observational techniques were used on to gain insight into deformation mechanisms and resulting pore structure. The sub-samples were derived from the discs cut from the ends of the consolidated samples. A number of sub-samples were commercially vacuum impregnated with blue stained RF 1366 resin and thin sectioned, while others were vacuum impregnated manually with rhodamine-B doped Spurr Low-Viscosity resin and thin sectioned by a Buehler IsoMet saw. Fresh aggregate fragments were broken from sub-samples by hand to expose clean surfaces that exhibit sample cohesiveness, grain boundary characteristics, and other evidence of micro-processes. Observational devices include optical and scanning electron microscopes (SEM). A Leitz Ortholux II optical microscope equipped with a Leica camera and Leica Application Suite software was used to examine unetched/etched cleaved chips and thin sections, point count, and capture images. Three SEM's (JEOL 5800LV, FEI Nova 200 Nanolab, Tescan Vega3 LM) were used to view Au-Pd coated etched thin sections, etched cleavage chips, and freshly broken aggregate surfaces. Etching allows for heavily deformed grains under multiple mechanisms to be highlighted and is completed using a solution of methanol saturated with PbCl₂ as the etchant followed by transferring to butanol. Point counting on thin sections was done to manually determine the porosity of a sample by counting the number of void spaces and solid spaces in a grid-like pattern for a minimal of 300 counts. Finally, thin sections were scanned at 4800 dpi for processing in ImageJ software to contrast pore space and grains to be used in pore size distribution analysis.

2.2.4 Permeability measurements

Permeability measurements were made on the central portion of the consolidated core. The core sections were cast in a rubber membrane so they had a standard diameter of 10 cm. The core length varied from 6 to 8 cm. Porous metal discs were placed on the ends, and the cores were jacketed with a Viton sleeve and steel end pieces. The jacketed sample was placed in a pressure vessel which applied a hydrostatic stress to the sample up to 0.7 MPa using nitrogen. The ends of the jacketed sample were connected to a differential pressure gas permeameter. This permeameter can control the pressure on the upstream and downstream side of the sample. High-resolution absolute and differential pressure transducers and thermocouples are connected to a data acquisition system. Because the upstream and downstream volumes of the permeameter are small and precisely known, the permeameter serves as a porosimeter. Steady-state and transient permeability tests can be conducted, covering the range from approximately 10^{-14} to 10^{-20} m^2 .

3. Results

3.1 Consolidation tests

Ten tests focused on hydrostatic consolidation were conducted using the improved test methods described in Section 2.1. Test conditions are described in Table 1. Six of ten tests were completed with the initial consolidation stage and the subsequent hydrostatic consolidation (creep) stages. Four of the tests failed during the initial consolidation testing; most of these failures were jacket failures.

Table 1 – Summary of hydrostatic consolidation tests.

Sample label	Salt type	Temp	Stress conditions	Moisture added	Frame	Dates (2015)	Comments
UNM-WP-HY-175-01	WIPP	175	Hydrostatic 20 MPa	No	A2	6/17 - 6/19	Possible jacket leak
UNM-WP-HY-90-03	WIPP	90	Hydrostatic 20 MPa	1%	A3	6/25 – 6/26	Jacket failure during ic
UNM-WP-HY-90-04	WIPP	90	Hydrostatic 20 MPa	1%	A3	7/02 - 7/07	
UNM-WP-HY-175-02	WIPP	175	Hydrostatic 20 MPa	No	A2	6/26 – 7/8	Failed after ic
UNM-WP-HY-90-05	WIPP	90	Hydrostatic 20 MPa	1%	A3	7/16	Jacket failure during ic
UNM-WP-HY-175-03	WIPP	175	Hydrostatic 20 MPa	1%	A2	7/15-7/17	Possible jacket leak
UNM-WP-90-06	WIPP	90	Hydrostatic 20 MPa	1%	A2	7/23	Jacket failure during ic
UNM-WP-HY-90-07	WIPP	90	Hydrostatic 20 MPa	1%	A3	7/24 – 8/17	
UNM-WP-175-04	WIPP	175	Hydrostatic 20 MPa	No	A3	7/24 – 8/31	
UNM-WP-HY-90-08	WIPP	90	Hydrostatic 40 MPa	No	A3	7/29 – 8/7	

3.1.1 Initial preconsolidation

Table 2 summarizes the fractional densities of the as-built samples and after initial consolidation. Missing data from this table are largely because systematic procedures for obtaining external measurements were implemented after a number of tests had already been conducted.

Table 2 – As-built and post initial consolidation fractional densities. An X indicates these data are not available.

		Initial consolidation stage		
Sample label	As Built - External measurements	Pressure (MPa)	Fractional density	
			Fluid immersion	External measurements
UNM-WP-HY-175-01	X	20	0.72*	X
UNM-WP-HY-90-03	X	20	0.87	X
UNM-WP-HY-90-04	0.66	19.4	0.78	X
UNM-WP-HY-175-02	0.65	20	0.66	X
UNM-WP-HY-90-05	0.76	19.9	X	X
UNM-WP-HY-175-03	0.72	20	0.8	0.82
UNM-WP-90-06	0.70	20	0.79	X
UNM-WP-HY-90-07	0.72	20	0.85	0.87
UNM-WP-175-04	0.75	20	0.82	0.88
UNM-WP-HY-90-08	0.62	38.3	0.87	0.88

* = Value is believed to be low due to measurement error based on initial sample volume required to obtain a final fractional density consistent with post-test measurements.

The average as-built density was 0.70 based on the measured geometry and mass of the constructed sample (assuming a specific gravity of 2.16). While greater densities were possible, excessive compaction in the jacket was deemed detrimental to the jacket integrity.

The initial consolidation stage produced an average fractional density of about 0.80 for a 20 MPa hydrostatic stress. This average excludes samples that failed during the initial consolidation stage. For the single test where the sample was subjected to 38 MPa during the initial consolidation stage, the fractional density reached 0.87.

3.1.2 Hydrostatic creep test

Fractional density data from the subsequent hydrostatic creep consolidation tests are given in Figures 4 through 11. A summary of the data used to interpret fractional density are given in Table 3. Lateral strain from the Schuler gages was the preferred data set but was not available in every test due to malfunction or exceeding its range. The initial volume used in calculating the fractional density was based on the fluid immersion measurements; adjustments in this value were necessary in some tests to produce a better match between the fractional density and the post-test average porosity. The adjustments to the initial volume for 90_07 and 90_08 were within the expected accuracy of the method whereas the initial volume adjustments for 90_04 and 175_01 were larger and were believed to be attributable to measurement error. The volume changes the confining fluid experienced during the loading and temperature changes was corrected by a temperature-dependent fluid compressibility, this value was adjusted to better match final average porosities and the lateral strain data in a few tests.

Table 3 – Summary of data used to estimate fractional density from creep consolidation tests.

Sample	Volume strain interpreted from	Post-test adjustment of fractional density
90_04	Lateral strain and confining fluid volume (they coincide).	Initial sample volume and fluid compressibility offset.
90_07	Lateral strain for first day and confining fluid after day 4.	Initial sample volume and fluid compressibility offset.
90_08	Lateral strain.	Initial sample volume.
175_01	Confining fluid volume.	Initial sample volume.
175_03	Lateral strain.	None
175_04	Confining fluid volume.	None

Data from the three tests at 90 °C are given together in Figure 4 and individually in Figures 5, 6 and 7. The effect of the hydrostatic stress is evident; sample 90_08 was consolidated at 38 MPa whereas the other two samples were consolidated at 20 MPa. For the test on sample 90_07

(Figure 7), the Schuler gages were lost after about 1 day. The confining fluid was subsequently used to measure volumetric deformation beginning on day 4 through the end of this test.

Data from the three tests at 175 C are given together in Figure 8 and individually in Figures 9, 10 and 11. The drop in the fractional density at about day for sample 175_03 is believed to be an electrical issue with the Schuler gages during this time period. The fractional density for sample 175_04 is derived from the fluid volume change; the fluctuations in this response were due to temperature variations caused by intermittent heater performance.

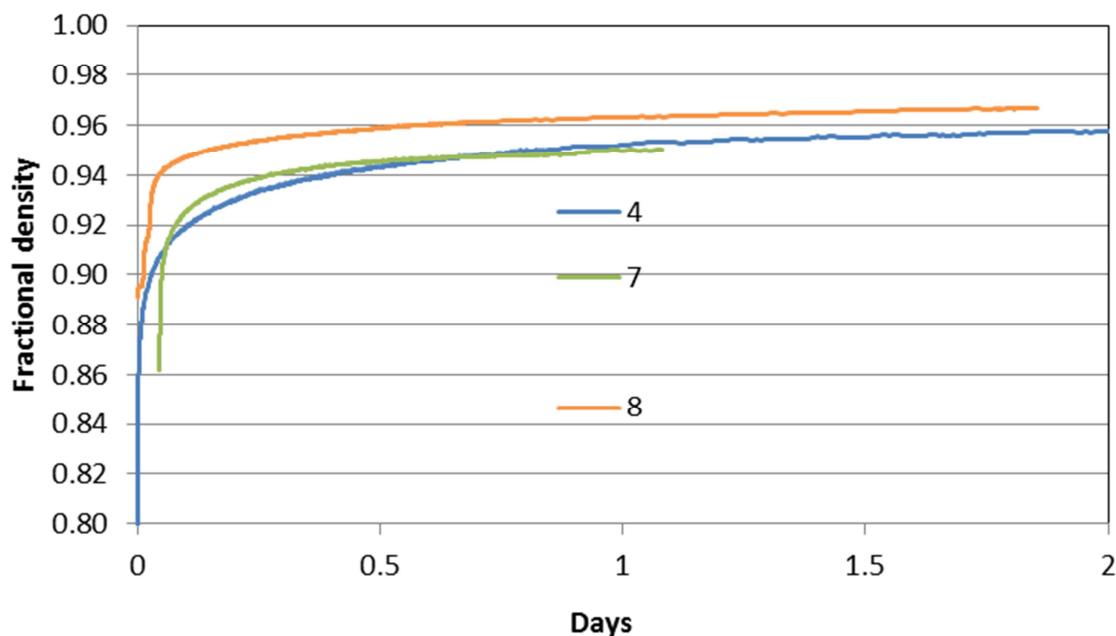


Figure 4 – Creep consolidation data for tests conducted at 90 °C for 2 days.

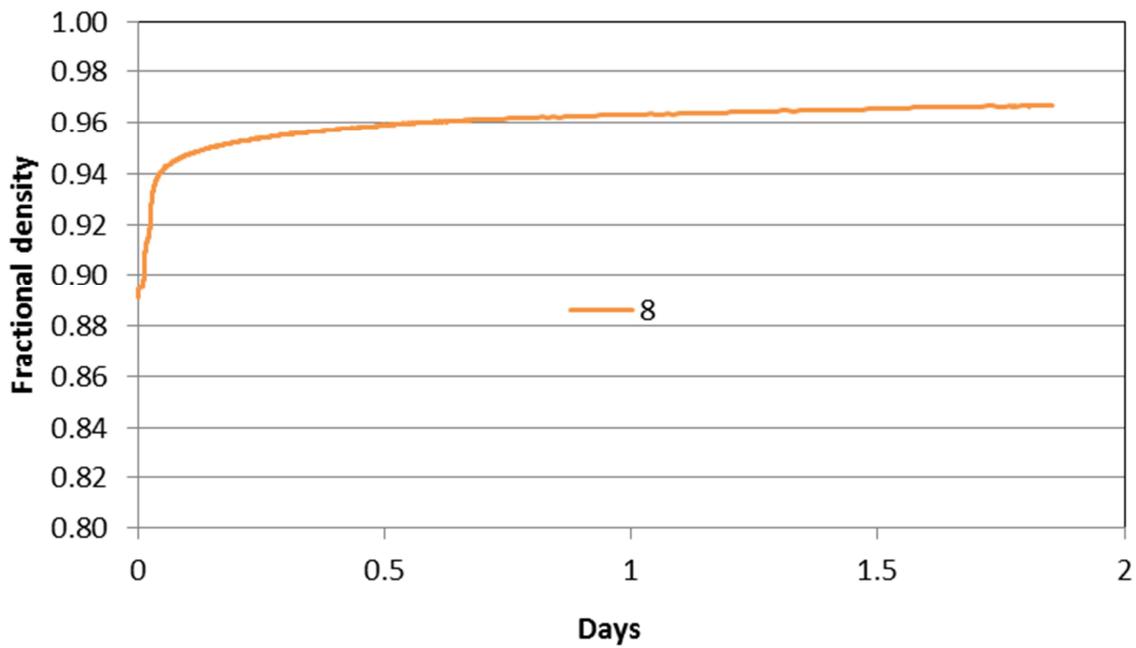


Figure 5 – Creep consolidation data for UNM_WP_HY_90_08.

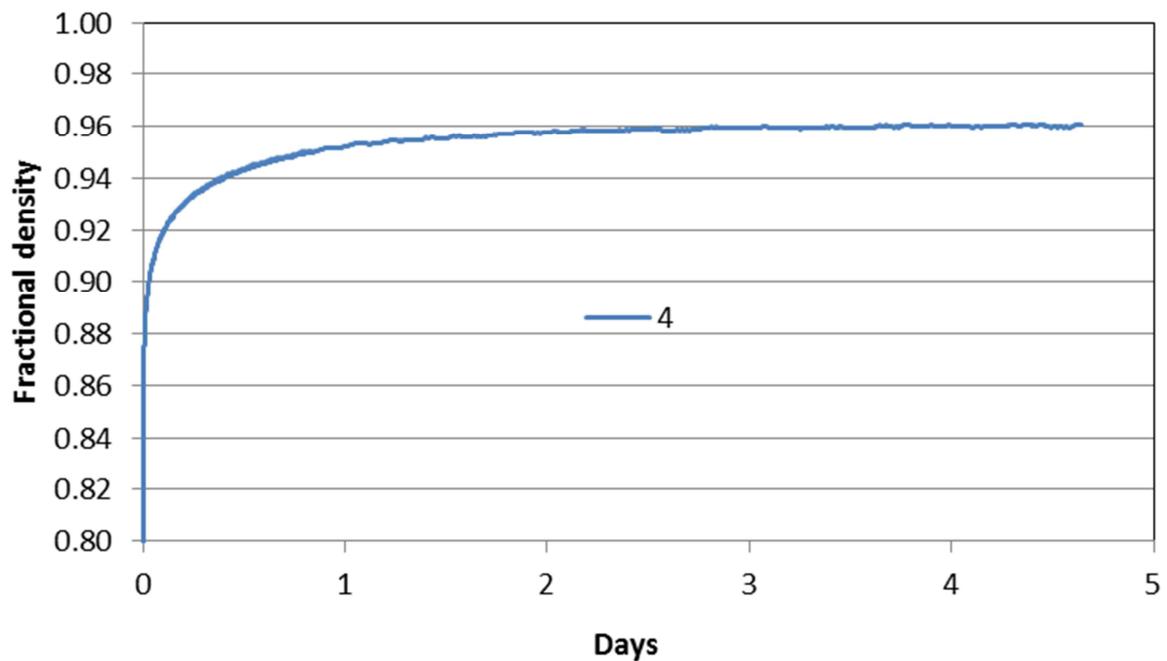


Figure 6 – Creep consolidation data for UNM_WP_HY_90_04.

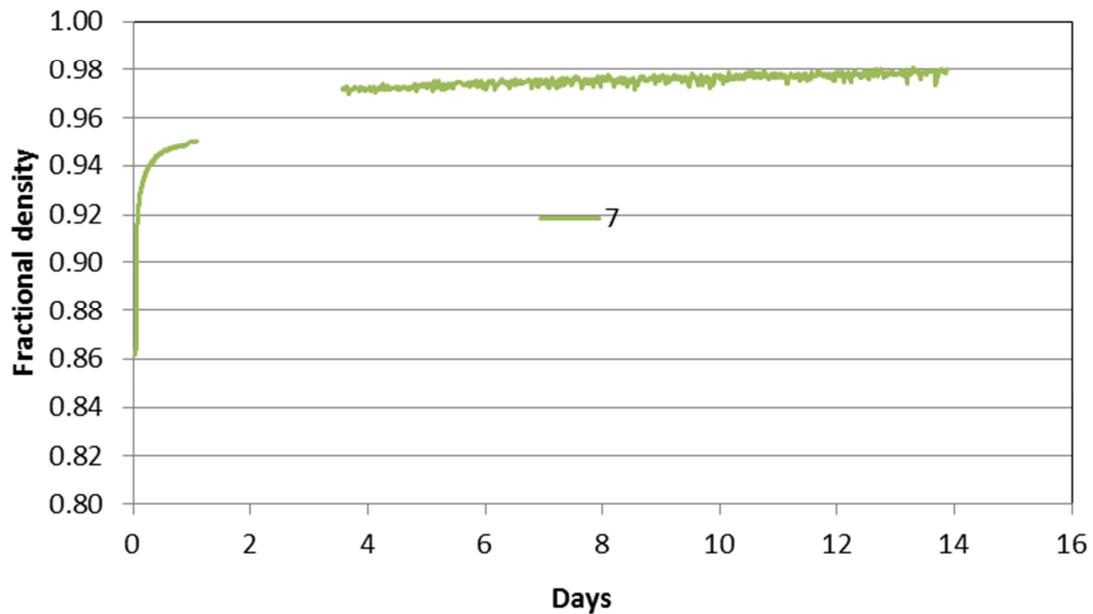


Figure 7 – Creep consolidation data for UNM_WP_HY_90_07.

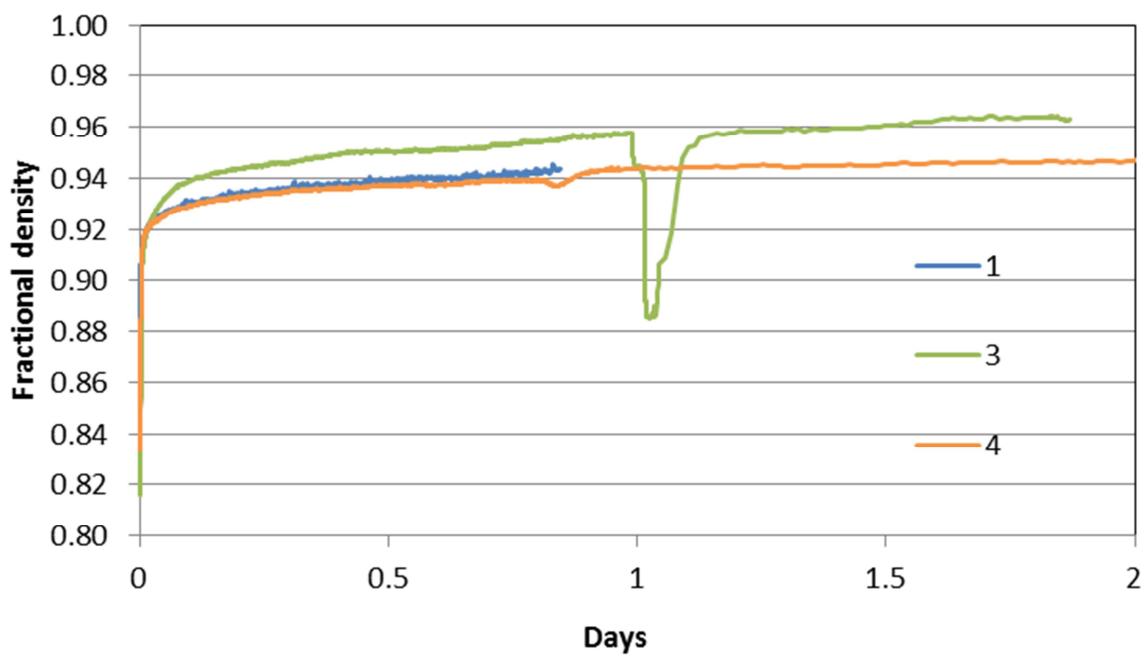


Figure 8 – Creep consolidation data for tests conducted at 175 °C.

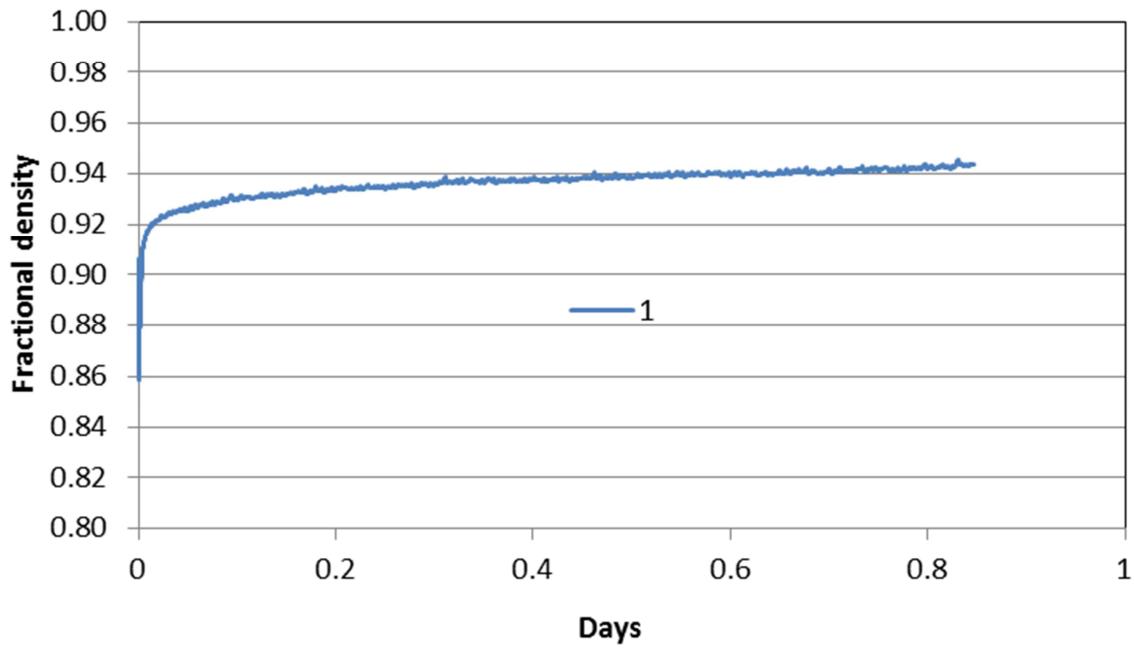
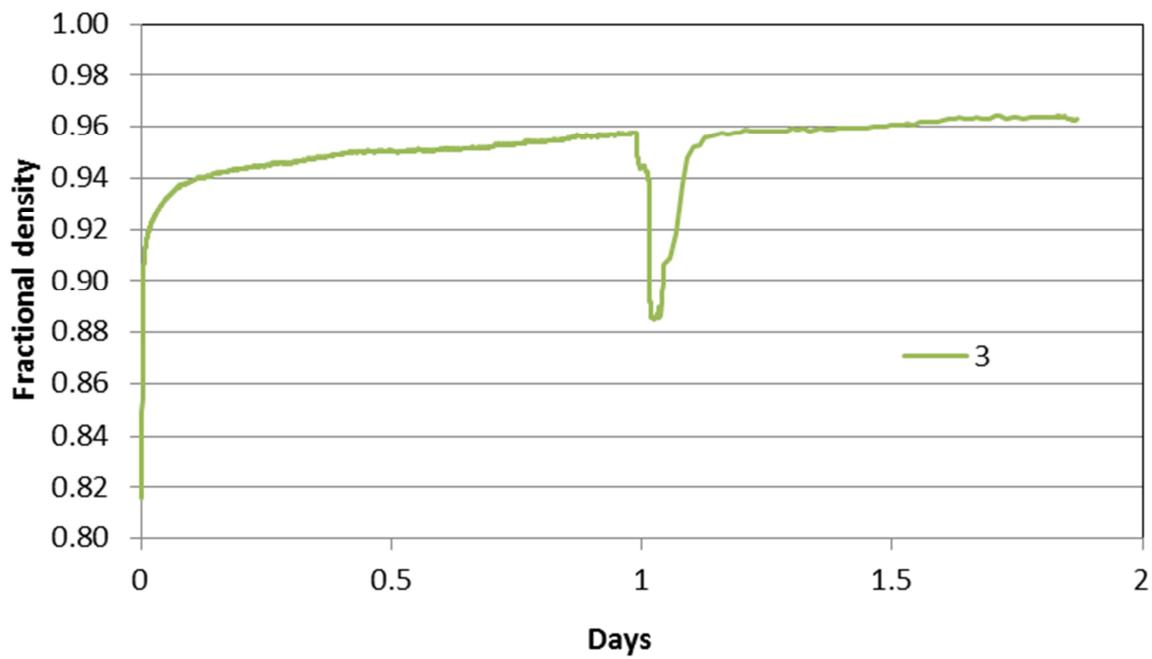


Figure 9 – Creep consolidation data for UNM_WP_HY_175_01



. Figure 10 – Creep consolidation data for UNM_WP_HY_175_03

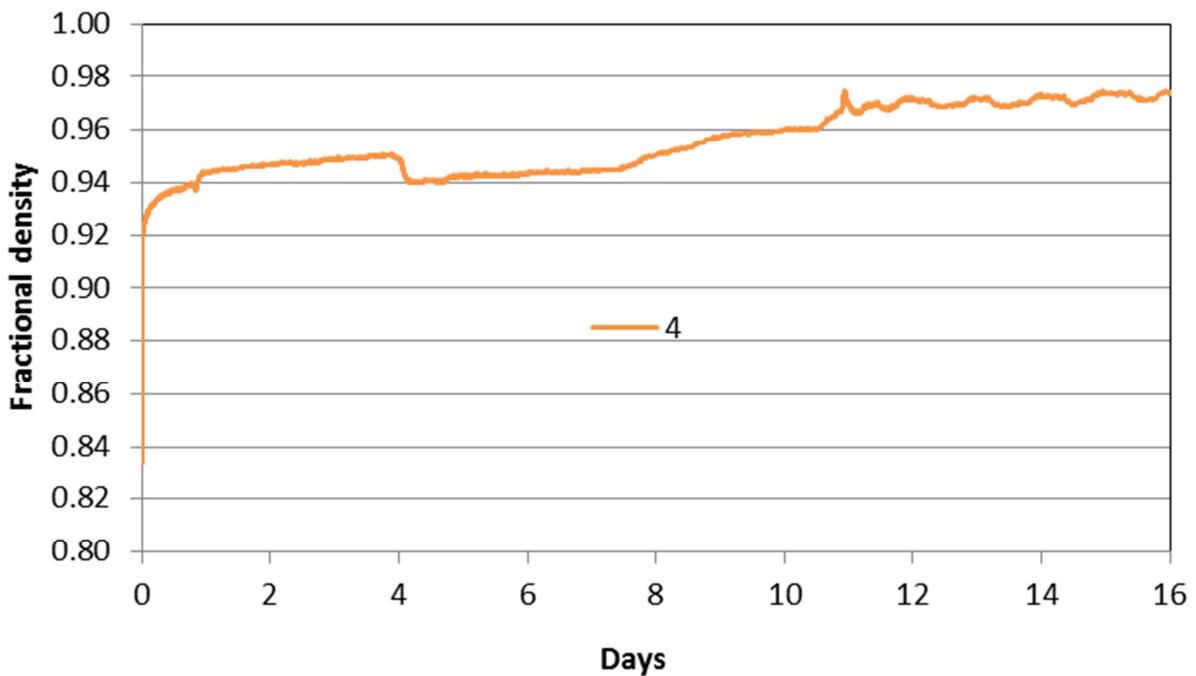


Figure 11 – Creep consolidation data for UNM_WP_HY_175_04

3.2. Post-consolidation testing

Results from post-consolidation tests are given in the following sections. These data include samples included in this study as well as data from samples tested prior to the changes in test procedures described in this report.

3.2.1 Porosity

Porosity data are compiled in Figure 12 below. In general, there is good agreement between the methods used to determine porosity on the discs cut from the sample ends. The central core has a somewhat smaller porosity. This result is consistent with the observation that most samples appeared to have a slightly hourglass shape after creep consolidation. The water displacement values are much higher than other, more direct methods for estimating porosity. This discrepancy is the subject of continued investigation.

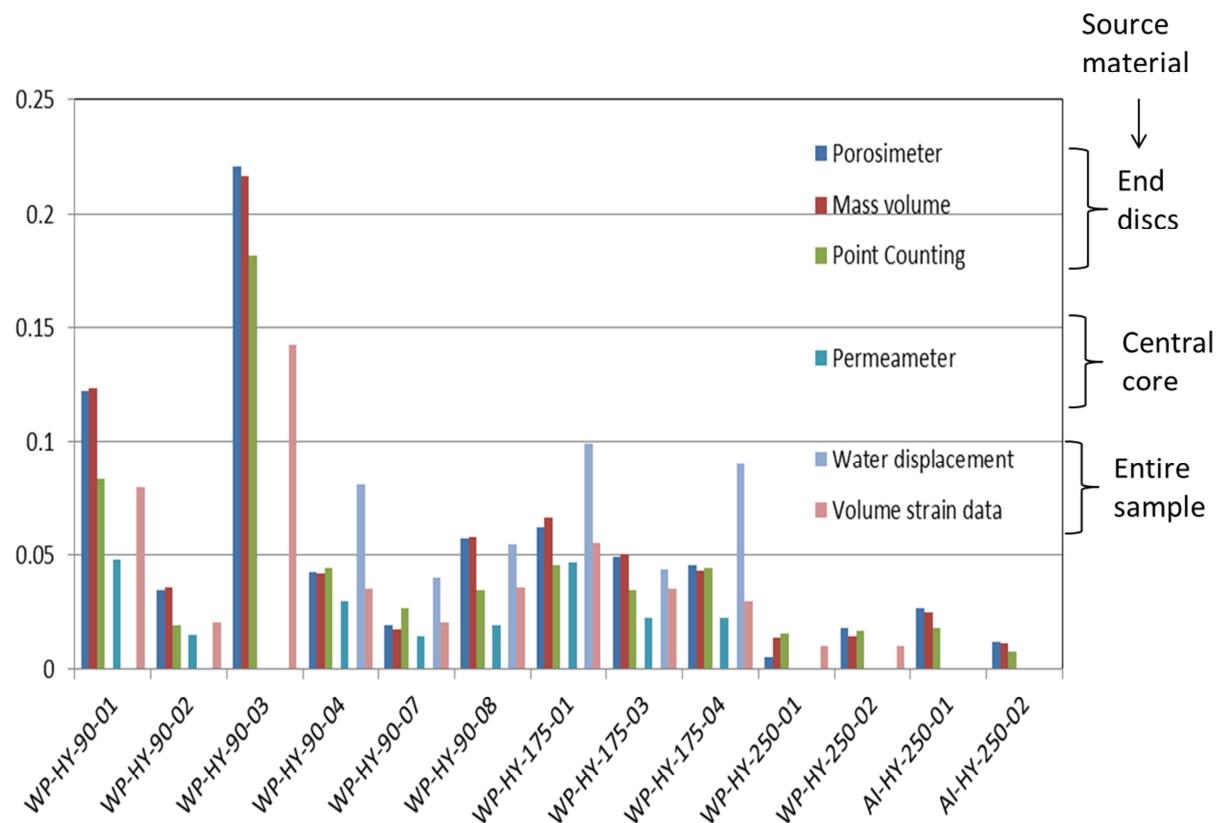


Figure 12 – Compilation of porosity measurements for consolidation samples. Volume strain data for samples WP_HY_90_08, WP_HY_90_04, WP_HY_90_07 and WP_HY_175_01 were adjusted to better match average porosity measured on the post-consolidation sub-samples.

3.2.2 Thermal properties

The thermal conductivity vs. porosity is shown in Figure 13. The thermal conductivity is normalized by dividing it by the thermal conductivity of an intact salt crystal at the test temperature. These data are well fit by an exponential function.

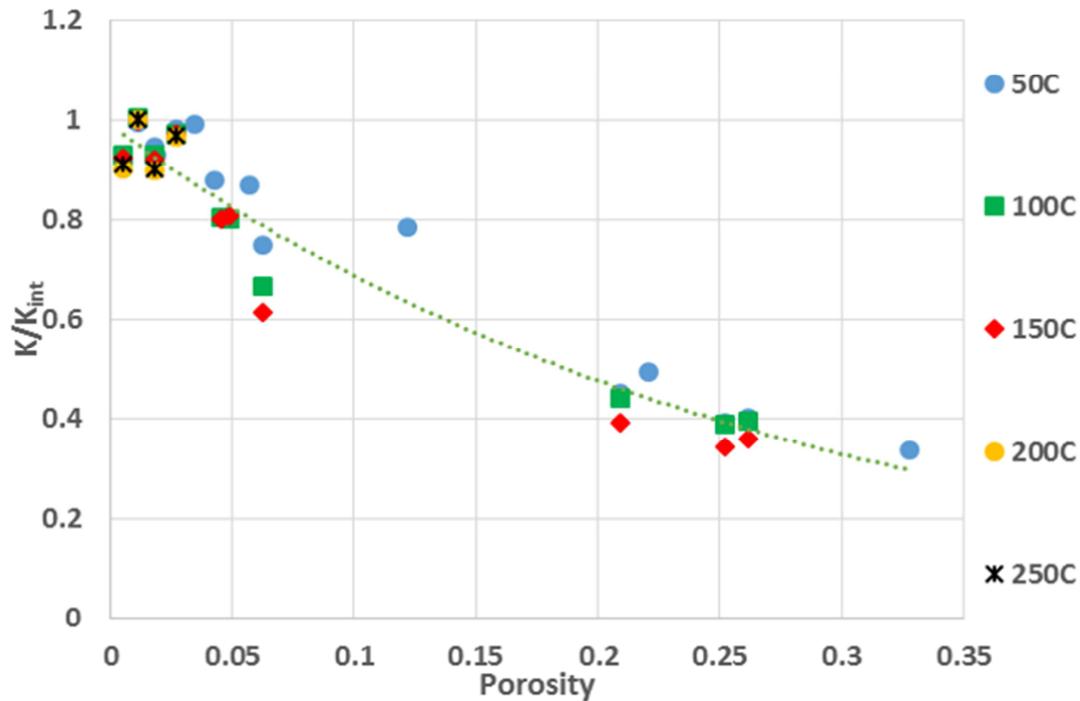


Figure 13 – Normalized thermal conductivity vs. porosity on consolidated salt samples. The dashed line is an exponential fit to the data.

3.2.3 Permeability

Permeability and porosity data obtained on post-consolidated samples is given in Figure 14. A trend of decreasing permeability with decreasing porosity is evident. These data indicate the dramatic reduction in permeability experienced by granular salt during consolidation may occur at a porosity of 2% or less. Keller et. al. (2015) suggest critical porosities of about 5% will result in the pore network becoming disconnected along with a permeability decrease. However, tests concurrent with consolidation indicate the porosity at which the permeability

decrease is accelerated may be nearer 2% (Stormont et. al, 2015). Bechthold et al. (2004) report a reconsolidated slurry sample recovered from an operational mine had a permeability of 10^{-17} m² with a porosity of 1.4% - this is consistent with the data reported here.

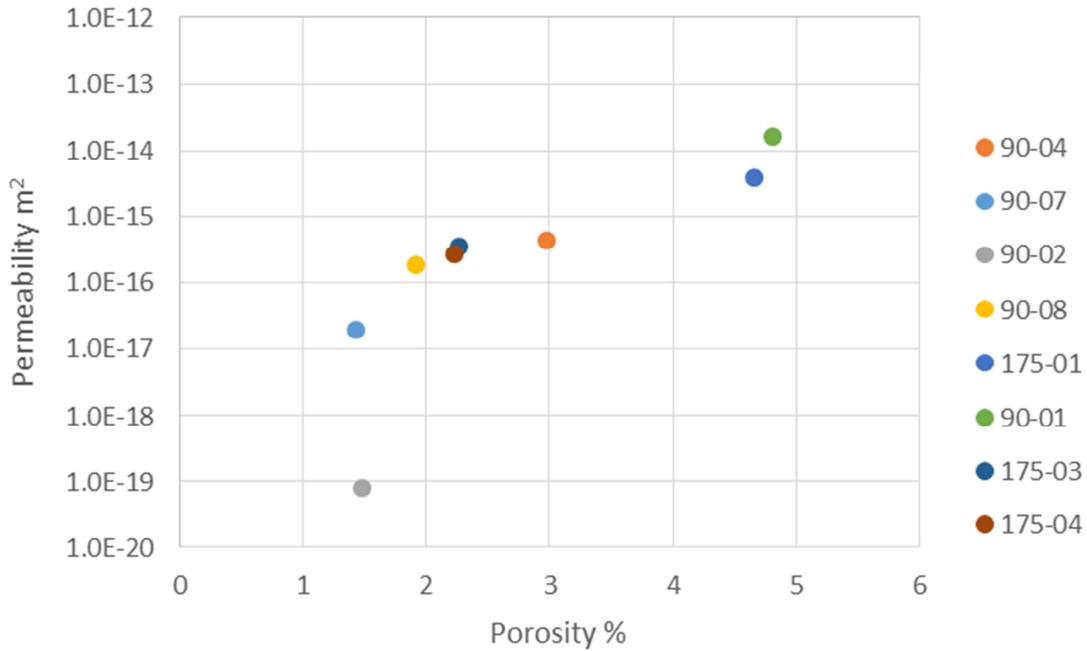


Figure 14 – Permeability vs. porosity measured on post-consolidated samples.

3.2.4 Microstructural observations

The most striking and important conclusion from microstructural observations of consolidated granular salt using SEM and other techniques is that samples consolidated with added water were different than those consolidated without water. The samples without added water had more mechanically ground or abraded surfaces; in contrast, the samples with added water had many more cleaved surfaces, plasticity, and indications of pressure solution processes. The cleaved surfaces indicate that when broken, the grain boundaries were more fused or healed together, and they broke through the grain instead. An example of post-consolidation microphotographs on sample with and without water is given in Figure 15.

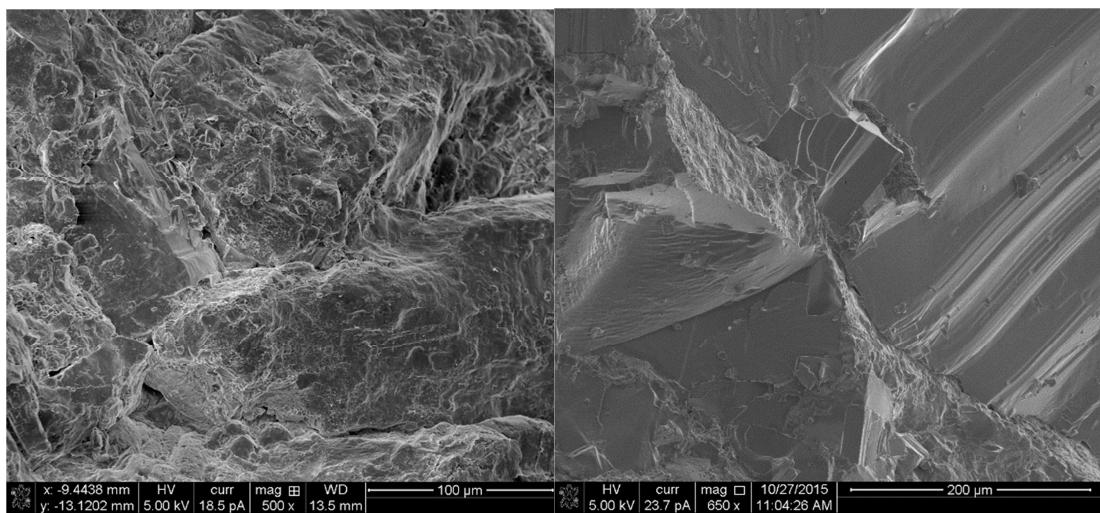


Figure 15 - SEM images of 90-01 (left, no added water) and 90-07 (right, 1% added water).

4. Discussion

The initial consolidation stage achieves an initial fractional density of about 0.8 with 20 MPa and 0.87 with a hydrostatic stress of 38 MPa. Thus, the amount of deformation that occurs during the subsequent creep consolidation testing is significantly reduced which improves the test conduct and data quality. The deformation that occurs during the initial consolidation stage is not of particular interest to the use of granular salt as a backfill material and is not relevant to the evaluation of constitutive models for consolidation.

The initial consolidation is consistent with a range of compacted in place densities, depending on the particular placement method. Thus, the initial consolidation stage serves as a reasonable method for preparing samples for subsequent consolidation testing to evaluate as placed granular salt.

Due to the critical role of water in consolidation, we emphasize that samples should be prepared with the same amount of water (if any) as is planned for the field emplacement. We can contrast the properties of a preconsolidated wet sample with that of a dry placed sample recovered from a mine after many years. Sample WP_HY_90_03 was prepared with 1% moisture and preconsolidated, but not subsequently consolidated further due to a jacket leak. This sample had a porosity of 22% and a thermal conductivity of 2.70 W/mK. A sample recovered from the Bambus experiment (Hansen, 2016), where the salt was emplaced dry, had a comparable porosity (23%) but a significantly lower thermal conductivity (2.28 W/mK). This result is believed to be a consequence of the condition of the grain boundaries: when water is added, the grain boundaries are tightly sutured together due to pressure solution mechanisms. In contrast, in dry samples the grain boundaries may be tight but they remain a discrete discontinuity. Similar contrasts in thermal properties are seen between samples recovered from our consolidation tests with those that were statically pressed to relatively high densities (Bauer and Urquhart, 2015). This response is consistent with the microstructural observations made on specimens compacted with and without water (Figure 15).

In Figure 16, the fractional density vs. time during consolidation tests at 90 °C and 20 MPa are given. All three samples were prepared with 1% additional moisture. One of these tests (90-02) was conducted with the previous test procedures which did not include a separate

preconsolidation stage. The results are compared to tests 90-04 and 90-07 which both used an initial preconsolidation stage. Results from 02 and 07 compare very well. Results from 02 and 04 compare less well, but these tests of are of much different duration.

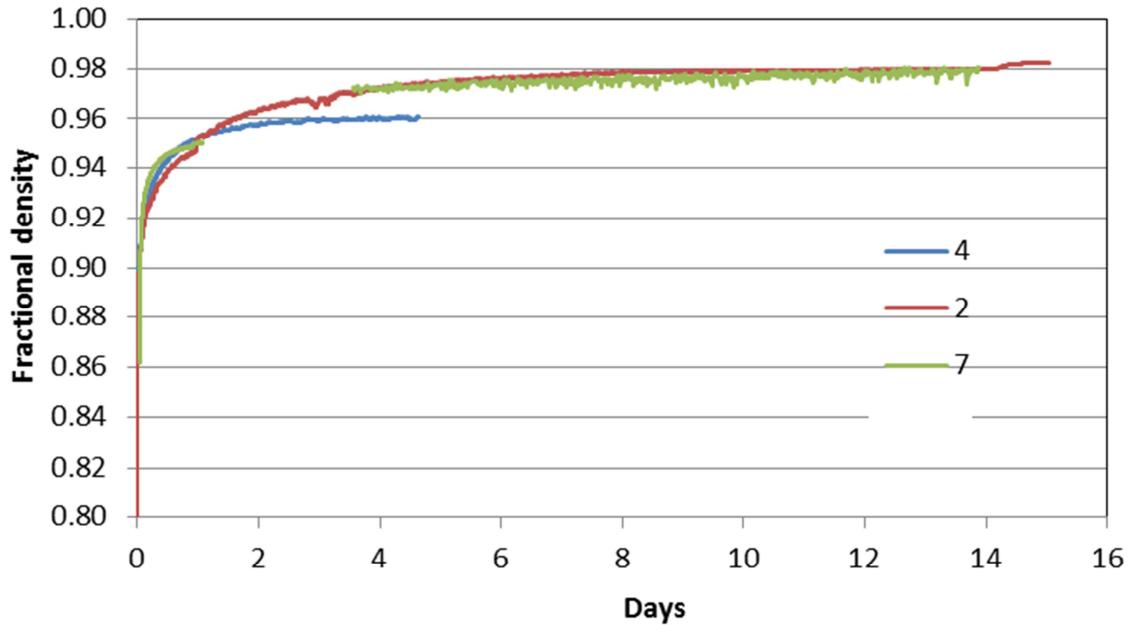


Figure 16 – Comparison of consolidation data from tests with an initial consolidation stage (4, 7) and without (2). These tests were conducted at 90 °C and 20 MPa. All samples had 1% added moisture.

Table 4 compares thermal and transport properties for these three samples. While 90_07 and 90_02 had very similar porosities, their permeability values are different by more than two orders of magnitude. Thermal conductivity values are slightly lower for 90_02.

Table 4 – Comparison of post-consolidation properties from three samples consolidated at 90°C and 20 MPa with 1 % water.

Sample	Porosity (%)	Permeability (m^2)	Thermal conductivity (W/mK)
90_02	1.49	8×10^{-20}	4.78
90_04	1.44	2×10^{-17}	5.09
90_07	2.98	5×10^{-16}	4.81

Subsequent image analysis revealed that 90_02 had some limited residual canals/pores presumably from moisture within the sample (Figure 17). Similar structures were not found in 90_04 or 90_07.

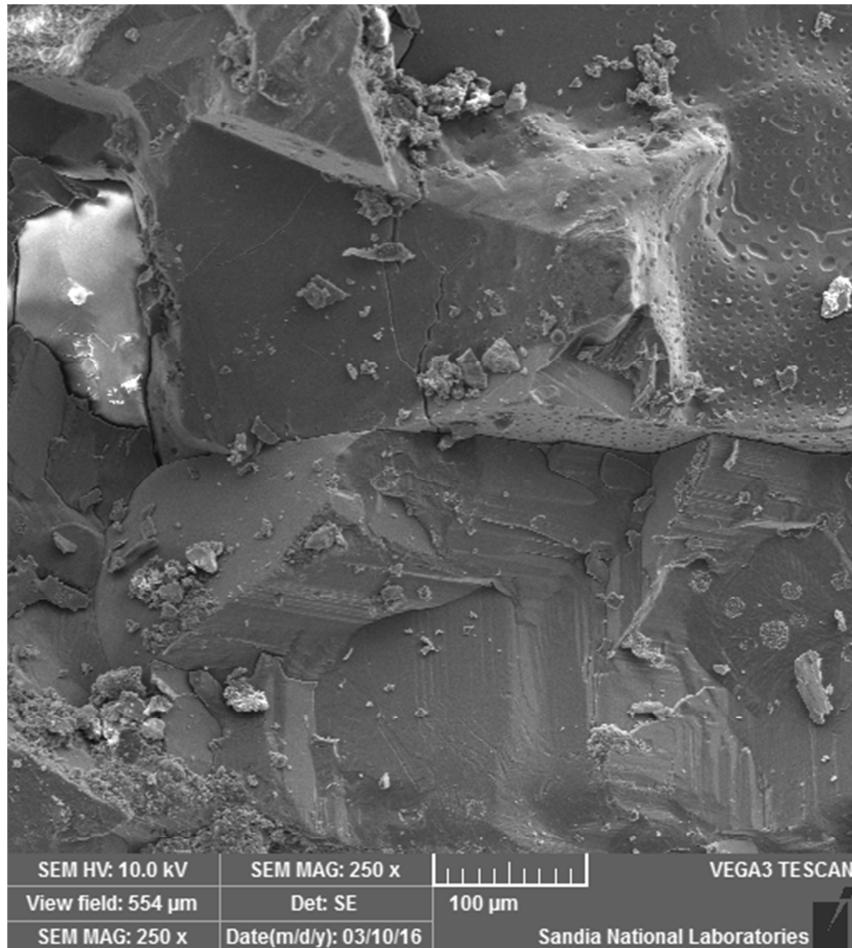


Figure 17 – Image of 90_02 showing residual moisture canals/pores (right hand side of image).

The investigation has revealed some differences in measured and observed response of samples consolidated with an initial consolidation stage compared to a single sample consolidated without such a stage. Any differences are most likely principally attributable to the variation in these samples, and not necessarily related to the consolidation test procedures.

5. Summary and conclusions

A number of changes were made in the consolidation test procedure with the goal of producing better quality data. In particular, an initial consolidation (or preconsolidation) stage was developed to prepare samples for subsequent creep consolidation testing. This initial consolidation stage involves rapid, unheated loading. Other changes included modest compaction of the sample during construction and applying the hydrostatic stress strictly with confining fluid. The development of the methods and procedures for the initial consolidation stage improve the consolidation testing in that there is more confidence in the measured creep data and there is more control over sample loading.

With the initial consolidation stage, samples can be prepared with a fractional density in the range of 0.8 to nearly 0.9 using hydrostatic stresses between 20 and 38 MPa. The initial consolidation is consistent with a range of compacted in place densities, depending on the particular placement method. Thus, the initial consolidation stage serves as a reasonable method for preparing samples for subsequent consolidation testing to evaluate as placed granular salt.

Creep consolidation data were obtained for six samples that had an initial consolidation stage and then were subsequently consolidated under hydrostatic stress and elevated temperature. All but one test was conducted with 20 MPa hydrostatic stress, the exception was tested at 38 MPa and 90 °C, and did not have water added. The remaining samples tested at 90 °C had water added; the samples tested at 175 °C did not have water added. The data produced from these tests is consistent with expected behavior, and results in final porosities generally below 5%. Post-consolidation testing of porosity, thermal properties and permeability provide data sets that reveal the degree to which consolidation affects thermal and hydrologic properties.

The measured response during subsequent creep consolidation test was compared for samples with and without an initial consolidation stage. While there were some differences between these samples, the data is very limited and the source of these differences is not obvious.

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