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Salt Reconsolidation Applied to Repository Seals

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ABSTRACT: An excellent scientific understanding of salt reconsolidation mechanisms has been established from experimental results and observational microscopy. Thermal, mechanical, and fluid transport properties of reconsolidating granular salt are fundamental to design, analysis and performance assessment of potential salt repositories for heat-generating nuclear waste. Application of acquired knowledge to construction techniques could potentially achieve high-performance seal properties upon construction or during the repository operational period, which lessens reliance on modeling to argue for evolving engineering characteristics and attainment of sealing functions at some future time. The robust database could be augmented by select reconsolidation experiments with admixtures and analogue studies with appropriate documentation of microprocesses.

1 INTRODUCTION

Reconsolidation of granular salt has long been recognized as a fundamental element of seal systems and backfilling of salt repositories. In addition to mechanical and thermal properties, the most essential phenomena pertain to permeability as a function of porosity. The fact that disaggregated salt can be reconstituted to characteristics nearly equivalent to native salt has been widely demonstrated. However, for repository applications, the overriding concerns are how soon under variable conditions does reconsolidating salt attain desirable performance characteristics. This paper summarizes the abundant information on this topic, from first principles to full-scale applications and analogues.

Material in this document generally progresses from small to large scale. The physical and mechanical processes of reconsolidation at the micro-scale have been studied to an impressive level of understanding and documentation. Initial portions of this review describe mechanisms of reconsolidation from high void fractions to low porosity. The consolidation region of most interest pertains to the reduction of permeability as connected porosity is eliminated.

Salt reconsolidation mechanics have been investigated by means of several experimental procedures over time, with increasing sophistication and test parameter control. Improvements in laboratory techniques as well as test-to-test comparisons have enabled a more complete analysis of test data and understanding of the consolidation processes than possible from earlier work. Interpretation of the effects of temperature, stress, moisture and test techniques are vital to repository-relevant application of laboratory results. The all-important regimes of low strain rates and low stress magnitudes have now been explored in numerous lab experiments. It is clear from these studies that presence of small amounts of moisture greatly facilitates the consolidation process.

The applications emphasized here pertain to seal systems and backfill within salt repositories for nuclear waste, which embody large-scale construction and long-term performance. Analogues provide useful long-term, full-scale anecdotal information, which confirm reconstitution of granular salt or slurry to mechanically viable solids that can attain characteristics of low porosity and low permeability. In repository applications, understanding and quantifying attainment of performance specifications are essential to demonstrate regulatory compliance. Additives such as moisture and clay improve placement properties of engineered structures and can ensure both early and long-term performance.

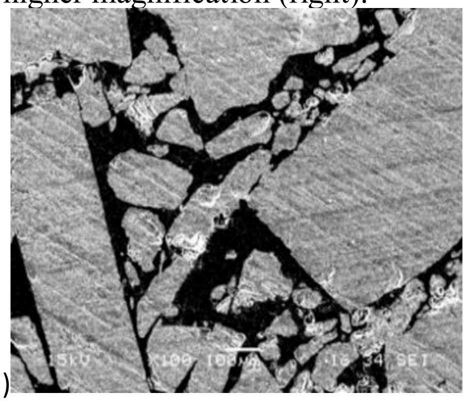
Crushed or granular salt reconsolidation will play an important role if a salt formation is selected for permanent isolation of nuclear waste. In the salt disposal concept, crushed salt is naturally the most suitable backfill material. Crushed salt is readily compacted and reconsolidated. Through appropriated construction techniques, granular salt can be placed in a condition favorable to evolving thermal, mechanical and hydrological properties approaching those of the undisturbed surrounding rock salt. Reuse of mined salt in the underground facility provides operational efficiency, reduces hoisting and optimizes material transport. Depending on the closure concept of the respective repository the main functions of reconsolidating salt as backfill and seals are

- to act as a long-term barrier against inflowing brine or water
- to eliminate release pathways via drifts and shafts
- to conduct heat generated from the waste to the host rock
- to stabilize the repository excavations
- to provide low permeability and/or diffusivity and/or long-term retardation

The remainder of this report provides technical information pertaining to these functions.

2 MICROMECHANICS

Compaction and consolidation of granular salt result from several processes. In a disaggregated state, granular material comprises about 35% porosity. Upon application of pressure, densification from the initial state proceeds by translational sliding, grain fracturing, pulverization, and mechanical compaction. Brittle processes usually accompany construction practices, such as dynamic compaction. For purposes of salt repository applications and related industrial functions, micromechanical mechanisms during late stages of consolidation are the most relevant. Identification and documentation of these processes are inferred from optical and scanning electron microstructural observations. As porosity is eliminated, grain-to-grain interference gives rise to plastic distortion and grain-boundary processes. Individual salt grains can deform by glide on crystallographic planes, which promotes ductile deformation into void space. As will be shown throughout this paper, local contact stresses induce pressure solution, solution transfer, and precipitation. Photomicrographs in Figure 1 are examples of field-scale and laboratory samples that illustrate progression of consolidation processes from high porosity to low porosity. Figure 1a) is taken from the BAMBUS II field test (discussed later) and depicts brittle cleavage fracture and translational sliding at 25% porosity. Figure 1b) is a sample from a room that was back-filled with salt slurry. The cubic habit exemplifies brittle cleavage fracture; fine particles result from pulverization along grain boundaries; well meshed grain boundaries are achieved through pressure solution. Figure 1c) is taken from laboratory sample that was consolidated at 250˚C and exemplifies well sutured grain boundaries in the larger view (left) and extensive plastic deformation of individual grains at higher magnification (right).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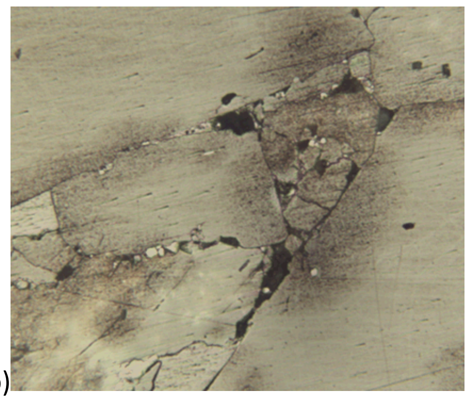
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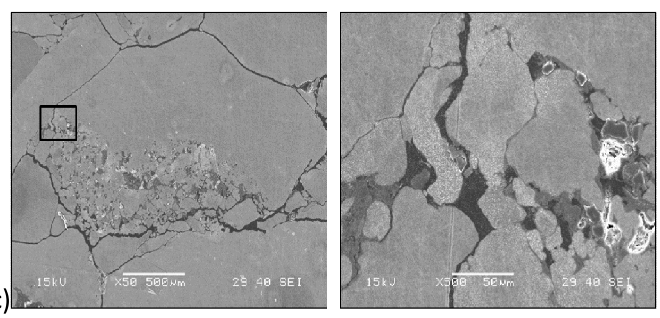
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Figures 1a, b, and c. Examples of consolidation mechanisms from high to low porosity

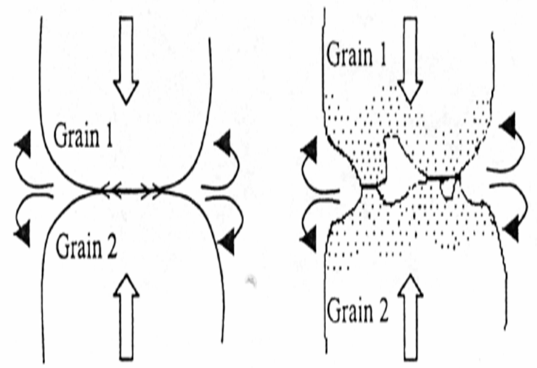
2.1 *Moisture Effects*

Salt deformational mechanisms have been widely studied and shown to depend on external boundary conditions and extant internal conditions. Identifiable influences include stress state, instantaneous porosity, deformation rate, water content, and temperature. In the underground setting, granular salt response is compliant at high porosity and offers limited resistance to closure. Underground stress conditions are induced by creep closure of the surrounding salt formation, which imparts an effective volumetric strain rate on the granular salt. Most granular salt reconsolidation will occur at ambient temperature, although thermal effects will become important in some disposal situations, such as annular backfilling around a heat-generating disposal canister. As porosity diminishes more grain surfaces are brought into contact. Further consolidation mechanisms at low porosity have been identified and documented in previous microstructural studies (e.g., Spiers and Brzesowsky 1993), which revealed the effects of moisture on the contact surface. Crystal plastic mechanisms promote shape change of grains allowing distortion into void space. In the specific interest of achieving a seal function in a nuclear waste repository, the most important transformations occur when porosity reduces to 10% and less. Low porosity states have been approached in the laboratory on many occasions applying a wide variety of test techniques and conditions. Fewer measurements of permeability have been made because of the inherent difficulty.

Because pressure-solution creep is considered to be an important mechanism of crushed salt compaction, it warrants additional description here. Although documentation of the operative densification mechanisms via observational microscopy is not routinely performed on test specimens, comprehensive reviews regarding the fundamental processes, thermodynamics, and models of pressure solution have been published (e.g., Hellmann et al., 2002; Spiers and Brzesowsky, 1993). In fact, experimental approaches focusing on pressure solution during the deformation of unconsolidated crushed salt aggregates have been described by several authors (e.g., Raj, 1982; Urai et al., 1986a, b; Spiers et al., 1990; Spiers and Brzesowsky, 1993; Hellmann et al., 1998). In salt aggregates where the solid grains are plastically deformable, two types of pressure solution densification mechanisms are possible:

1 grain boundary diffusional pressure solution
2 plasticity-coupled pressure solution

The driving force for pressure solution in a granular aggregate is related to stress variations along the grain surface (Paterson, 1973). Figure 2a) (left) presents a sketch of pressure solution as it occurs in response to a non-zero effective stress, i.e., the normal stress component across a grain contact is greater than the stress on the free pore surface of the same grain (from Spiers and Brzesowsky, 1993). The chemical potential variation along the surface of a grain drives a diffusive flux of solutes from the contact area to the free pore surface. The high stress at grain contacts causes dissolution of the minerals at the grain boundary, transport of the dissolved material in a fluid phase out of the grain boundary and precipitation of this material in the pore space on the less stressed faces of the grains. Figure 2a (right) illustrates boundary sliding and additional internal dislocation creep. A scanning electron photomicrograph of these operating mechanisms is shown in Figure 2b), taken from a low porosity consolidation specimen. Grain distortion and remnant shear induced fracture suggest extensive dislocation creep. Individual grains exhibit internal plastic deformation, as evidenced by shape change and extremely small subgrains in the center of the image. In this particular sample using bedded run-of-mine salt, it appears the crystal plasticity has facilitated movement of internal fluid inclusions to grain boundaries whereupon pressure solution re-deposition processes are actively consuming smaller grains. Processes are likely to be influenced by temperature, confining pressure, and impurities, but are most strongly dependent on the presence of sufficient water at grain boundaries to enable solution-precipitation phenomena.



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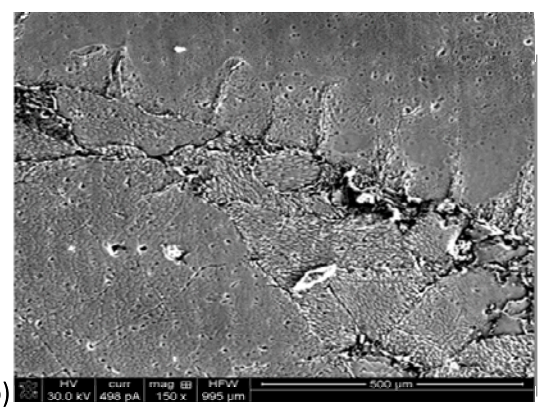

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Figures 2a and b. Plasticity-coupled pressure solution processes in granular salt.

Investigations found that without added moisture the importance of the diffusional creep mechanism diminishes. If moisture is available in the contact area, even very small amounts are sufficient to activate pressure solution processes. Thus, grain boundary diffusional pressure mechanism dramatically enhances the densification rate in crushed salt (Spiers et al., 1990; Callahan et al., 1996; 1998; Schenk et al., 2006).

In summary, these reconsolidation processes have been documented in laboratory experiments on natural and artificial salt aggregates, large-scale tests, and natural analogues. Empirical evidence indicates that fluid-aided processes will be operative in typical bedded salt as porosity reduces below 10%, even if no construction moisture is added. Observations concerned with bedded salt show adequate moisture is available from negative crystals, grain boundary fluid and hydrous minerals to sustain fluid-assisted processes. Nominally, domal salt contains much less moisture than bedded salt, so enhanced compaction and reconsolidation may be facilitated by addition of small amounts of water during construction.

2.2 *Hydromechanical Interactions*

The engineering performance goal for reconsolidating salt in a repository is achievement of low permeability. As granular salt reconsolidates at low porosity, there comes a point at which the formerly porous material occludes capillary pathways and no longer allows porous flow. Grain boundary structural changes and attendant fluid distributions have been photographed at various stages from natural occurrences to laboratory experimental results. Grain boundary structure is believed to change in presence of fluids, such that grain boundary migration is assisted by thin fluid films residing on the grain boundaries (Urai et al., 1986b; Drury and Urai, 1990). In addition to mechanical aspects, the distribution and mobility of water existing inside the pore space may play an important role with respect to safety-assessments of salt repositories. For example, the quantity of accessible moisture controls the volume of water available for corrosion.

Two aspects are of primary importance in the complex hydro-chemical-mechanical interactions:

1 advective release of moisture and/or
2 retention, which may impede the consolidation process by developing pore pressure

The presence of brine strongly affects microstructural evolution and the mechanical and transport properties of the material, although the structure of the halite grain boundaries which contain water is still a matter of debate. One model (personal communication Spires to Popp) illustrated in Figure 3 proposes a thin fluid film transmits the contact stress, therefore diffusion transports dissolved material. On the other hand, the thin film fluids may be squeezed out resulting in islands of solid-solid contact, through which the contact stresses are transmitted. Water-filled channels surround islands of solid-solid contact, and are conduits through which material diffuses. Here the starting configuration is stylized as cubic grains with fluid represented as tubular pores that are transformed to isolated spheres at the corners.

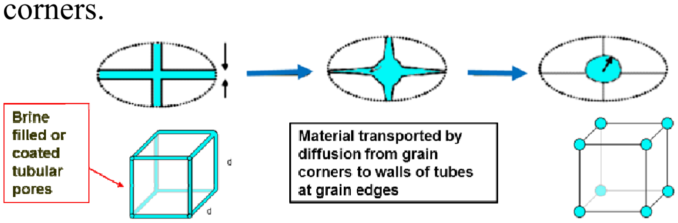
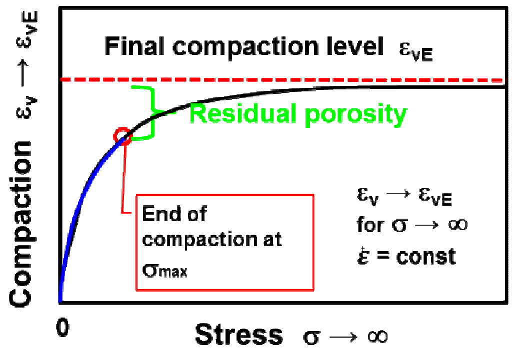


Figure 3. Schematic of fluid redistribution in granular salt aggregates during consolidation.

The fluids existing in the primary pore space (mostly air and water vapor) are compressed and partially squeezed out during the transition to a low-pore-space regime. Migration out of the consolidating material continues as long as a connected porosity and adequate permeability exists. All observations confirm effective reconsolidation until only a few % porosity remains. At that point, the relative saturation within the intergranular pore space increases. As the granular salt continues to consolidate, further fluid transport out of the consolidating mass would undoubtedly involve two-phase flow of both brine and trapped air. Experimental results indicate that intrinsic permeability approaches zero as the porosity of the consolidating salt reduces. As this condition is approached, the brine or air effective permeability is even lower than the intrinsic permeability and the mobility of fluids in highly compressed salt is very low. Of course, this range of conditions is very challenging to interrogate experimentally and remains an area of active research.

3 EXPERIMENTS

Two principal investigation procedures are used to execute consolidation tests, as illustrated in Figure 3 (after Zhang et al., 1993). Type I shown in Figure 3a) involves stress induced compaction using a constant deformation rate. Type II shown in Figure 3b) involves time-dependent compaction under constant stress conditions. Type I simulates converging underground openings with a constant displacement or loading rate. Due to the induced deformation, progressive hardening occurs until the stress approaches a practical limit, which corresponds to some residual porosity. The reliability of such tests may be limited due to time restrictions, i.e., within a reasonable period of time only limited compaction can be achieved. Experiments at Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) realized compaction rates and experimental conditions close to those in situ ($\dot{\varepsilon} \le 10^{-9}$ s^{-1}) by interpolating and extrapolating the curves of axial stress versus void ratio (σ_1/e) plots obtained at a number of different rates. Stepwise increased compaction rates (from $\dot{\varepsilon} = \sim 7 \cdot 10^{-10}$ s^{-1} to $\dot{\varepsilon} = \sim 7 \cdot 10^{-7}$ s^{-1}) were used. Type II experiments are constant-load creep tests that simulate time-dependent compaction processes, i.e., volume creep after pre-loading. Due to time-dependent relaxation processes (probably amplified by humidity-assisted weakening processes) a quasi-steady state compaction process is realized with decreasing rate according to the progressive porosity reduction.



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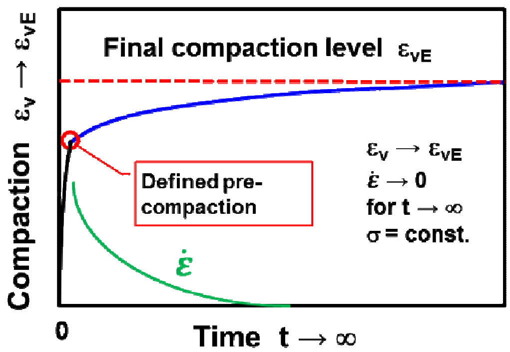

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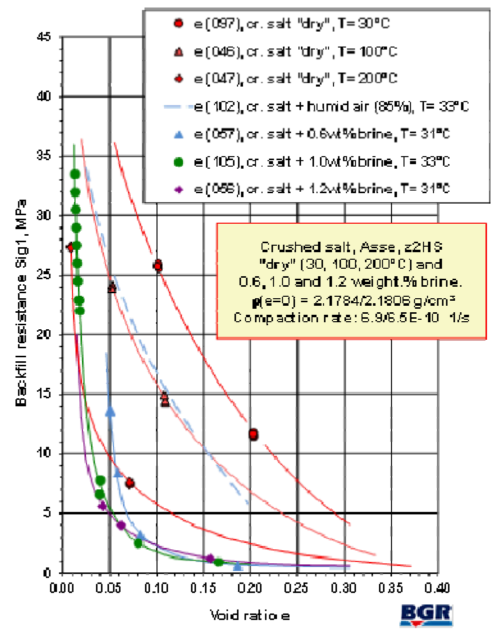
Figures 3a and b. Generalized consolidation test results.

In this section, we focus reconsolidation principles toward salt repository applications and the specific advantages of moisture and clay additives. There have been many granular salt consolidation tests performed since radioactive waste disposal in salt has been subject of active research and application. The interested reader can find further examples and extended references in a larger report the authors prepared on this topic (Hansen, et al., 2014). Application of straightforward construction techniques should readily affect high-performance seals within the nominal operational period of a nuclear waste repository. Other relatively simple considerations such as mixing to reach a final grain distribution may be advantageous, as well. In general, elevating the temperature of salt aggregate accelerates reconsolidation. However, first-order improvement of consolidation can be attributed to modification with small additions of moisture and the addition of clay has the potential to achieve performance specifications upon construction. Representative test data are shown in Figure 4. Figure 4 a) illustrates modest effect of elevated temperature between 30 and 200˚C contrasted to the dramatic effects of moisture. Figure 4 b) extends laboratory results to admixtures of crushed salt and bentonite.

Recent research sponsored within the European Union research project NF-PRO (Stührenberg, 2004; 2007) focused on laboratory testing mixtures of crushed salt and bentonite for conventional shaft sealing purposes. The addition of Ca-bentonite and natural clay can reduce permeability of the backfill considerably at room temperature. Examples of the effective reconsolidation enabled by adding Ca-bentonite to crushed salt (with or without added brine) are shown in Figure 4 b). Tests were conducted at the BGR (Stührenberg, 2007) using an oedometer arrangement and applying a consolidation rate of $6.9 \cdot 10^{-10}$ s^{-1}. Figure 4 b) plots backfill stress versus void ratio for several mixture ratios. A curve for dry crushed salt is plotted for comparison. Results clearly document the favorable effects of additives. At a void ratio of e = 0.1, for example, the dry crushed salt backfill resistance is more than 25 MPa. With an addition of 10 to 20% Ca-bentonite the backfill resistance can be reduced to values between 6 and 8 MPa. A further decrease to less than 4 MPa is attained with a small amount of brine in the sample. An 85% salt/15% bentonite mixture shows the smallest backfill resistance in comparison to those without added brine until a void ratio of e ≈ 0.05 is achieved. Further reconsolidation tests (e.g., performed by IfG, 2012) confirmed this effect showing similar backfill resistance values for the respective mixture.



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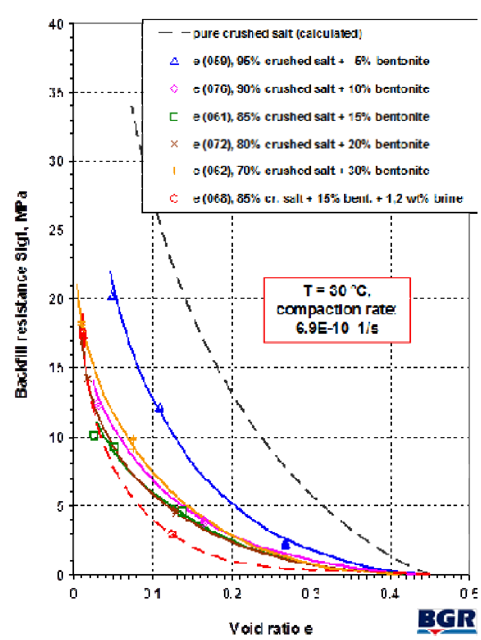

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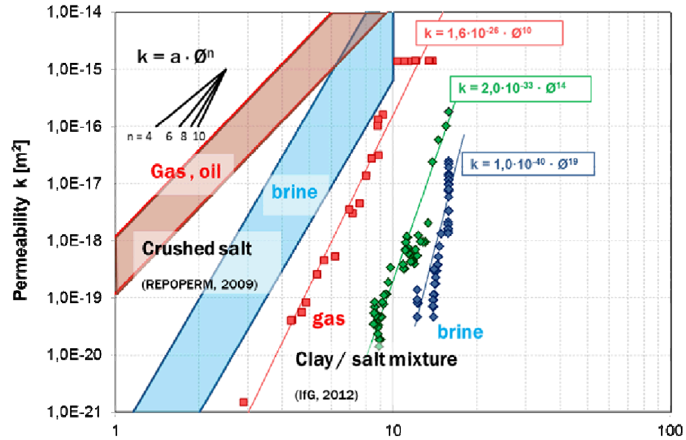
Figure 4. Impact of moisture and bentonite on consolidation of granular salt.

4 TRANSP0RT PROPERTIES

The systematic study of transport properties of crushed salt has included extensive work by different research groups, which applied a variety of experimental approaches and setups. Key studies of WIPP salt are Brodsky (1994), Brodsky et al., (1996), Hansen and Ahrens (1996), and Case et al., (1987). Relevant German studies are reviewed in the framework of the REPOPERM project (Kröhn et al., 2009), which also considers the datasets already represented in Müller-Lyda et al., (1999). Figure 5 is a synoptic diagram of these myriad results.



Porosity [%]

Figure 5 Permeability-porosity data sets for crushed salt and mixtures.

In evaluating the various sources of permeability data for pure granular salt and clay/salt mixtures-as depicted in Figure 5-the following conditions are considered:

- Porosity: the porosity of crushed salt ranges from 40% as unconsolidated debris, to a lower construction porosity depending technique, to a negligible porosity comparable to undisturbed rock salt, say 1-2%. Accordingly, the magnitude of permeability varies over several orders. The main focus of our study is the porosity range <10%, because performance measures of interest are attained at low porosity. Once again we note that permeability results from interconnected pore space and its shape, which is described as effective porosity.
- Crushed salt lithology:
  - Grain size distribution: the influence of grain size distribution may be relevant at higher porosities because the finer particles fill the voids between the larger grains. However, construction techniques that apply dynamic compaction or other densification measures will greatly modify particle size and distribution.
  - Mineral composition: the amount and distribution of impurities may impede consolidation. For example, coarse grained anhydrite aggregates along grain boundaries may hamper closure of grain boundaries and cracks and inhibit healing.
- Fluid content:
  - Water has been shown to enhance local deformation processes at grain contacts, which interrupt fluid pathways.
  - Water films along grain boundaries may induce two-phase flow processes and capillary threshold effects, thus lowering the effective permeability.

In addition, because physical-chemical interactions may also be of importance; the nature of the fluid used for permeability measurements has to be taken into account. The results documented in REPOPERM (Kröhn et al., 2009) represent measurements which were determined using the following fluid media:

- oil - due to the use of a nonpolar liquid hydrochemical interactions between the measuring fluid and the crushed salt are excluded but humidity-induced deformation processes at grain boundaries are hampered.
- gas - in the laboratory inert dry nitrogen is generally used, which means that drying of a naturally wet salt sample cannot be excluded.
- brine – saturated salt solutions, which are chemically equilibrated against the salt matrix. However, due to physical-chemical interactions (solution/precipitation) at typical stress and temperature gradients within a loaded sample the measurement of brine flow during loading at increased temperatures is extremely challenging. Although temperature effects have limited application in salt repository seals, there are a few reliable results available, mostly from the BGR and the Working Group Darmstadt (Elliger, 2004).

Figure 5 summarizes various permeability data sets which were identified as reliable and comparable for crushed salt, measured with gas and brine and depicted in two variation fields. Also plotted are individual measurements of three test series on clay/salt mixtures measured with gas and brine, respectively. The relevant porosity ranges from around 20% to 1%, i.e., the backfill material represents compaction levels as might be applied in salt repositories. Despite the data scatter for salt/clay mixture and somewhat broad bands indicated for crushed salt, it becomes obvious that

- independent of the material (crushed salt or clay-salt mixtures) the permeability-porosity relationship under wetted conditions lies always below the field determined with non-polar fluids or nominal “dry” conditions, i.e., for the same porosity the corresponding permeability is several orders lower for wet conditions (brine) than for dry conditions (oil or gas). As indicated by the parameter n the slope of the corresponding permeability/porosity relationship is much steeper for wet conditions than for the dry state.

- the permeability of clay/salt mixtures lies several orders below the bands for dry and wet crushed salt. In addition, Figure 5 shows the slope for the clay/salt curves is much steeper than for crushed salt.

Despite the observed scattering and lithological differences the permeability data are remarkably consistent and provide a basis for defining the upper and lower bounds of crushed salt permeability during time- and stress-dependent reconsolidation. Because natural salt always contains small amount of fluids, the most relevant data sets are those measured with brine. Testing with moistened or wet salt is more relevant to in situ conditions because long-term consolidation of crushed salt in an underground repository is facilitated by small amount of accessible moisture. Thus it follows that permeability data measured during dry consolidation or using dry nitrogen or oil for measuring permeability are not representative of the in situ state because physical-chemical deformation processes at grain boundaries are suppressed.

5 ANALOGUES

The purpose of accumulating scientific evidence for salt consolidation is to support a license application for disposal. The licensing process involves presentation of scientific, engineering and experimental evidence to a regulatory body. Conveyance of rigorous technical information is often made clearer by using full-scale, long-term analogues. Time and geometric scales are recurring criticisms of applying laboratory reconsolidation test results to a nuclear waste repository in salt. Uncertainty of extrapolating experimental data obtained from laboratory test research arises because small-scale phenomena may only be representative of limited size and relatively short test duration. Field-scale observations and analogues can help connect laboratory results to full repository scale applications. At the same time, micro-mechanical observations can be used to demonstrate that the same deformational processes are acting in laboratory and field-scale salt deformation.

Analogue comparisons of many types may be important within the framework of a safety case. As an example, a specific topic of the German project ISIBEL (ISIBEL, 2010) identified and assessed natural analogue applications to a salt repository safety case. We expect analogue arguments will be necessary to establish safety functions inherent in the licensing process. Although analogues are imperfect renditions of salt repository seal elements, long-term processes and properties of underground workings can be related to the functionality of salt repository seal systems.

Ancient salt mines can provide anthropogenic analogues, dating back thousands of years. Archeological evidence includes preserved artifacts and evidence of impermeability. Further confirmation of long-term salt encapsulation via aperture closure and healing can be obtained from ancient salt mines. Conventional salt mining also provides analogues dating back more than 100 years. Salt backfill has often been used to slow closure by providing confinement and rock mass support. Therefore, old salt-mine backfill can provide anecdotal characteristics of long-term consolidation magnitudes, resulting permeability, and a chance to examine operative consolidation mechanisms.

Analogues also provide opportunity to evaluate characteristics of the damaged rock zone. Local damage or dilatancy around excavations is another geophysical property that has been mitigated by crushed salt backfill. After backfilling, loading conditions will become more favorable toward healing and restoration of rock-mass tightness. Analogue examples show that the disturbed salt permeability decreases in short time scales.

Finally, natural geologic depositions themselves provide evidence that high-porosity evaporite hopper crystals solidify readily into salt rock with negligible porosity. Processes of evaporite rock formation at low temperatures and pressures are reflected in grain size and texture changes due to crystal growth, recrystallization, back reactions and replacements in the salt matrix, accompanied by fluid squeeze off, as long as the effective porosity is not occluded by compaction and secondary evaporite cementation. The pervasive early loss of porosity from more than 50% near the surface to essentially zero by 100m depth is well documented in various studies (e.g., Warren, 2006). For instance, Casas and Lowenstein (1989) showed that Quaternary halite layers only 10 m below the land surface have typical porosities of <10% and that layers at depths below 45m are cemented without visible porosity. By 100m of burial, almost all halite units were tight and impervious.

The BAMBUS and BAMBUS II projects (Bechthold et al., 2004) provide the best available full-scale, long-term, thermomechanical information on granular salt reconsolidation at in situ conditions. The principal scientific objective of the project was to extend the basis for optimizing salt repository design and construction and for predicting long-term performance of barriers, including reconsolidation of crushed salt backfill. In situ investigations were conducted in the Asse salt mine subsequent to completion of the large-scale Thermal Simulation of Drift Emplacement (TSDE). The TSDE (also discussed in Bechtold et al., 2004) involved an emplacement drift that was electrically heated to between 170 and 200°C for more than 8 years. The photograph shown in Figure 6 is the BAMBUS II setting as the test room was re-entered. The large heater is surrounded by reconsolidated granular salt, which had various porosities depending upon location. Most porosity measurements ranged from 20 to 25%. Initial porosity was approximately 35% in 1990. After ten years of in situ reconsolidation, porosity was reduced by 10 to 15% and closure rate had levelled off at 0.5% per year. An additional 20 years or more under these conditions would be required to reduce the porosity sufficiently to produce a low permeability medium.

Figure 6 Photograph of the BAMBUS II re-excavation.

Structural stability is often achieved in the salt and potash industry by backfilling excavations. Backfilling is performed for operational efficiencies and seldom are the physical or mechanical properties of the backfill measured. Two forensic examinations are presented here, recognizing that further anthropogenic analogue studies are strongly desired. On one technical visit to the Sigmundshall mine, a sample of reconsolidated slurry was obtained from the mine workings. This sample had a very low porosity (1.4%) and an approximate permeability of 10^{-17} m^2 (Bechthold et al., 2004). Sutured intergranular structures are ubiquitous, produced by the introduction of large amounts of water when the slurry was placed. This analogue demonstrates that slurry will reconsolidate to near intact conditions in the working life time of a mine. Samples of a younger slurry backfill operation were obtained from the Canadian K2 mine. The reconsolidated K2 salt was originally deposited by slurry from the surface in 1988 (Kaskiw et al., 1989). The slurry was approximately 30% solids consisting of salt tailings. Rooms were filled completely with slurry and excess brine decanted by gravity. Room closure rate was measured at 1-2 inches per year in rooms 25 feet wide and 12 feet tall. Intact cubes measuring approximately 4 inches on a side were obtained for optical microscopy to evaluate the reconsolidation process. In this particular case between 20 and 40% of the void space has been removed.

Reconsolidation of granular salt has practical structural and production implications in salt mines, such as the K2 mine. In repository applications, permeability would be the primary attribute of concern. In this field example we note that grain boundaries mesh extremely well and would be impermeable at that boundary. As natural creep closes the room, the remaining water is expelled as the pressure solution re-deposition removes the void space. The process of reconsolidating salt here is analogous to the process by which the Permian Basin bedded salt became an impermeable formation, originating as embayed salt slurry choked with hopper crystals. For repository closure systems, panel closures would be constructed by utilizing engineering techniques to achieve low emplacement porosity. However, it is also important to recognize that fluid slurry will consolidate to intact conditions.

6 PERCEPTIONS

The technical basis or state of knowledge regarding granular salt reconsolidation is mature. Crushed or run-of-mine salt makes an excellent backfill material for salt repositories because its healing properties will ultimately reestablish impermeability to brine flow and radionuclide transport. By virtue of creating underground space, mine-run salt is readily available and relatively easy to emplace in drifts, although high emplacement density in a horizontal configuration remains an engineering challenge. A large number of laboratory and in situ tests have been conducted to determine the properties of crushed salt under a wide variety of conditions. The science supporting the technical basis for properties of reconsolidating granular salt is objective and thorough. Despite the foundation of supporting evidence, the repository licensing process requires scientific evidence to be conveyed to stakeholder and regulators in a fashion that simultaneously demonstrates the supporting information and convinces a nontechnical audience. Whereas some technical experts believe phenomena associated with crushed salt reconsolidation are well understood, it is clear that this view is not held by other experts and informed lay personnel. The perception that salt reconsolidation processes and associated phenomena are imperfectly known is vital to license application for a salt repository. A regulatory authority will ultimately weigh the evidence and decide the merit of performance arguments. In consideration of our own high expectations for scientific rigor, some areas of uncertainty were identified:

- Test scale: Testing time and space scales need to be reconciled with the desired predictions for repository applications. Laboratory tests comprising the bulk of empirical evidence are principally small-scale and short duration; whereas the application involves meter scale drifts and times ranging from year operations to perhaps hundreds of years.

- Additives: Most backfill research and design now uses run-of-mine crushed salt without additives such as bentonite. Evidence suggests that performance characteristics could be improved with admixtures. Admixtures provide greater placement density and performance. This engineering achievement reduces uncertainty and perceived reliance on modeling.
- Characteristics at low-porosity: Determining permeability at low porosity presents difficult experimental conditions. The technical basis for the crucial transition to low permeability could benefit from further study.

Given these perceptions, we put forward the following questions, observations, and recommended activities:

- • What final porosity of crushed salt is necessary to achieve an efficient seal and at which time can it be reached?
- This topic has been controversial in the past because most oedometer tests demonstrate a residual porosity on the order of 5%. The test results seem to contradict the assumption of a final negligible porosity within a limited time scale. A preponderance of technical information provided within this document clearly demonstrates that granular salt can achieve final porosity on the order of 1% within 10 to 50 years due to time dependent consolidation processes. These processes may have been neglected somewhat in past research, which focused more on the stress-dependent compaction. However, differences between tests performed in oedometer and triaxial equipment are apparent and the experimental variability should be elaborated upon as future experimental work is considered.
- • Capability of additives such as moisture and clay can be optimized for construction and attainment of sealing properties.
- It is well known that small amounts of moisture can enhance the salt compaction and reconsolidation, but the optimal content remains in question. Apparently, added moisture less than 1% is very effective. But what is the optimal moisture addition if the granular salt is mixed with clay? The potential of possible additives for improving backfill and sealing properties has not been exhausted.
- • The nature of testing fluids (brine or gas) and the resultant permeability/porosity relationships warrant further examination.

Although up to now only few data are available, the results document that the decrease of permeability is more effective if brine is the test fluid. In addition, if bentonite is added the compacted backfill becomes tighter. That means it is not possible to derive a unique permeability/porosity relationship for granular salt with and without additives. The apparent differences result from physical-chemical processes on the grain scale.

- • Numerical modeling lacks low porosity verification:

Several numerical tools and models are available for calculations involving reconsolidation. However, the codes need to be qualified for characteristics appearing at lower porosities, i.e., <5% based on experimental results. Model evaluations of backfill reconsolidation were important to the VSG safety analyses. Questions remain regarding effects of humidity in the long term, transport parameters, and the role of two-phase flow.

- • Further analogue experiences from underground sources is imperative.

Revisiting the BAMBUS II site after more than 10 additional years of natural reconsolidation would be worthwhile. Investigation could include core sampling, permeability testing, microscopy, and further reconsolidation in the laboratory. In addition, the salt repository community should continue to pursue relevant information from forth-coming projects involved with abandoning conventional mines.

Large data bases support reconsolidation of granular salt to low porosity and very low permeability, which equate to undisturbed native salt. This review has summarized existing information with a view toward salt repository applications. The role of granular salt reconsolidation in a repository for heat-generating waste will vary among programs because attainment of safety functions depends on the natural setting, waste inventory and concept of operations. Contingent upon repository design and safety concept, reconsolidating crushed salt can function well as a sealing material in shafts or drifts depending on construction techniques and time-dependent tightness evolution. Existing evidence provides high confidence for excellent reconsolidation performance because processes are well understood and achievable with practical engineering measures.

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Additional material