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Experimental and Modeling Results for Reconsolidation of Crushed Natural Rock Salt Under Varying Physical Conditions

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Experimental and Modeling Results for Reconsolidation of Crushed Natural Rock Salt Under Varying Physical Conditions*

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Abstract

Mined salt from the underground facility at the Waste Isolation Pilot Plant (WIPP) Project is a candidate material for use as backfill around the waste packages and in the underground openings during and after the operational phase. We have conducted a series of hydrostatic and triaxial compression experiments on the time-dependent compaction behavior of crushed salt under nominally dry, "damp," (0.5-3 wt% added water), and brine-saturated conditions. Though the compaction of dry crushed salt is very slow in the laboratory, damp salt is likely to compact as rapidly as the mine walls can converge. Drained tests on brine-saturated crushed salt indicate that, though effects associated with saturation do retard consolidation rates slightly, high fractional densities (≥ 0.95) can still be obtained on laboratory time scales at pressures below lithostatic at the WIPP. Triaxial compression experiments indicate that small deviatoric stresses have little impact on consolidation rates. Micromechanical models for the compaction of dry and damp crushed salt, based on isostatic hot-pressing models, are discussed.

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1.0 Introduction

The Waste Isolation Pilot Plant (WIPP) is a U.S. Department of Energy research and development facility intended to demonstrate the safe geologic disposal of transuranic wastes. The facility is located approximately 40 km east of Carlsbad in southeastern New Mexico. Underground workings at the WIPP are situated at a depth of about 650 m in a halite-rich horizon of the Salado Formation, part of a 1000-m thick sequence of bedded evaporites.

Mechanical behavior of crushed rock salt is of interest to the WIPP Project because the mined salt (referred to hereafter as "WIPP salt") is a candidate material for use as backfill around the waste packages and in the underground openings during and after the operational phase. It is anticipated that in response to the convergence of the mine openings, the crushed salt will compact sufficiently to serve as an effective component in WIPP seal systems. Desirable features of a long-term seal material will almost certainly be low permeability, and geochemical and mechanical compatibility with the surrounding, intact formation.

Consequently, a number of studies has been performed at Sandia National Laboratories (SNL) and elsewhere on the time-dependent compaction behavior of salt of varying degrees of purity, under both dry and wet conditions, and in hydrostatic and triaxial compression. The ultimate objectives of these test programs are to develop constitutive models for crushed salt that can predict fractional densities and permeabilities as a function of time under loading conditions anticipated at the WIPP.

A comprehensive review of all work on this topic is beyond the scope of this brief report, but reviews of much of the recent work have been given by Holcomb and Hannum (1982), Holcomb and Shields (1987), Holcomb and Zeuch (1988; 1990), and Zeuch (1989; 1990). The focus here is on testing done at SNL over roughly the last decade.

2.0 Test Specimens, Experimental Apparatus, and Procedures

Specimen materials and preparation, experimental apparatus, and procedures are virtually identical in all studies done at SNL. Details have been given by Holcomb and Hannum (1982), who developed the test technique, as well as Holcomb and Shields (1987), Holcomb and Zeuch (1988; 1990), and Zeuch et al. (1991); discussion here is restricted to a few brief, general remarks about experiments.

The crushed salt was strictly "mine run" material obtained from mine faces at the WIPP Site in several different batches. The salt was sieved to remove any particles that could not pass through a 0.96-cm mesh, but was not otherwise treated or modified. The resulting stock material was stored in plastic bags in the laboratory, taking no special precautions to control moisture content, which Holcomb and Shields (1987) have determined to be 0.19 wt%. Particle size distribution analyses done from time to time confirm that the distributions used in the various investigations are comparable (Holcomb and Hannum, 1982; Holcomb and Shields, 1987; Zeuch et al., 1991).

The salt was assembled into jacketed, cylindrical specimens. When assembling specimens, care was taken to ensure that no segregation occurred owing to particle size differences. Those experiments that were run under damp conditions were treated with brine during sample assembly, and procedures were used to ensure an even distribution of liquid (Holcomb and Shields, 1987). Experiments to be run under brine-saturated conditions (Zeuch et al., 1991) were similarly treated with 3.5 wt% brine during assembly, but were not saturated until they had been preconsolidated or "conditioned" (see below).

Experiments were performed in two similar triaxial test apparatuses developed by W. R. Wawersik. One apparatus has been described in detail, both as it is used in testing of intact rock (Wawersik, 1985) and in compaction experiments on crushed salt (Holcomb and Hannum, 1982; Holcomb and Shields, 1987; Zeuch et al., 1991). The apparatus is equipped with a combination dilatometer/intensifier for precision volume-change measurements, which makes it well suited to this type of experiment.

The tests were run at constant confining pressure, and the measured variable was sample volume change. Knowing the starting volume, V_o, and mass of the crushed salt, the starting fractional density, D_o, "instantaneous" volume and fractional density changes on loading (ΔV_q, and ΔD_q respectively), and time-dependent changes in volume and fractional density (ΔV_c and ΔD_c, respectively) can be calculated. Fractional density, D, is the ratio of the sample density to the density of dry, intact WIPP salt, 2.14 g cm^{-3}. Calculations treated the brine as completely free to escape from the pore space. By referring density measurements to that of intact WIPP salt, data more clearly reflect the approach of the samples to the density of the intact formation.

In a typical experiment, the sample was initially compacted ("conditioned") in the pressure vessel under manual control. The specimen was quickly raised to the desired test pressure and then held for approximately one minute. The sample was removed from the vessel and the "instantaneous," or quasistatic volume and fractional density changes, ΔV_q and ΔD_q, respectively, were determined by the immersion method.

At this point, specimens to be run under saturated conditions were saturated with brine insofar as possible. Specimens were then returned to the pressure vessel, rapidly repressurized to the test pressure, and the dilatometer/intensifier was turned on to measure the time-dependent volume change (ΔV_c). At this point, shear-consolidation specimens were loaded axially.

All experiments were run in the drained configuration. Nominally dry and damp specimens were vented through both top and bottom endcaps. In brine-saturated experiments, the lower endcap vent was plugged to prevent drainage of the brine from the specimen under the influence of gravity; however, brine was permitted to drain from the upper ported endcap into a graduated cylinder. The cylinder was capped to prevent evaporation of brine, and the amount of brine expelled was logged on a regular basis throughout the experiment.

3.0 Experimental Results

3.1 Nominally Dry Crushed WIPP Salt

Holcomb and Hannum (1982) conducted a series of quasistatic and creep compaction tests on nominally dry crushed WIPP salt. "Nominally dry" means that the salt contained no added water beyond the estimated 0.19 wt% that occurs naturally in the crushed salt from the WIPP Site. In the creep tests, samples were compressed hydrostatically at constant pressures ranging from 1.72 to 10.1 MPa and temperatures varying from 21 to 100°C. A typical test ran about 3×10^5 seconds (3.5 days). In the quasistatic tests, samples were hydrostatically compressed at steadily increasing pressures up to 21 MPa in about 8000 seconds (2.2 hours) over the same range of temperatures. The creep consolidation rates were found to be extremely low and seemed relatively insensitive to changes in stress and temperature.

The volumetric strain data were well fit by an empirical model,

$$\frac{\Delta V}{V_o} = \varepsilon_v = 2.303a \ln (t) + b, \tag{3.1}$$

where t is in seconds and a and b are empirical constants. Clearly, the equation is not valid for $t=0$, and in fact, the fit was poor in the first few hundred seconds of the test. To avoid both the poor fit and the singularity at $t=0$ a cut-off time of a few hundred seconds was used.

Using the relationship,

$$D = \frac{D_o}{1 + \varepsilon_v} ,$$

Equation 3.1 can be recast in terms of fractional density and differentiated with respect to time, finding that the densification rate decays as t^{-1}:

$$\dot{D} = \frac{-2.303aD_o}{t(1 + 2.303a \ln(t) + b)^2} . \tag{3.2}$$

Based on extrapolation of their empirical model for consolidation, Holcomb and Hannum (1982) concluded that unacceptably long times were required to attain the low porosity necessary for the backfill to have a permeability approaching that of the surrounding formation, $\leq 10^{-8}$ darcies (Nowak et al., 1988).

3.2 Damp Crushed WIPP Salt

The bedded evaporites of the Salado Formation contain both inter- and intragranular brine inclusions comprising 0.1-1 wt% of the rock (Nowak et al., 1988). Thus, influx of small quantities of brine into the mine openings is inevitable (Nowak et al., 1988), and the crushed salt backfill will be damp, not dry. Holcomb and Shields (1987) evaluated the influence of the addition of small amounts of water (0.5 to 3 wt%) on the compaction rate of crushed WIPP salt under hydrostatic pressures. All experiments were done at $20 \pm 0.5°C$ and pressures of 1.72 or 3.45 MPa. The tests ran for durations up to 4.5×10^{-6} seconds (52 days). Representative plots of fractional density versus time, and densification rate versus fractional density, are shown in Figures 3.1a and 3.1b.

Holcomb and Shields (1987) observed that the data for damp salt could also be fitted by a relationship in the form of Equation 3.1. However, compared to experiments on nominally dry salt, those on damp salt exhibited greater instantaneous fractional density changes upon loading, and densification rates greater by more than an order of magnitude at comparable times. Differences in densification mechanisms will be discussed later in this report. As stated, varying quantities of brine were added to these experiments, yet no differences in the magnitude of the effect were detected even at the lowest amount added, 0.5 wt%.

Using their empirical model, Holcomb and Shields (1987) concluded that the backfill would offer little resistance to closure of the disposal rooms. Subsequent modeling work supports this contention (Sjaardema and Krieg, 1987).

Finally, Holcomb and Shields (1987) performed one long-term hydrostatic compression test involving a series of pressure steps ranging from 0.34 to 6.90 MPa. Argon gas permeability measurements were taken at various fractional densities. Over the range from $D=0.90$ to 0.95, the permeability decayed rapidly from approximately 4.5×10^{-5} darcies to 1×10^{-8} darcies.

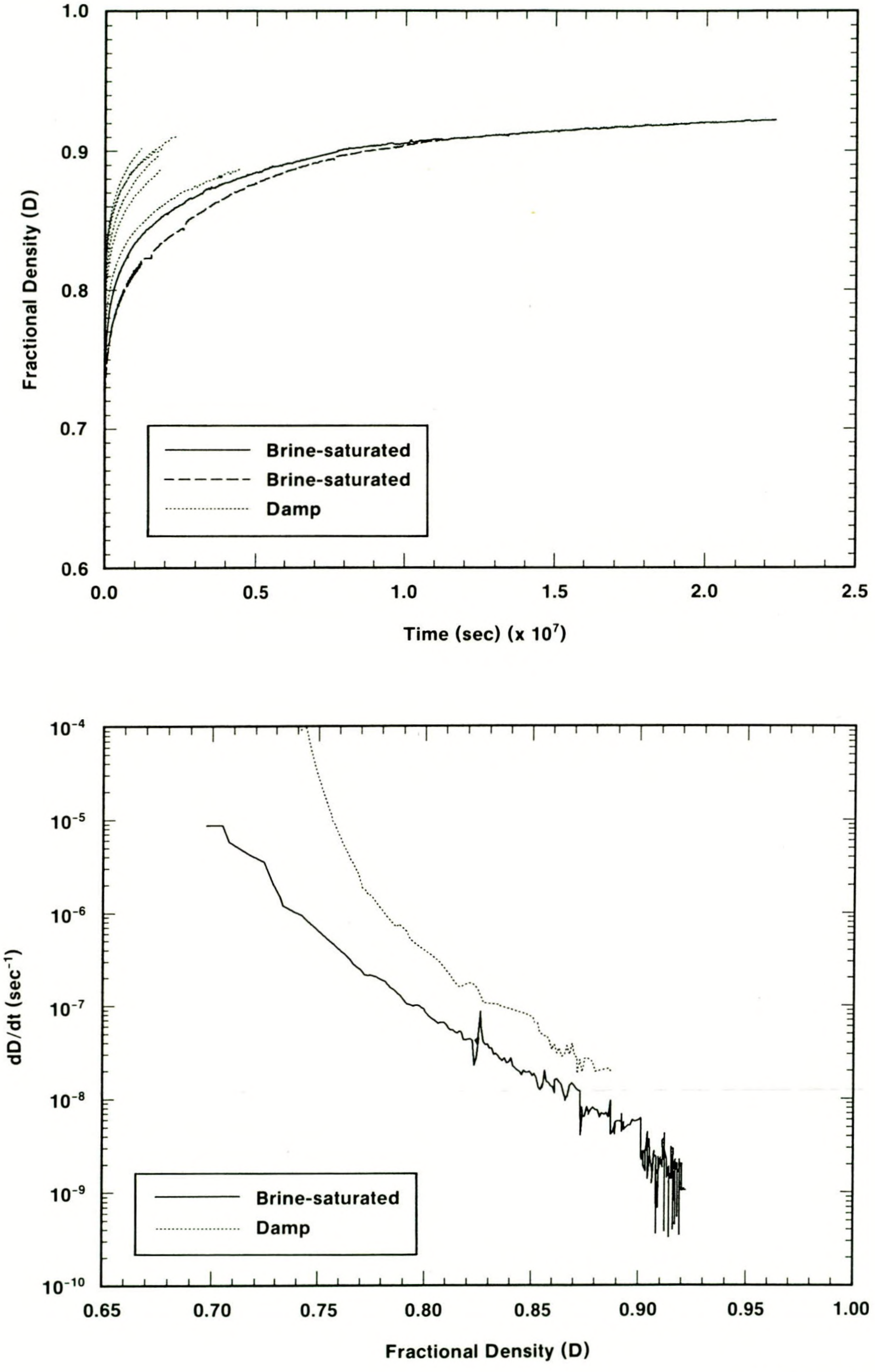

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Figure 3.1. (a) Fractional density-time and (b) densification rate-fractional density plots for compaction experiments on brine-saturated and "damp" crushed rock salt.

3.3 Brine-Saturated Crushed WIPP Salt

Both observations and calculations indicate that the total influx of brine into the underground openings will be small. It is expected that by the time the crushed salt backfill is fully reconsolidated (≈100 years), only 1.2 wt% of the rock mass will consist of trapped brine (Nowak et al., 1988); this is not much greater than the original brine content of the intact formation. Nevertheless, concerns exist that large quantities of brine might somehow unexpectedly saturate the backfill during the early stages of consolidation and prevent the attainment of final densities approaching those of the intact formation. Even though such a "worst-case" scenario is thought to be extremely unlikely (Nowak et al., 1988), Zeuch et al. (1991) have undertaken an experimental investigation of the effects of high degrees of brine-saturation on the consolidation rates of crushed WIPP salt under hydrostatic compression.

Tests were conducted at 20±0.5°C under nominally drained conditions and at pressures of 1.72, 3.45, 6.90 and 10.34 MPa, comparable to those used by Holcomb and Shields (1987). The experiments ran for up to 11 months. Plots of fractional density versus time and densification rate versus fractional density for the 3.45 MPa experiments are shown in Figures 3.1a and 3.1b for direct comparison with the results of Holcomb and Shields (1987) for damp salt. It should be noted that at the higher pressures in this test series, fractional densities in excess of 0.95 have been reached.

Results to date suggest that the brine-saturated specimens compact somewhat more slowly than damp specimens at all fractional densities. However, the differences are less than an order of magnitude, with no indications that the brine-saturated tests stop densifying altogether. Microstructural studies on the brine-saturated specimens have not been done yet, but we believe that the slower consolidation rates are attributable to increasing inability of brine to escape from the specimens owing to the "pinching off" and isolation of previously connected pores, resulting in entrapment of brine.

3.4 Shear-Consolidation Experiments

Numerical simulations of disposal-room/backfill interactions indicate that the backfill will be subjected to small shear stresses during compaction, principally in the corners of the drifts (Sjaardema and Krieg, 1987). Shear stresses are generally believed to enhance the compaction of granular or porous media (Zeuch et al., 1991); nevertheless, the concern arises that these shear stresses may somehow impede consolidation rates of crushed salt. Zeuch et al. (1991) have completed two preliminary shear-consolidation experiments on damp crushed WIPP salt. The experiments were done at 20±0.5°C, mean stresses,

$$\sigma_m = \frac{\sigma_1 + 2\sigma_3}{3} \quad ,$$

of 3.45 MPa, and stress differences, $(\sigma_1 - \sigma_3)$, of 0.69 MPa, to facilitate direct comparison with the results of Holcomb and Shields (1987).

The results of the two experiments bracket Holcomb and Shield's (1987) hydrostatic compaction experiments at 3.45 MPa on damp salt, as shown in Figures 3.2a and 3.2b. Based on these results, small shear stresses have little effect on the consolidation rate, positive or negative.

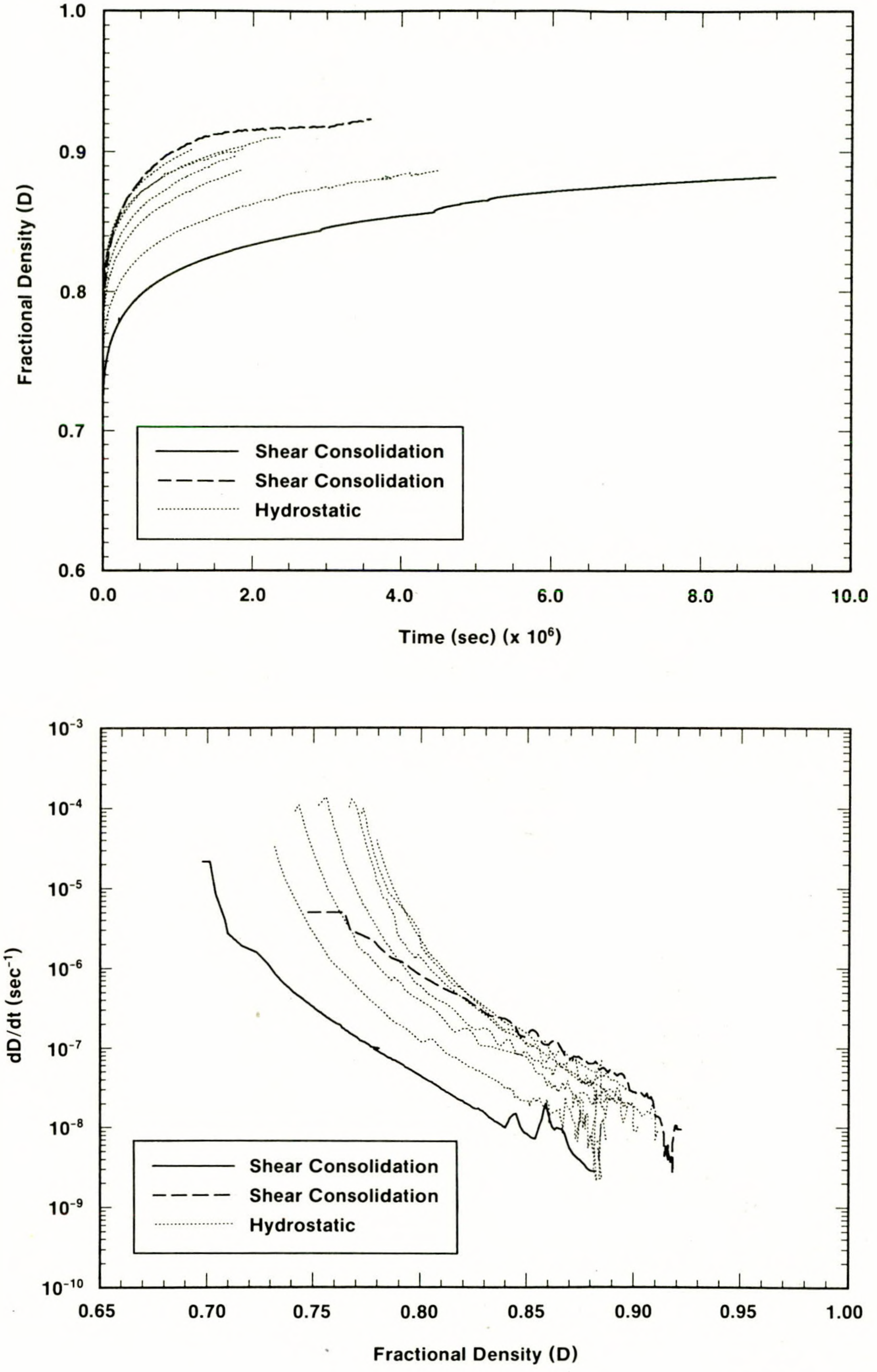

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Figure 3.2. (a) Fractional density-time and (b) densification rate-fractional density plots for shear-consolidation and hydrostatic compaction experiments on "damp" crushed rock salt.

4.0 Modeling of Crushed Salt Consolidation

Long-term prediction of the behavior of crushed salt backfill under repository conditions necessarily involves extrapolation of experimental data beyond time spans accessible in the laboratory. Such extrapolations can only be done with confidence if the underlying micromechanisms of consolidation are understood; predictions based on purely empirical formulae such as Equations (3.1) and (3.2) are of doubtful value beyond the laboratory time scale. Whether in the laboratory or in situ, the problem of crushed salt consolidation is fundamentally identical to the materials fabrication process of isostatic hot-pressing, in which ceramic or metallic powders are subjected simultaneously to heat and hydrostatic pressure to manufacture finished or near-finished components approaching theoretical density. Owing to its industrial importance, a great deal is known about the micromechanisms contributing to densification.

Zeuch (1989; 1990) combined what is known about the deformation and creep micromechanisms of dry, *pure* sodium chloride (NaCl) with a comprehensive, multimechanism model for hot-pressing, to isolate the micromechanisms likely to contribute to consolidation of *dry,* crushed WIPP salt under repository conditions. Zeuch (1989; 1990) showed that under those conditions, only time-independent plasticity by dislocation movement and time-dependent dislocation creep were likely to contribute to densification in the absence of brine; diffusional mechanisms were unlikely to contribute to compaction.

Based on this result, Zeuch (1989; 1990) combined the well-documented dislocation creep model for WIPP salt (Wawersik and Zeuch, 1986) with the hot-pressing model to develop a densification model for WIPP salt. The model assumed that the only compaction mechanisms were instantaneous (time-independent) plastic deformation by dislocation movement and time-dependent dislocation creep. The quasistatic compaction data of Holcomb and Hannum (1982) were used to estimate/constrain the single material constant required for the model. Zeuch (1989; 1990) showed that the model described the time-dependent portions of Holcomb and Hannum's (1982) compaction data reasonably well, although the instantaneous densification that occurred upon loading was not well described. Specifically, it was typically underestimated. Using these results, Zeuch (1989; 1990) nevertheless generated *densification mechanism maps* for dry WIPP salt. Despite the sluggish consolidation rates in the laboratory, the results indicated that under rapid (instantaneous) loading, dry crushed salt could consolidate to fractional densities of about 0.95 in about 30 years at pressures comparable to lithostatic at the WIPP (approximately 15 MPa).

Holcomb and Zeuch (1988; 1990) attributed the poor agreement between the observed instantaneous compaction in experiments (Holcomb and Hannum, 1982) and that predicted by Zeuch's (1989; 1990) model to a component of densification by brittle processes (fracture and particle rearrangement) that is generally acknowledged to occur during hot-pressing, but which has not been realistically incorporated into any model at this time. Holcomb and Zeuch (1988; 1990) empirically included this effect and achieved a significantly better fit to the observations. Recently, Holcomb, Wawersik and Zeuch (in preparation) conducted acoustic emission (AE) experiments on compacting aggregates of both dry and damp crushed WIPP salt. Acoustic emissions were detected in the early stages of both types of experiments, but AE rates decayed rapidly with time. Vastly more acoustic emissions were detected in the damp experiment, indicating that much more fracturing occurred in the presence of water. This result is significant for three reasons: 1) it verifies the assertion that brittle processes contribute to densification in the early stages of compaction; 2) it explains why greater instantaneous densities were reached in the damp experiments of Holcomb and Shields (1987) than in the dry experiments of Holcomb and Hannum (1982); 3) it suggests that the presence of water facilitates fracturing in salt.

Densification of damp and brine-saturated crushed salt almost certainly occurs by fluid phase-enhanced, diffusional creep mechanisms. No detailed effort has yet been undertaken to extend the model of Zeuch (1989; 1990) and Holcomb and Zeuch (1988; 1990) to include these processes. However, Zeuch (1989; 1990) outlined how such an extension could be accomplished, assuming that densification is rate-limited by diffusional transport of matter in the fluid phase. A comparable approach has already been undertaken by Spiers and Schutjens (1990) for pure salt, with good agreement obtained between model and experiments. Of course, it will also be necessary to empirically incorporate brittle compaction mechanisms, as with dry salt.

5.0 Conclusions and Direction of Future Work

It has been demonstrated that under the conditions most likely to pertain to the repository, (damp), crushed WIPP salt will consolidate rapidly at pressures significantly lower than lithostatic pressure at the depth of the repository. Preliminary results indicate that at high fractional densities ($D \geq 0.95$) permeabilities approach that of the intact formation ($\leq 10^{-8}$ darcies).

The work by Zeuch et al. (1991) on the effects of brine-saturation and shear stress on consolidation of crushed WIPP salt is still in progress at SNL and at RE/SPEC, Inc., where brine-permeability measurements are also being done (Brodsky, 1990). It is expected that most of this work will be completed within a year of this writing. Results to date indicate that even though effects associated with brine-saturation may retard consolidation slightly, high fractional densities are attainable under drained conditions on the laboratory time scale, at hydrostatic pressures lower than lithostatic at the WIPP. The results of brine-permeability measurements are still preliminary and subject to revision, but indicate that at fractional densities in excess of 0.95, permeabilities are in the 10-100 nanodarcy range (Brodsky, 1991). Other results to date indicate that small shear stresses have little effect on consolidation rates of damp salt.

A viable model for compaction of dry crushed salt has been developed, and work on extension of the model to include the effects of moisture is in progress. There are several obvious directions for future work to go. First and most important, it is essential to investigate the consolidation mechanisms of damp and brine-saturated crushed salt. This investigation will entail microstructural studies and experiments to evaluate sensitivity of the densification rate to particle size, stress, and temperature. The results will be important in evaluating the existing model and revising it as needed. It would also be useful to test the model for consolidation of dry salt using temperature- and stress-changing experiments as outlined by Zeuch (1989; 1990).

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