Mechanical Behavior of Bedded Salt Interfaces and Clay Seams Subjected to Shear

Steven R. Sobolik [1*], Stuart Buchholz [2], Benjamin Reedlunn [1], Evan Keffeler[2], Lance Roberts[3]

[1] Sandia National Laboratories, Albuquerque, NM, USA; [2] RESPEC, Rapid City, SD, USA; [3]South Dakota School of Mines and Technology, Rapid City, SD, USA

* srsobol@sandia.gov

ABSTRACT: Extensive collaborations between United States and German salt repository researchers have identified four key research areas to better understand the behavior of salt for radioactive waste repositories. One subject area includes the influence of inhomogeneities, specifically interfaces between the host salt and other in situ materials such as clay seams within bedded salt, or different materials such as anhydrite or polyhalite in contact with the salt. The potential increases in creep rate, roof collapse, and permeability near and along these inhomogeneities are thought to be first-order effects. Despite their importance, characterizations of the peak shear strength, residual shear strength, and permeability of interfaces in salt are extremely rare in the published literature. This paper presents preliminary results from laboratory experiments designed to measure the mechanical behavior of a bedding interface or clay seam as it is sheared. The series of laboratory direct shear tests reported in this paper were performed on several samples of materials typical of Waste Isolation Pilot Plant (WIPP) emplacement drifts. These tests were conducted at several normal and shear loads up to the expected in situ pre-mining stress conditions, and at multiple shear velocities to scope for potential velocity-dependence of shear stress evolution. These tests were performed on samples with a clay seam, and other samples with a halite/anhydrite or halite/polyhalite contact. As part of the analysis of the data from these tests, a preliminary constitutive model for interface behavior as a function of stress and rate of strain is being developed.

1 Introduction

Extensive collaborations between American and German salt repository researchers have identified four key research areas to better understand the behavior of salt for radioactive waste repositories (Hansen et al., 2016b and 2017). One subject area includes the influence of nonhomogeneities. No characterization testing has been published, and nonhomogeneities have first-order effects. Included among these nonhomogeneities are clay seams in bedded salt, or other interfaces such as halite/anhydrite and halite/polyhalite. These interfaces are prevalent in bedded salt formations such as in the Delaware Basin where the WIPP facility resides near Carlsbad, New Mexico, USA; the stratigraphy at WIPP is illustrated in Figure 1. The effects of shear along these interfaces has long been thought to have significant impact on the mechanical behavior of storage drifts built for the long-term storage of radioactive waste, particularly as they pertain to the evolution of room closure and roof falls, and to the changes in strength and permeability at these interfaces. The tests reported in this paper were performed to gain additional understanding of these processes.

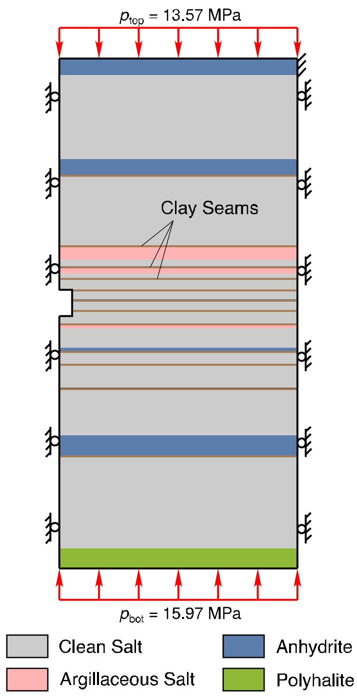

Figure 1. Illustration of WIPP stratigraphy.

There are essentially no in situ measurement data characterizing shear strength of an interface in salt and resulting effects of interface displacement and permeability. Munson and Matalucci (1983) proposed an in situ test for the WIPP site, with direct shear across a clay seam. A 1-by-1-m block in a wall containing a representative clay seam would be isolated by cutting around it. Flatjacks were proposed to be installed in slots cut around the block to apply shear and normal stresses. Displacements along and across the seam would be measured as a function of applied stress. This proposed test never occurred.

Some laboratory and computational investigations have evaluated the slip along interfaces under several different stress environments. Minkley and Mühlbauer (2007) documented direct shear laboratory tests on carnallite and salt blocks under varying normal and shear loads and shear velocities. With these data, they developed a shear model for interfaces that accounts for both velocity-dependent and displacement-dependent shear softening mechanisms. The plots in Figure 2, taken from Minkley and Mühlbauer (2007), show the evolution of shear stress as a function of shear displacement for two different shear velocities. Their results showed that under higher shear velocities, adhesive frictional resistance must first be exceeded before a loss of shear strength occurs; at lower shear velocities, no adhesion is apparent and cohesion is maintained. The direct shear experiments described in this paper were developed as a follow-on to the 2007 study.

The series of laboratory direct shear tests reported in this paper were designed to measure, evaluate and quantify the effects of shear displacement along a bedding interface or clay seam on shear and fracture strength of the interface and accompanying salt. The purpose of these lab tests is to provide data that will be used to develop a constitutive model for shear strength and fracturing along bedding interfaces and seams. This model is intended to improve understanding of shear stresses and strains on bedding interfaces that can be translated to current geomechanical and WIPP performance assessment models. In addition to applications directly related to WIPP, the data from these tests will be used to support US-German collaborative model development efforts for the Joint Project WEIMOS (2016 – 2019; "Further

Development and Qualification of the Rock Mechanical Modeling for the Final HAW Disposal in Rock Salt").

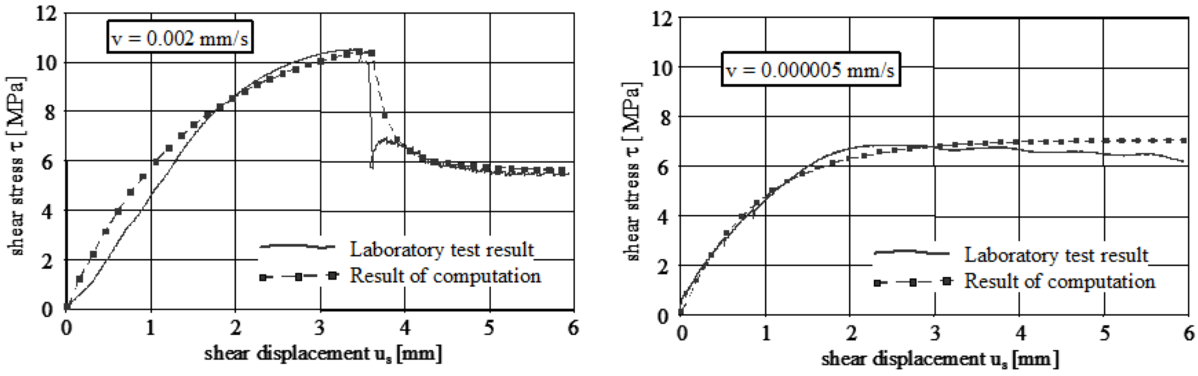

Figure 2: Shear stress vs. displacement for different shear velocities (Minkley and Mühlbauer, 2007).

2 Experimental Design and Procedure

A series of laboratory direct shear tests was performed on several samples of materials typical of WIPP emplacement drifts. Some test samples were control samples, i.e. machined blocks of halite. These tests were conducted at several normal and shear loads up to expected in situ pre-mining stress conditions, and at multiple shear velocities to scope for potential velocity-dependent shear stress evolution. Additional tests were then performed on samples with a clay seam, or a halite/anhydrite or halite/polyhalite interface in a similar manner as that in Minkley & Mühlbauer (2007). The direct shear test method was designed to measure the following mechanical properties of the interfaces:

- Intact normal stiffness
- Intact shear stiffness
- Shear yield strength relationship with normal stress
- Shear ultimate strength relationship with normal stress
- Shear residual strength relationship with normal stress
- Complete force-displacement characteristics for each specimen
- Residual normal stiffness
- Residual shear stiffness

The data generated by the direct shear tests will allow for constitutive behavior laws to be developed that describe complete stress-strain behavior of the interfaces. The data can also be used to determine which published constitutive behavior laws are appropriate for modeling the interfaces. The test method specified for this project includes specimen preparation, test setup, multi-stage shear tests, and data processing.

The test procedure followed three distinct phases, each of which is covered in one of the following subsections:

1. Extraction of test core from a salt/potash mine located near the WIPP facility. (Retrieval of core from the WIPP facility is currently not possible.)
2. Experiment preparation, including test sample preparation and setup of the direct shear machine.
3. Perform a suite of 30 direct shear tests, varying the interface between the samples, the normal stress load, and the shear velocity.

2.1 Test core extraction

Sample collection was conducted in a salt/potash mine located near the WIPP facility. According to the original plan, as many samples as possible were to be drilled from the floor of an inclined drift. An exposed seam in the rib (side wall) of the drift would be followed until it went below the drift floor, and core would be extracted from a location where the interface was estimated to be approximately 60 cm below the floor. Several sites along the drift of the mine were scouted for well-defined clay seams, or well-defined interfaces between halite and another material (anhydrite or polyhalite). Two such locations are shown in Figure 3.

Figure 3. Exposed clay seam (left) and halite/polyhalite contact (right) for test core collection.

The cores were drilled using a concrete coring rig with a diamond bit core barrel having dimensions of 300-mm diameter by 560 mm long. Several cores were drilled from the floor as planned, but nearly all exhibited damaged seams or interfaces, which made them unsuitable for testing. It was then decided to extract cores horizontally from the rib. This procedure was much more successful; several intact cores were extracted for all the desired interface types. The extraction of two such cores are illustrated in Figure 4.

Figure 4: Core extraction from side wall of drift.

2.2 Test preparation

For these laboratory tests to approximate in situ overburden stress conditions, normal stresses of 7-17 MPa (1000-2400 psi) were required. For this reason, the RESPEC direct shear machine, shown in Figure 5, was selected to perform the tests. It has an axial and shear load capacity of 130 kN (30,000 lb) each. Samples may be as large as 150-mm cubes, although for these tests, 100 mm-diameter cylinders were used. The shear velocities range from a minimum of 0.004-0.006 mm/sec to a maximum of 0.083 mm/sec. Potentiometric linear displacement sensors were mounted on the shear boxes to measure displacement, from which shear was derived. Load cells on the machine measured horizontal loads which were used to derive shear stress across the seam or interface. The shear displacement was applied to the top block. Tests were performed on intact salt samples with no interface to evaluate the test setup for any possible bending bias. Afterward, intact salt samples that include a distinct interface, such as either a clay seam or a halite/anhydrite or polyhalite interface, were tested.

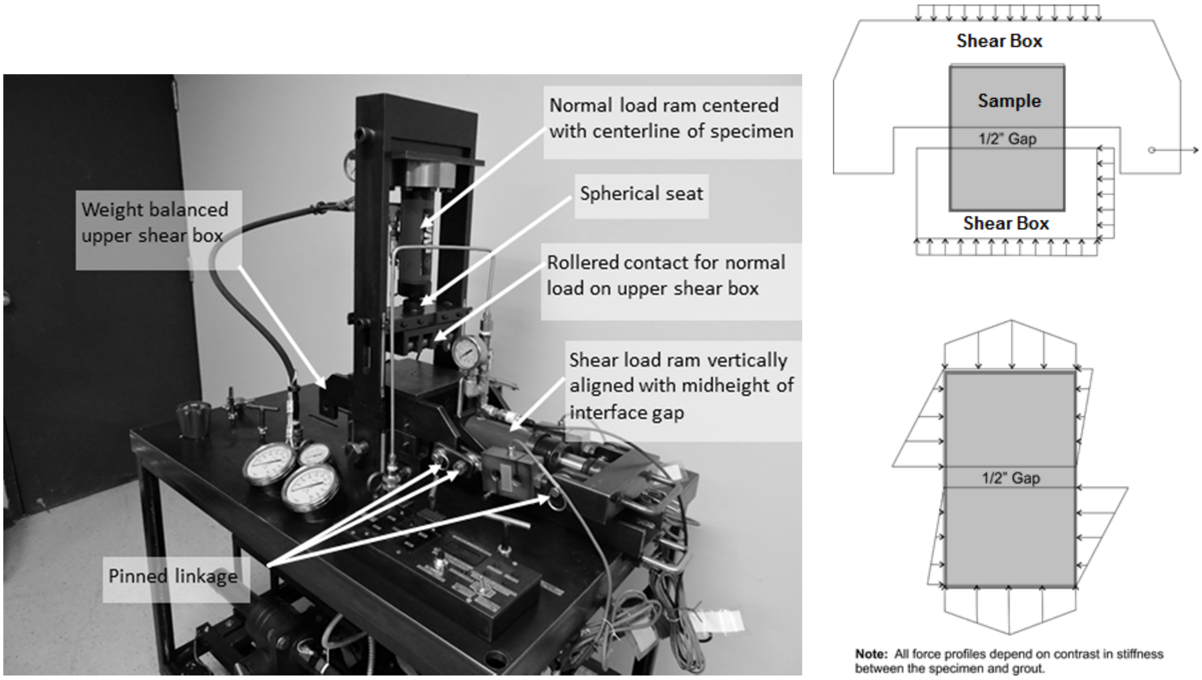

Figure 5. RESPEC direct shear machine and test setup.

100-mm diameter specimens were subcored from the field core samples using a vertical mill. Saturated halite brine was used as the coring fluid instead of lapidary oil to prevent chemical interaction between the coring fluid and geologic interfaces. The long-axes of the subcores were oriented perpendicular to the geologic interface to the extent possible. The subcores were trimmed so the specimen length on either side of the interface is between 50 and 88 mm. The specimens were then cleaned using an alcohol based degreaser.

The diameter of each specimen was measured at the interface. The specimens were coated with clear spray acrylic that protected the specimens from possible dissolution by the shear box encapsulation grout. After the acrylic coatings cured, the test specimens were encapsulated into the shear boxes using quick curing gypsum cement anchor grout. Each specimen was oriented so that the interface was centered in the gap between the shear boxes and aligned with the shear ram. To prevent damage to the interface, the shear boxes remained rigidly clamped together until the shear box assembly was mounted in the shear testing machine.

The shear test procedure begins with a load/unload/reload cycle of the normal stress. The cycle consists of loading to the target normal stress specified for that specimen, unloading to a normal stress of approximately 0.3 MPa (50 psi), and then reloading to the target normal stress. The initial loading reduces the softness of the shear box assembly in the normal loading direction so that the intact normal stiffness can be calculated from the reload portion of the cycle. After completing the normal stress unload-reload cycle, the nominal normal stress on the specimen remains constant through the remainder of the shear test.

Once the normal stress has stabilized, shear stress is applied to the specimen. The shear load application begins with a load/unload/reload cycle. Again, the purpose of the loading cycle is to reduce softness in the shear direction of the shear box assembly. The stress magnitude applied during the initial loading must be less than the yield stress of the specimen. Because the yield stress of an individual specimen is not known *a priori*, the technician must use judgement to determine when to terminate the initial shear loading and begin unloading the specimen; typically, the initial shear loading magnitude is chosen very conservatively. The shear stress is unloaded until the stress-displacement curve becomes non-linear. Shear loading then resumes, and the shear displacement rate is held constant until the residual strength of the specimen is achieved or until the shear displacement is equal to 20% of the specimen diameter. Shear loading encompasses the nominally linear force-displacement behavior before yielding, post-yield strength strain hardening behavior, post-ultimate strength strain softening behavior, and perfectly plastic residual behavior.

Upon attaining the residual strength or 20% shear displacement (whichever is achieved first), the shear stress is unloaded and reloaded to allow for the residual shear stiffness to be measured. The shear load is then removed, and the normal stress is unloaded and reloaded to allow for the residual normal stiffness to be measured. The normal force is then removed from the specimen, and the shear boxes are separated. The failed surfaces were then photographed.

After the intact interface has been tested, the shear boxes are reset to their original position, and the test procedure is repeated on the failed interface but at a greater normal stress. Additional information is gained about the residual deformation and strength characteristics with only a small increase in labor by testing the already failed geologic interface. Additionally, the effects of continued shearing and damage accumulation on the deformational properties can be determined. Up to two additional residual strength tests will be performed on the specimen with each subsequent test performed at a greater normal stress.

2.3 Test performance

There were two sets of shear tests performed for this investigation: the first set to evaluate the dependence of mechanical properties on applied normal stress; and the second to evaluate dependence on shear displacement rate. The force and displacement data recorded by the data acquisition system were converted to nominal normal and shear stresses; the initial cross-sectional area of the specimen was used to calculate nominal stresses. The normal and shear stiffnesses were calculated from the slopes of the linear portions of the stress reloads. The yield strength was identified as the transition point between linear shear loading behavior and strain hardening shear loading behavior. The ultimate strength was the maximum shear stress measured during the test. The residual strength corresponds to the shear stress when the specimen shows perfectly plastic shear deformation behavior. The dilation angle of the interface was calculated from the tangent of the slope of the normal displacement-shear displacement curve.

The relationship between shear strength and normal stress can be strongly non-linear, especially at low normal stresses. Consequently, the target normal stresses for the intact specimens were 3.4, 6.9, 10.3 and 16.5 MPa (500, 1000, 1500, and 2400 psi) for each interface type as shown in the test matrix in Table 1. Normal stresses for residual strength tests were 3.4, 6.9, 10.3, 13.8 and 16.5 MPa; the additional normal stress of 13.8 MPa for the residual strength tests is being specified to further define the shape of the strength criterion curve. For the constant shear rate portion of the testing, the shear displacement rate will be the standard 2.5 mm per minute used for direct shear tests by the RESPEC Materials Testing Laboratory.

Table 1: Test matrix for to determine relationship between interface properties and normal stress.

Specimen Type	Number of Specimens	Normal Stress #1 (MPa)	Normal Stress #2 (MPa)	Normal Stress #3 (MPa)	Normal Stress #4 (MPa)	Shear Displacement Rate (mm/min)
Clean Halite Specimens	4	3.4	6.9	10.3	16.5	2.5
Halite Specimens with Clay Seam #1	4	3.4	6.9	10.3	16.5	2.5
Halite Specimens with Clay Seam #2	4	3.4	6.9	10.3	16.5	2.5
Specimens with Halite/ Anhydrite Contact	4	3.4	6.9	10.3	16.5	2.5
Specimens with Halite/ Polyhalite Contact	4	3.4	6.9	10.3	16.5	2.5

In the second testing phase, the shear rate dependency of the interface properties were evaluated at a preliminary level. For each specimen type, two tests were performed at normal stresses of 10.3 MPa with each test at a different shear displacement rate. The shear displacement rates were 1.2 and 5.0 mm per minute as shown in the test matrix in Table 2. The test plan also calls for an additional 5 contingency tests that will be used to supplement the data obtained in the first two phases.

Table 2. Test matrix to determine shear rate dependency of the interface properties was evaluated.

Specimen Type	Number of Specimens	Rate #1 (mm/min)	Rate #2 (mm/min)	Normal Stress (MPa)
Clean Halite Specimens	2	1.2	5.0	10.3
Halite Specimens with Clay Seam #1	2	1.2	5.0	10.3
Halite Specimens with Clay Seam #2	2	1.2	5.0	10.3
Specimens with Halite/Anhydrite Contact	2	1.2	5.0	10.3
Specimens with Halite/Polyhalite Contact	2	1.2	5.0	10.3

3 Results and Analysis

The laboratory tests will be conducted during the months of December 2017 and February 2018. Results of at least some of the lab tests will be described in this section, along with an initial analysis of the dependency of intact and residual strength of the seams and interfaces as a function of normal stress.

4 Conclusions

Our conclusions will reflect the available results of the tests at the time of final submittal of this paper. They will also point to the constitutive model that will be developed from the results of the entire test suite.

Acknowledgements

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525. This research is funded by WIPP programs administered by the Office of Environmental Management (EM) of the U.S. Department of Energy. SAND2017-xxxxC

These experiments are based on a proposed suite of laboratory and field tests presented in 2016 (Hansen et al., 2016a). Several people have participated in discussions to develop the concept of these experiments, including: Mathew Ingraham, and Frank Hansen (ret.), SNL; Leo Van Sambeek, and Kerry Devries, RESPEC; Dr. Karl-Heinz Lux, Technical University Clausthal; and Dr. Andreas Hampel, Hampel Consulting, Mainz Germany.

References

HANSEN, F.D., SOBOLIK S.R., & STAUFFER, P., 2016a. Intermediate Scale Testing Recommendation Report, FCRD-UFD-2016- 000030 Rev. 0, SAND2016-9041R, Sandia National Laboratories, Albuquerque, NM.

HANSEN, F.D., STEININGER, W., & BOLLINGERFEHR W., 2016b. Proceedings of the 6th US/German Workshop on Salt Repository Research, Design, and Operation. FCRD-UFRD-2016-00069. SAND2016-0194R, Dresden, Germany, Sept. 2015. Sandia National Laboratories, Albuquerque, NM.

HANSEN, F.D., STEININGER, W., & BOLLINGERFEHR, W., 2017. Proceedings of the 7th US/German Workshop on Salt Repository Research, Design, and Operation, SFWD-SFWST-2017-000008. SAND2017-1057R, Arlington, VA, Sept. 2016, Sandia National Laboratories, Albuquerque, NM.

MINKLEY, W. & MÜHLBAUER, J., 2007. Constitutive Models to Describe the Mechanical Behavior of Salt Rocks and the Imbedded Weakened Planes. Wallner, M., K-H Lux, W. Minkley, H.R. Hardy, eds. The Mechanical Behavior of Salt: Understanding of THMC Processes in Salt. Taylor & Francis/Balkema, Leiden, The Netherlands.

MUNSON, D.E. & MATALUCCI, R.V., 1983. Planning, Developing, and Fielding of Thermal/Structural Interactions in situ Tests for the Waste Isolation Pilot Plant (WIPP). SAND83-2048. Sandia National Laboratories, Albuquerque NM.