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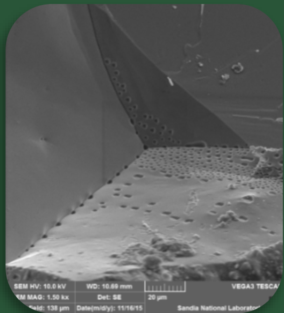
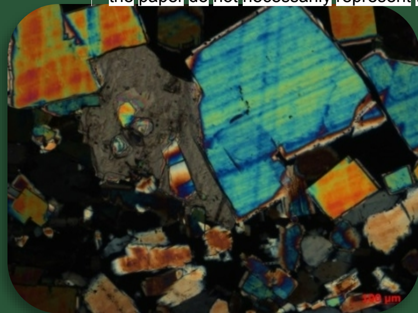

Clay Seam Laboratory Testing

11th US/German Workshop on Salt Repository Research, Design, and Operation

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Sandia National Laboratories, USA
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Part 3 of the online workshop
September 8, 2021

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Joint Project WEIMOS:

Further Development and Qualification of the Rock Mechanical Modeling for the Final HLW Disposal in Rock Salt

April 2016 – (March 2019) extended: September 2021,
(writing of synthesis report until March 2022)

Partners

Germany:

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Technische Universität Braunschweig (TUBS)

Technische Universität Clausthal (TUC)

United States:

Sandia National Laboratories, Albuquerque & Carlsbad

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PTKA
Project Management Agency Karlsruhe
Karlsruhe Institute of Technology

Joint Project WEIMOS:

Further Development and Qualification of the Rock Mechanical Modeling for the Final HLW Disposal in Rock Salt

Work Packages

WP 1: Deformation behavior at small deviatoric stresses

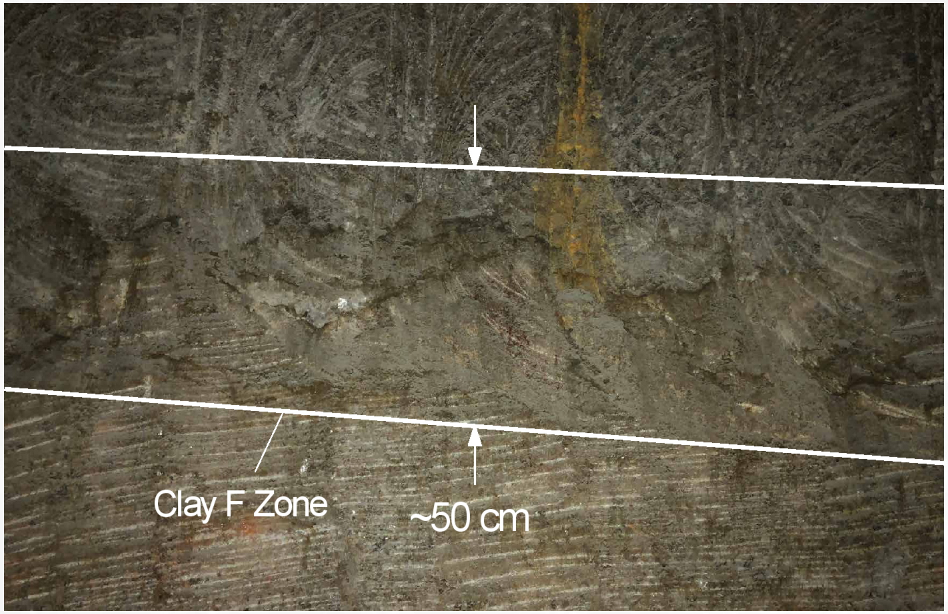
WP 2: Influence of temperature and stress state on damage reduction ("healing")

WP 3: Deformation behavior resulting from tensile stresses

WP 4: Influence of inhomogeneities (layer boundaries, interfaces) on deformation

WP 5: Virtual demonstrator

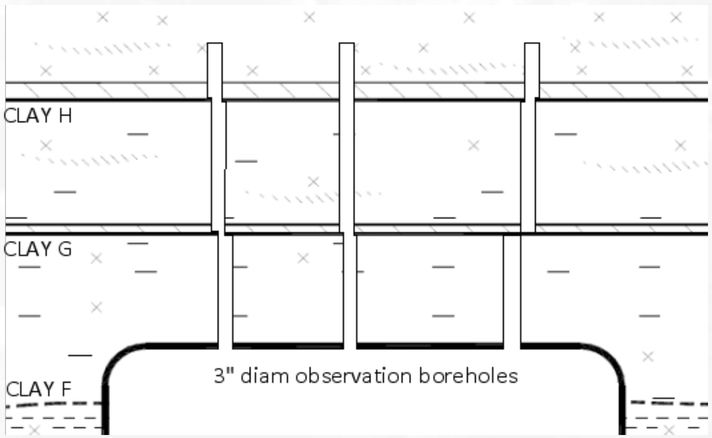
Pictures of Clay Seams at WIPP

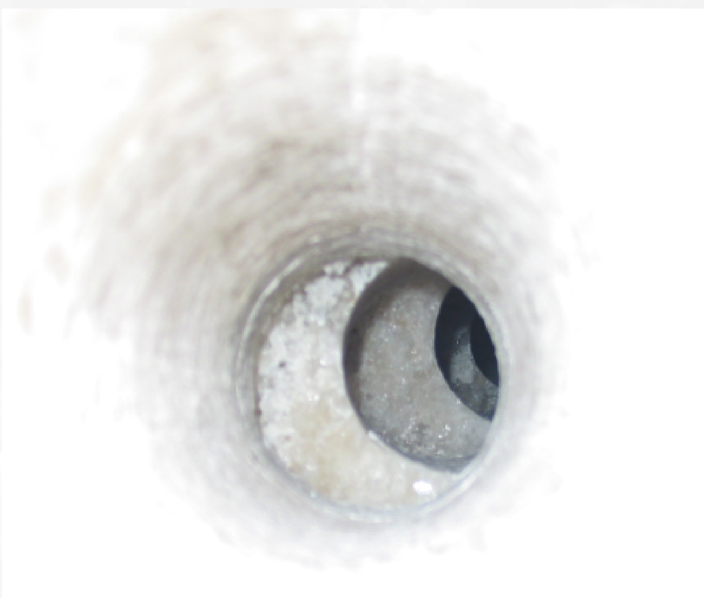


- Clay seam G is thin (~8-25 mm), somewhat linear, contains clay and little else
- Clay seam F is thick (up to 50 cm), wavy, contains clay + other materials, possibly has intersecting salt crystals

Motivation

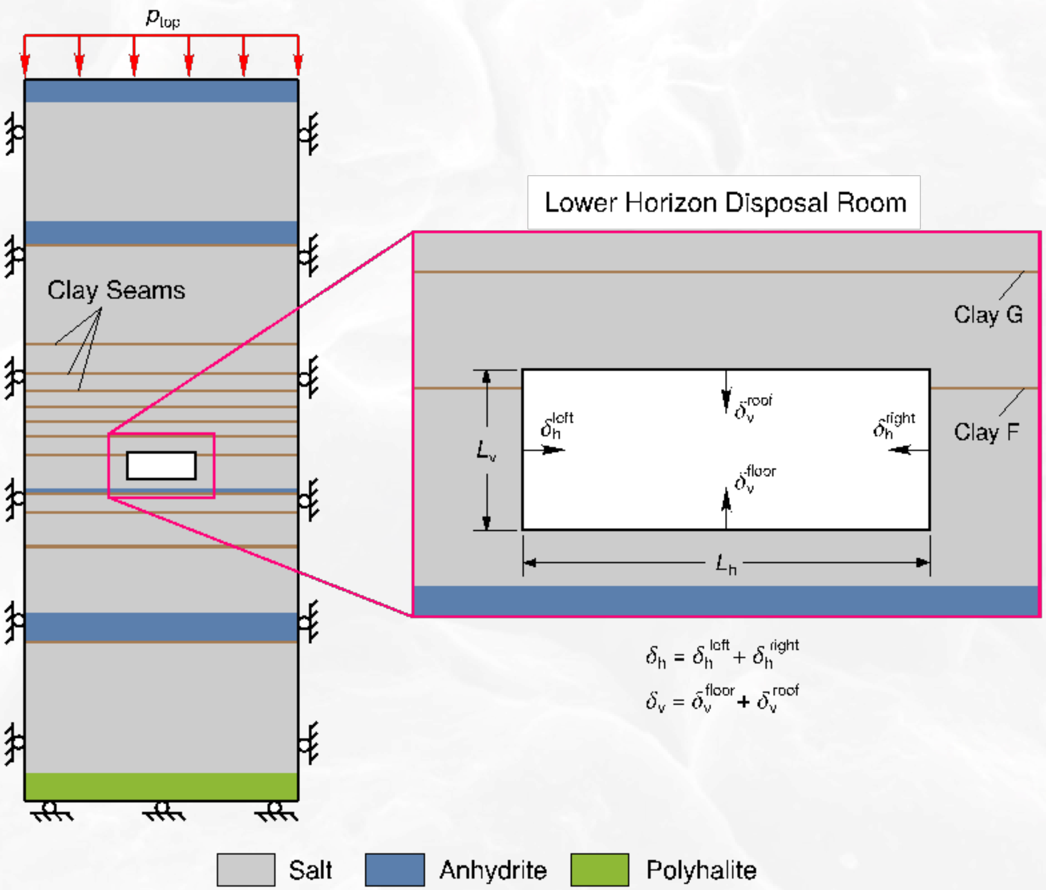
Interface Sliding

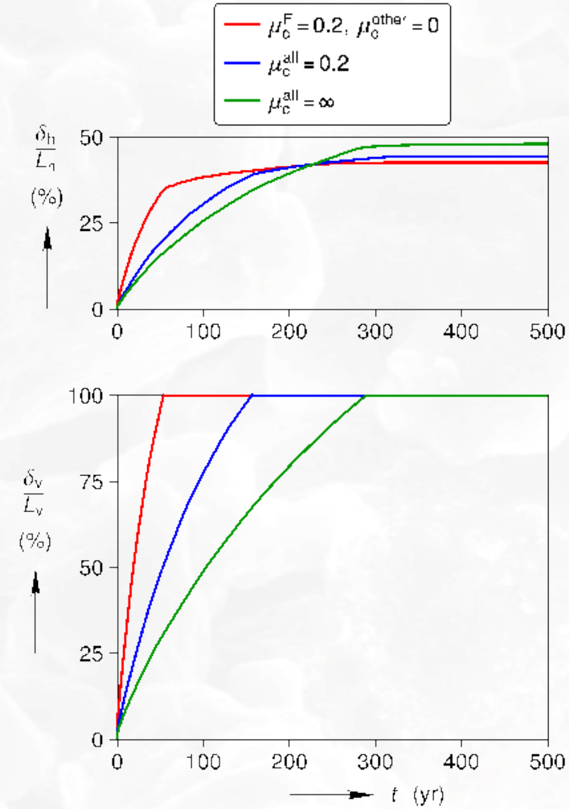




- Simulated room closure rates are highly dependent on bedding plane interfaces, such as clay seams.
- Roof falls frequently detach at clay seams
- The mechanical behavior of bedding plane interfaces is one of five Joint Project WEIMOS work packages.

WP 4: Influence of inhomogeneities (layer boundaries, interfaces)



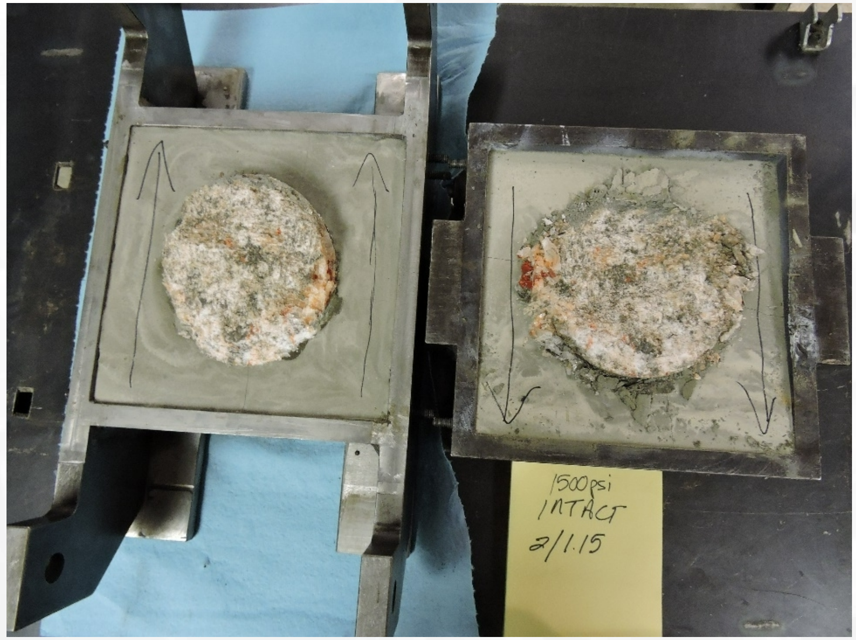


Reedlunn, B. and Bean, J. (2020). Impact of Properly Specifying the Clay F and Clay G Friction Coefficients in Disposal Room Closure Simulations at the Waste Isolation Pilot Plant. Memorandum. SAND2020-3575 CTF.

Modeling results show room closure rate is highly dependent on characterization of inhomogeneities such as clay seams.

1st series samples

Salt/clay interface Fracture shown is typical of all tests



Intact test, σ_n=1500 psi (10.3 MPa); salt crystals cross through interface

Intact test, σ_n=500 psi (3.4 MPa), side view

Influence of inhomogeneities (layer boundaries, interfaces) – First test series

Shear tests of interfaces in salt

First series of tests completed in 2018 at RESPEC with intact samples – NM salt, salt/clay, salt/polyhalite, salt/anhydrite.

Tests performed at four different normal stresses (3.4, 6.8, 10.3, 16.6 MPa), shear velocity of 0.25 mm/min.

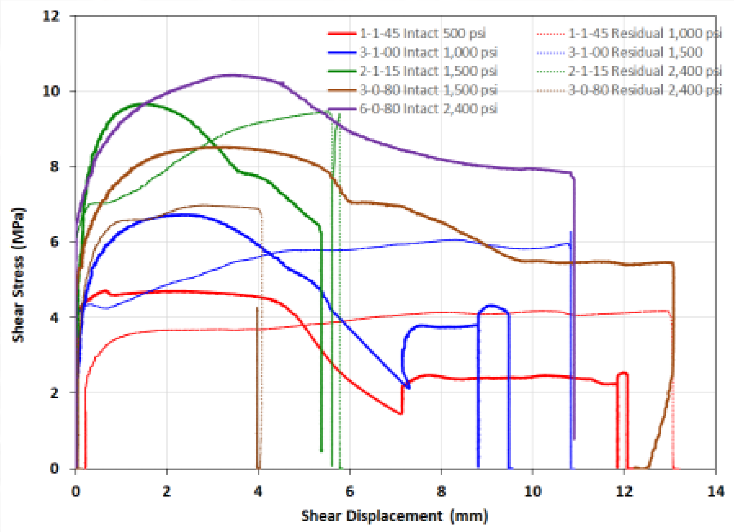
Some repeatability observed in maximum residual shear stress at same normal stress after interface fractured in intact test, fractured samples sheared in residual test.

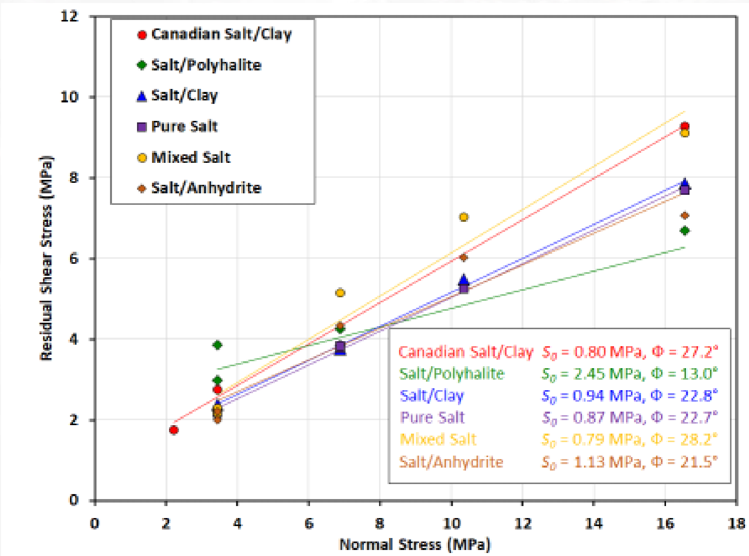
Clay/salt contacts much stronger than anticipated; interstitial salt crystals grown through contacts.

Sample stiffness much higher than anticipated.

Consistent behavior among different samples on intact tests.

Resulting stiffness, strength values assumed to be "upper bound".

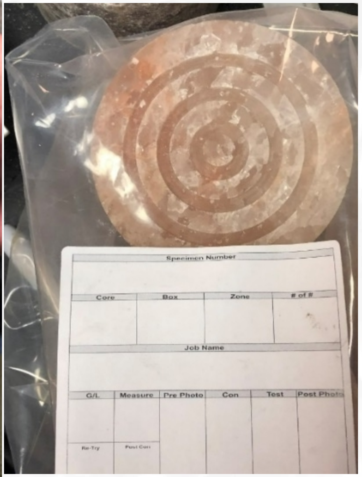


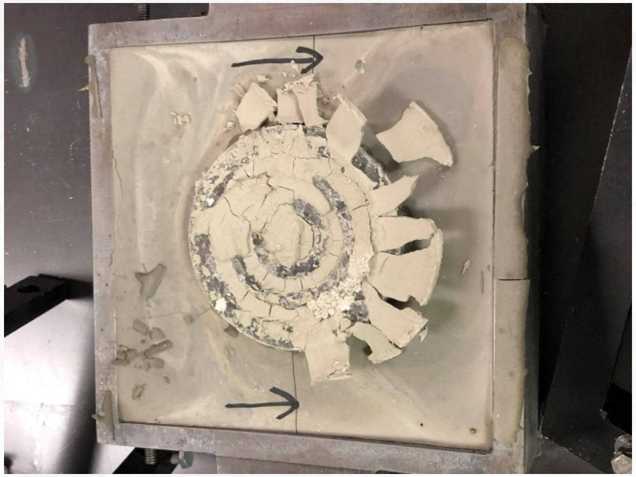


Influence of inhomogeneities (artificial clay seams) – Second test series

Artificial clay seam tests:

- **Goal: Establish plausible lower bound for strength and stiffness of clay seams in salt formations**
- **Shear tests with manufactured clay seam (consolidated in pressure chamber) using bentonite/brine mixture, available salt core samples.**
- **Prototype test (pictured at right) performed at 3.4 MPa normal stress, yielded at 0.6-0.7 MPa shear stress.**
- **Full test series completed March 2020: 8 tests performed by RESPEC**
    - **Pre-consolidation thicknesses of 6 mm, 12 mm (¼, ½ inches);**
    - **3 different normal pressures of 3.4, 6.8, 10.3 MPa (500, 1000, 1500 psi).**





Artificial clay seam shear tests – Description

- 8 samples total: 4 with seam with pre-consolidation thickness 6 mm (¼”), 4 with thickness 12 mm (½”)
- Clay was made with mixture of bentonite, nearly-saturated brine
- Moisture content of clay pre-consolidation: 60% (1st batch), 54% (2nd batch)
- Samples held in consolidation chamber at 3000 psi for 2 weeks
- Post-consolidation seam height thicknesses: 12 mm down to 4.8 mm (3/16”); 6 mm down to 1.6 mm (1/16“)
- Normal pressures for tests: 3.4, 6.8, 10.3 MPa (500, 1000, 1500 psi)
- Post-consolidation moisture content from chips: 13-17%
- Very little consolidation during test itself; less than 1 mm average normal displacement during test, nearly all salt deformation
- Shear ram velocity 0.004 mm/sec
- True residual tests were marginally achieved only on 4 tests

Specimen Construction – Samples from Core

Seam-side – where clay is applied

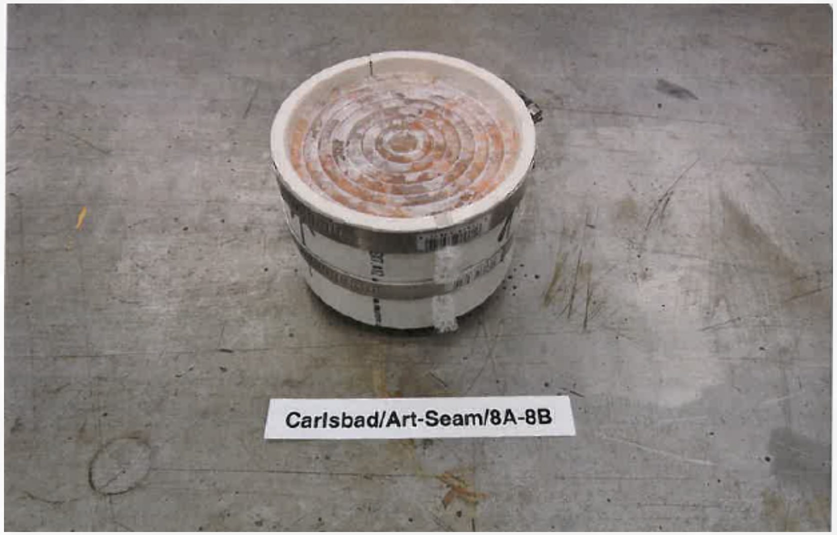
Outside – where normal stress is applied

Asperities were 1.3 mm deep, spaced 6 mm apart

Specimen Construction – Mixing Clay

- Clay is mixture of bentonite, nearly saturated brine.
- Moisture content of clay pre -consolidation: 60% (1st batch), 54% (2nd batch).

Specimen Construction – Clay Application



Top of PVC tube placed either 6 or 12 mm (¼” or ½”) above top of salt surface; clay mixture troweled into grooves up to top of PVC.

Specimen Construction

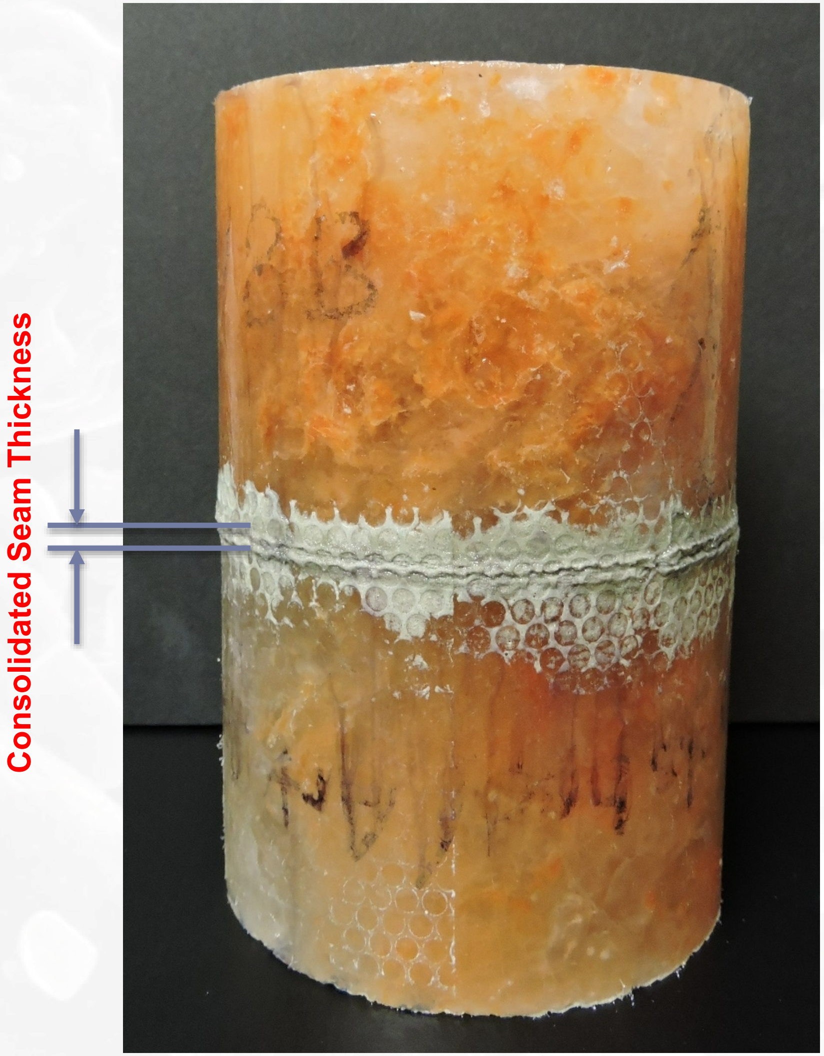
Other cylinder is placed on top of clay, pressed downward while PVC contains clay.

Specimen Construction – Consolidation

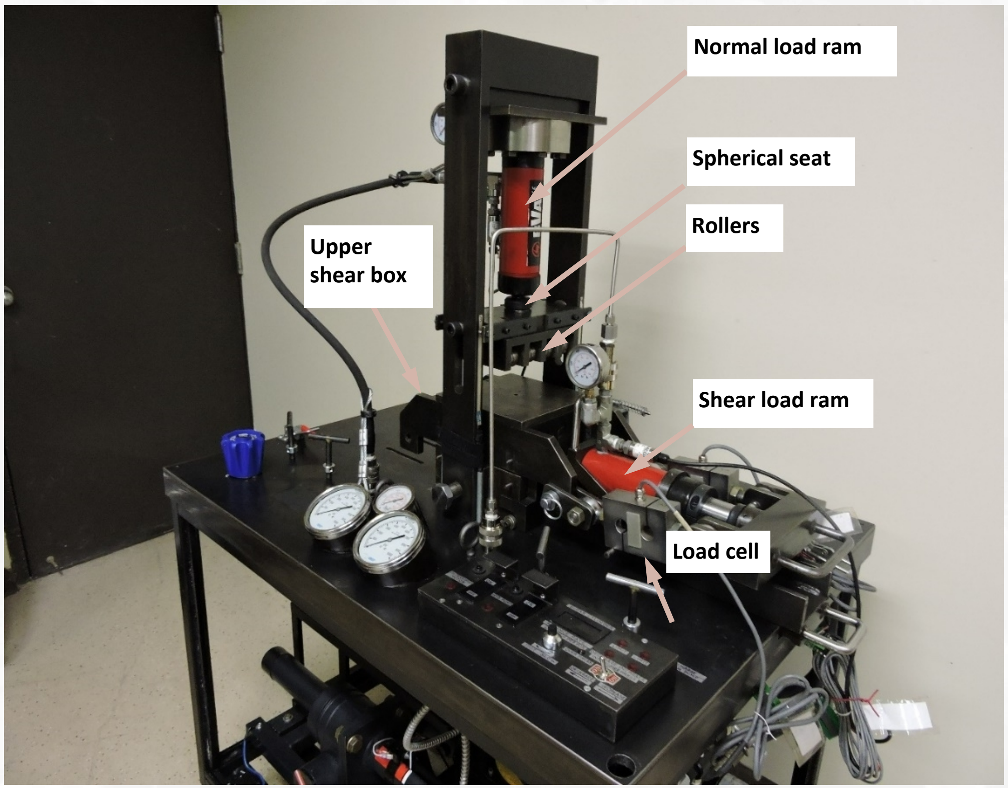
Specimen wrapped with Kimberly Clark BLOCK-IT wrap, electrical tape prior to placement in consolidation chamber.

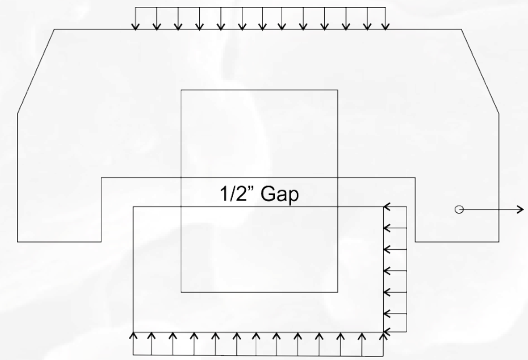
Specimen Fabrication

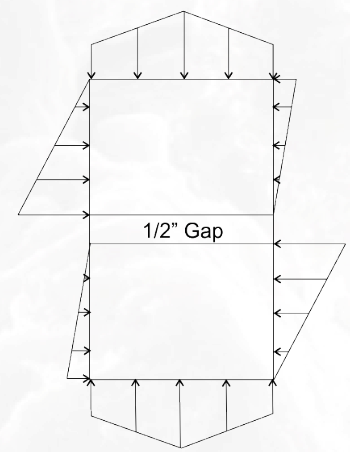
- 4 specimens with initial seam thickness of 6 mm
- 4 specimens with initial seam thickness of 12 mm
- Consolidated
  - 14 days at 20,7 MPa (3000 psi) hydrostatic stress and 21C
  - Excess pore fluid vented
- After consolidation
  - Approximately 1/3 of pre-consolidation thickness
  - Clay hardened
  - Fresh water moisture content 13 to 17%
  - No asperity-to-asperity contact



Direct Shear Test Setup

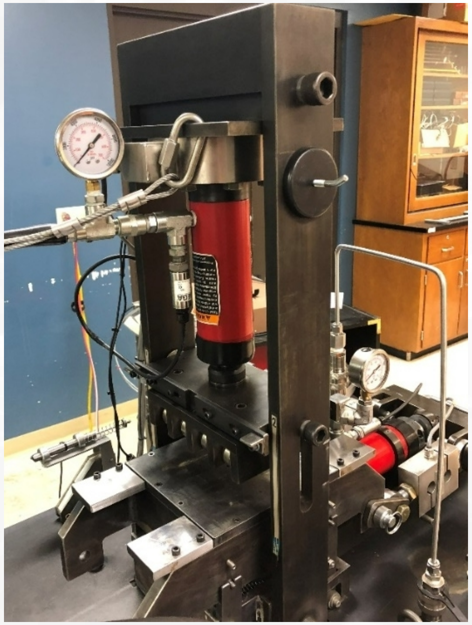


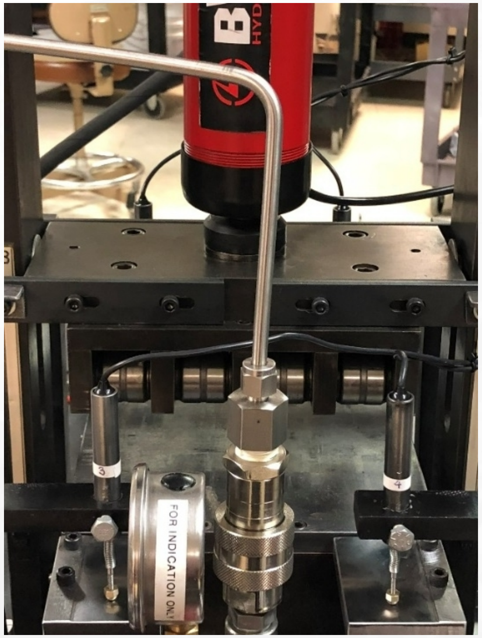


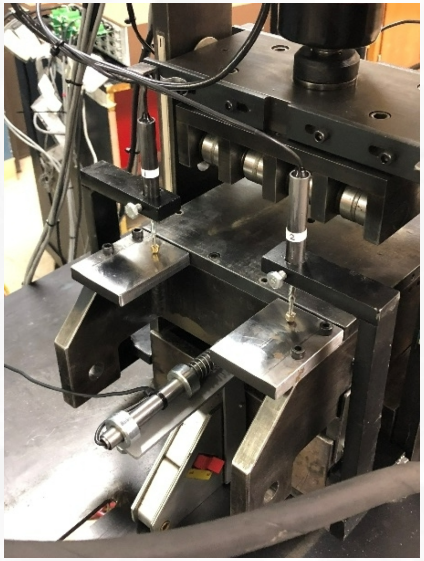


Note: All force profiles depend on contrast in stiffness between the specimen and grout.

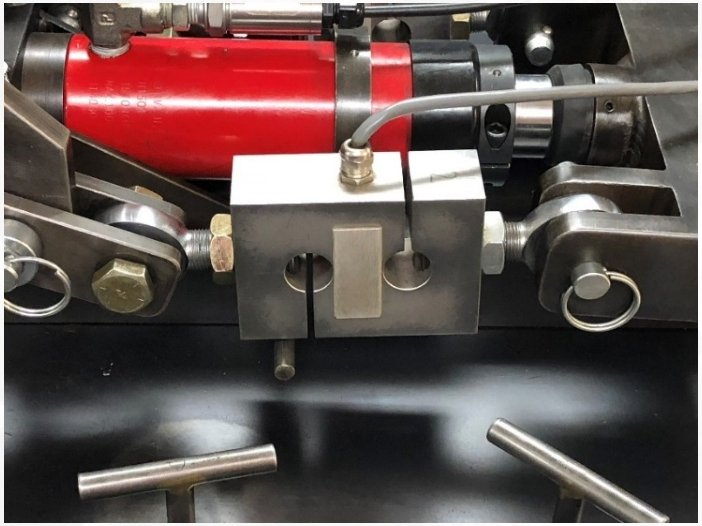
Direct Shear Test Machine



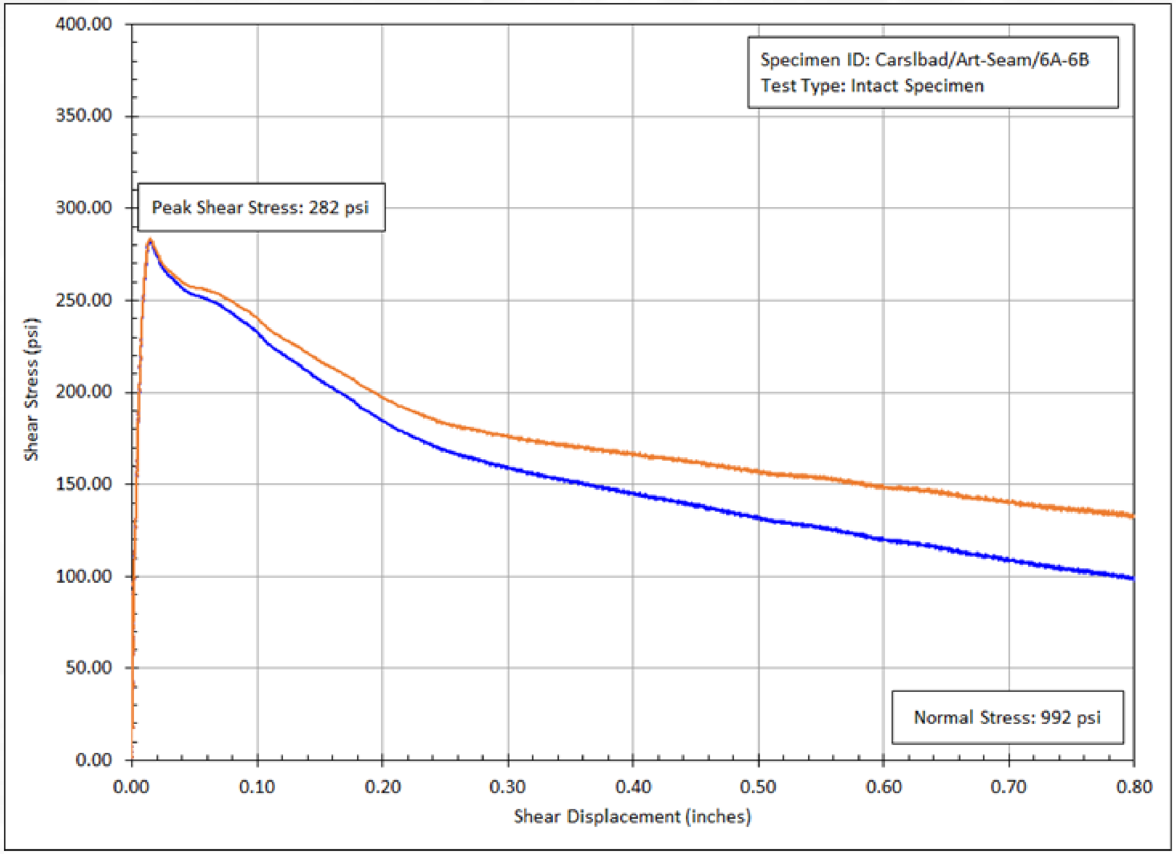




- S-shaped load cell – gaps opened during some tests
- 4 normal displacement gages, average displacement used to calculate stiffness

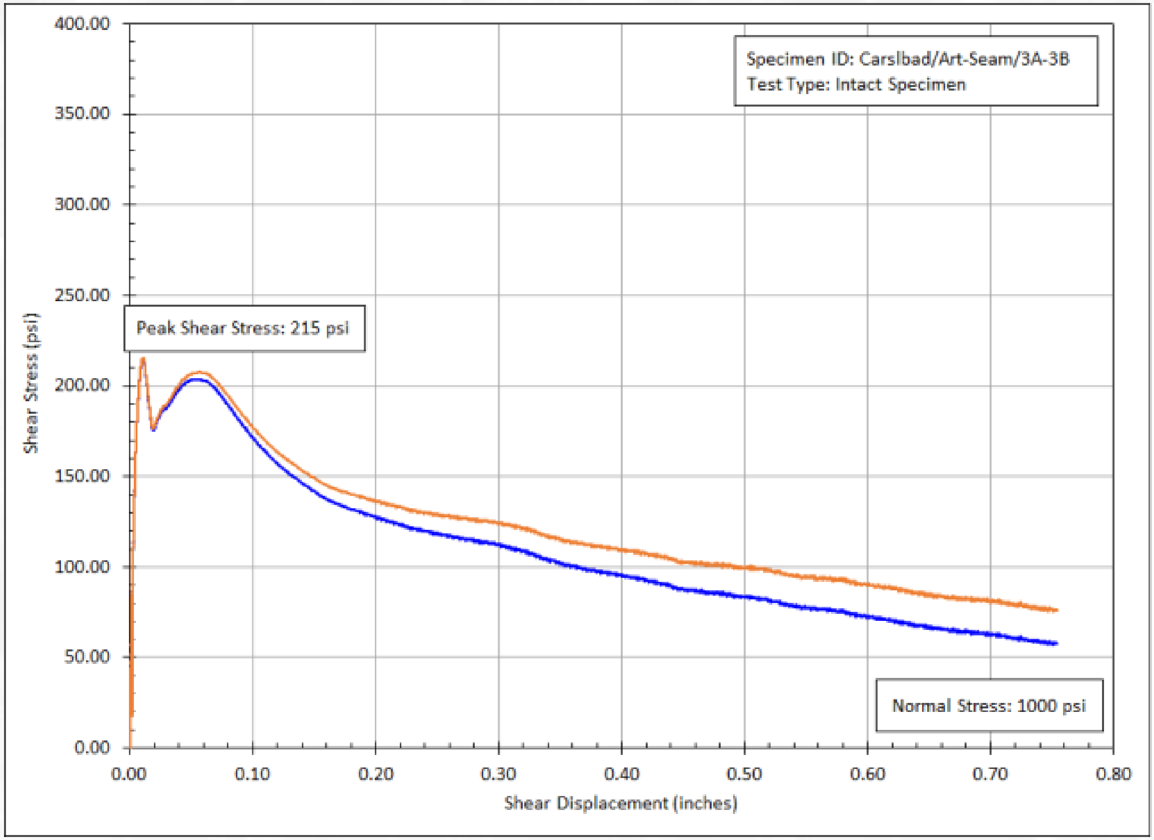


Shear Stress vs. Shear Displacement: Sample #6, 6-mm seam pre-consolidation, 6.89 MPa (1000 psi) normal stress



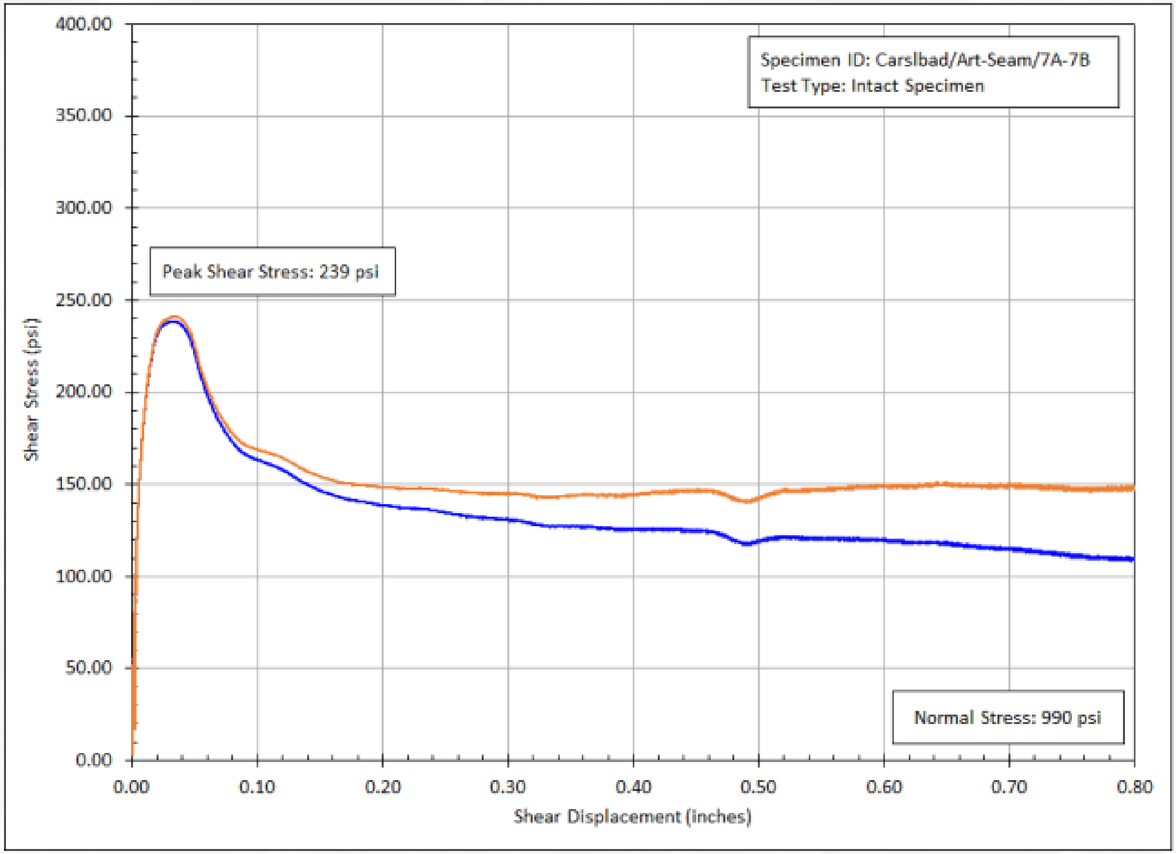
- **Blue: Stress calculated with constant contact area**
- **Orange: Stress calculated with contact area modified by shear displacement**
- **Actual nominal normal stress = 992 psi (6.84 MPa)**
- **Peak shear stress = 282 psi (1.94 MPa)**
- **Never reached residual stress after initiation of shear movement**

Shear Stress vs. Shear Displacement: Sample #3, 12-mm seam pre-consolidation, 6.89 MPa (1000 psi) normal stress



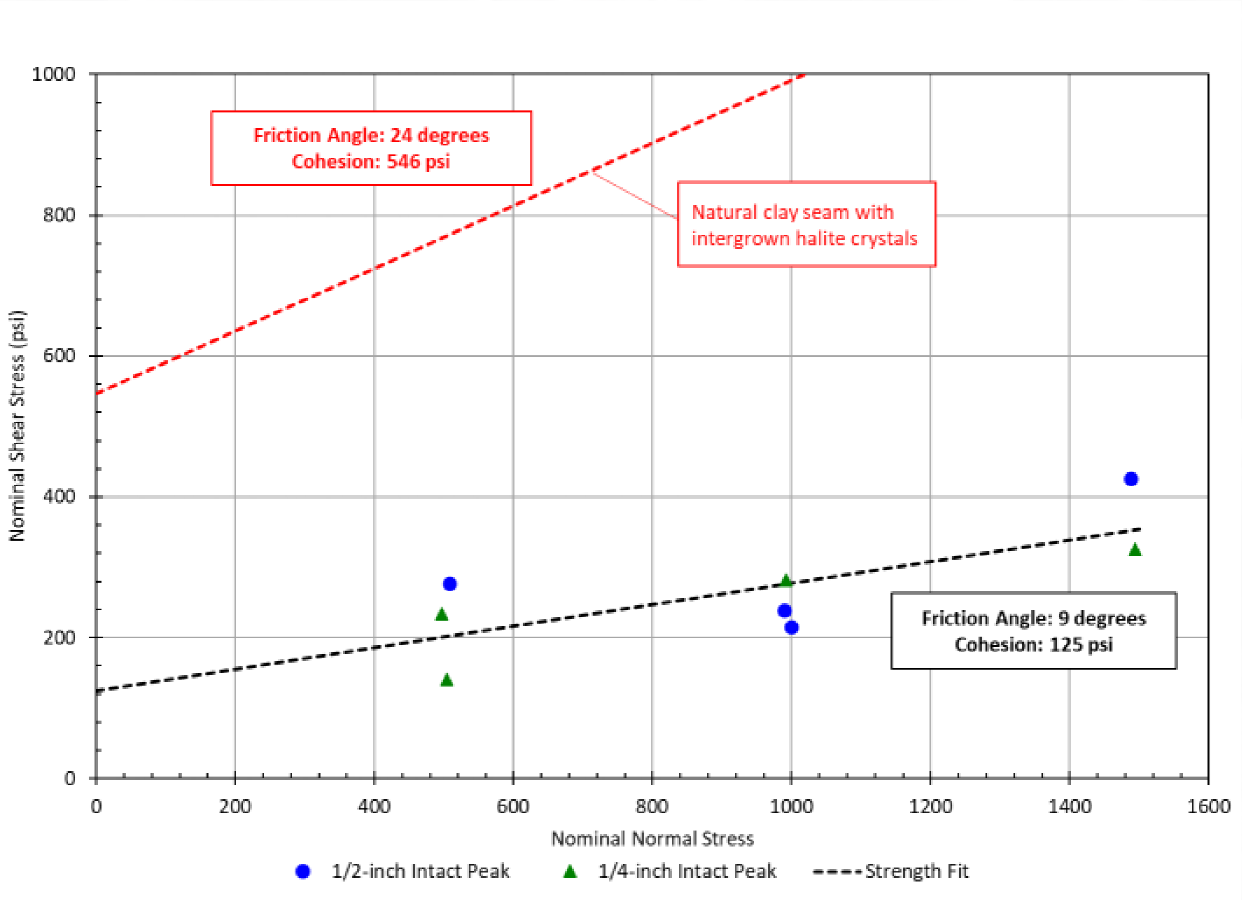
- **Blue: Stress calculated with constant contact area**
- **Orange: Stress calculated with contact area modified by shear displacement**
- **Actual nominal normal stress = 1000 psi (6.89 MPa)**
- **Peak shear stress = 215 psi (1.48 MPa)**
- **Never reached residual stress after initiation of shear movement**
- **Power-related disturbance near beginning of test**

Shear Stress vs. Shear Displacement: Sample #7, 12-mm seam pre-consolidation, 6.89 MPa (1000 psi) normal stress



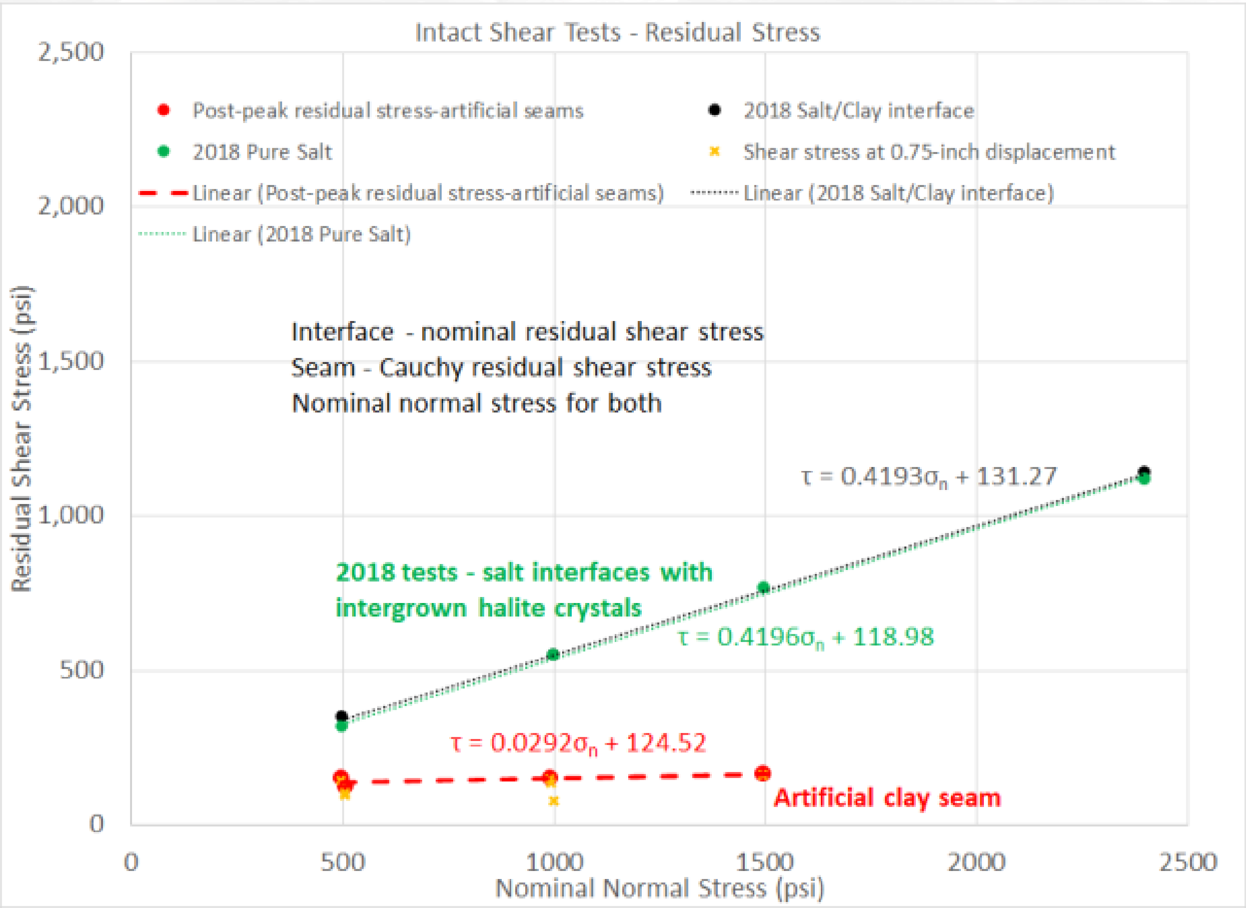
- **Repeat of Test #3 due to power-related disturbance near beginning of test**
- **Actual nominal normal stress = 990 psi (6.83 MPa)**
- **Peak shear stress = 239 psi (1.65 MPa)**
- **Reached apparent residual stress of ~150 psi (1.03 MPa) at 0.75” (19 mm) shear displacement after initiation of shear movement**
- **“Apparent” residual stress because unchanged normal load, changing contact area mean changing normal stress**

Intact Peak Stresses



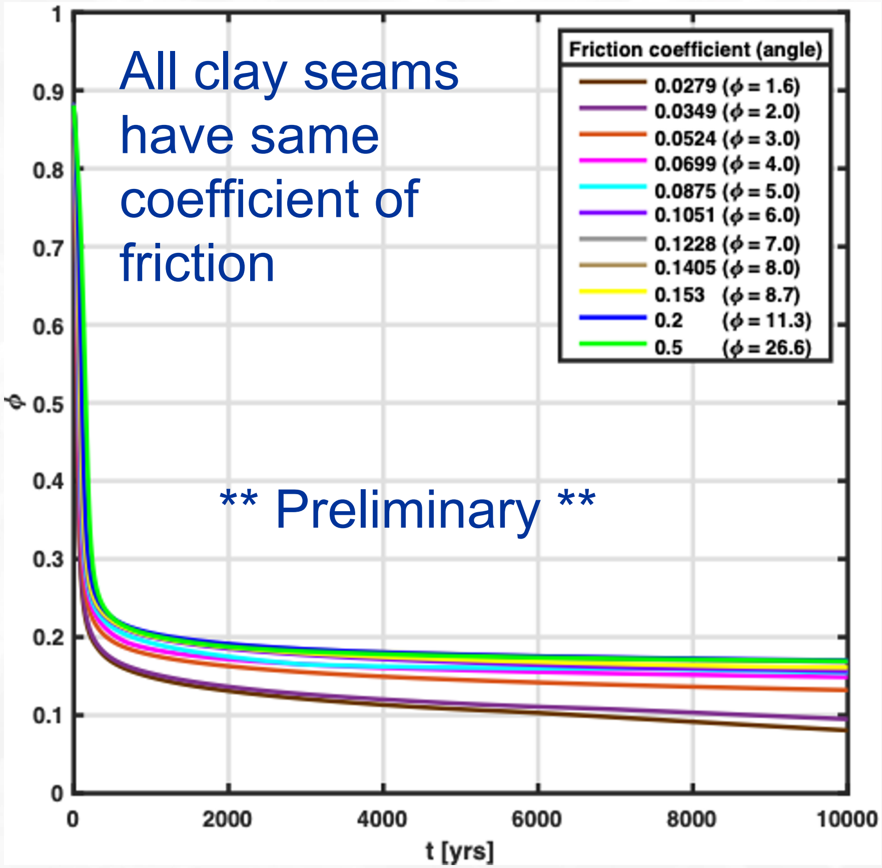
- **Average friction angle 8.7°, average cohesion 125 psi (0.86 MPa)**
- **Much lower than for previous salt interface tests: friction angle 24°, cohesion 546 psi**

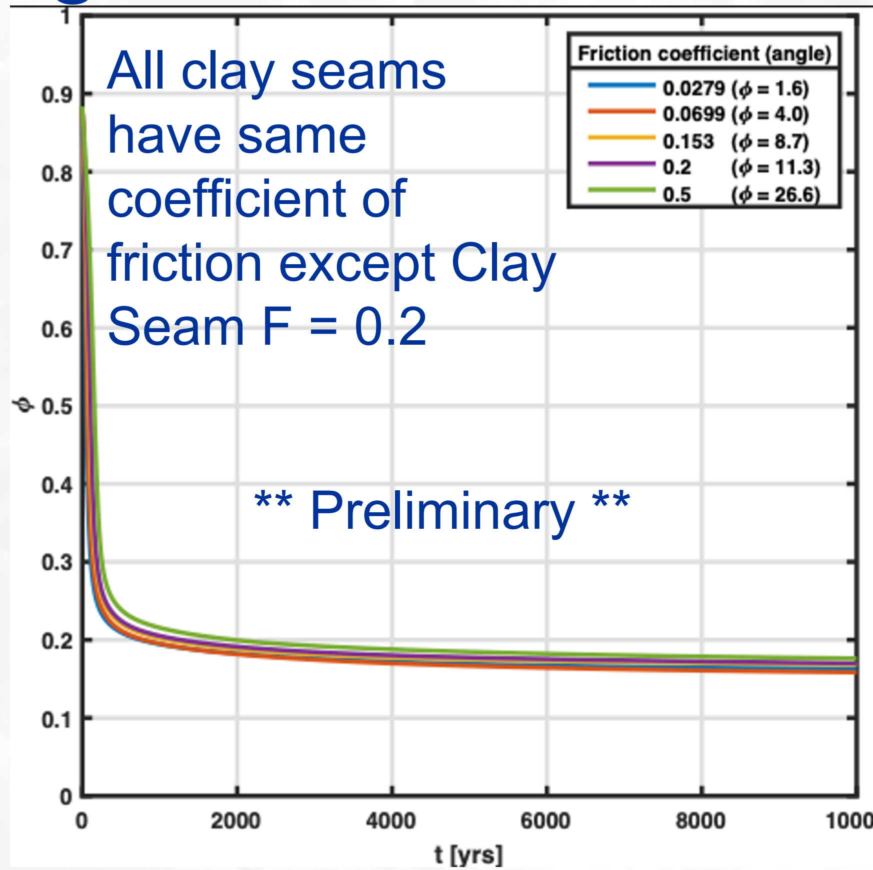
Intact shear tests – Residual Stresses



- Only 4 of 8 tests attained apparent residual stresses after initiation of shear displacement
- Friction angle 1.7°, cohesion ~125 psi (0.86 MPa)
- Lower friction angle than for previous salt interface tests: angle 13-23°, cohesion 119-355 psi (0.82-2.45 MPa)
- Values much lower than expected; softness of clay, asperity size may be factors
- Current assumption is that Clay Seam G test results will plot between interface and artificial seam results

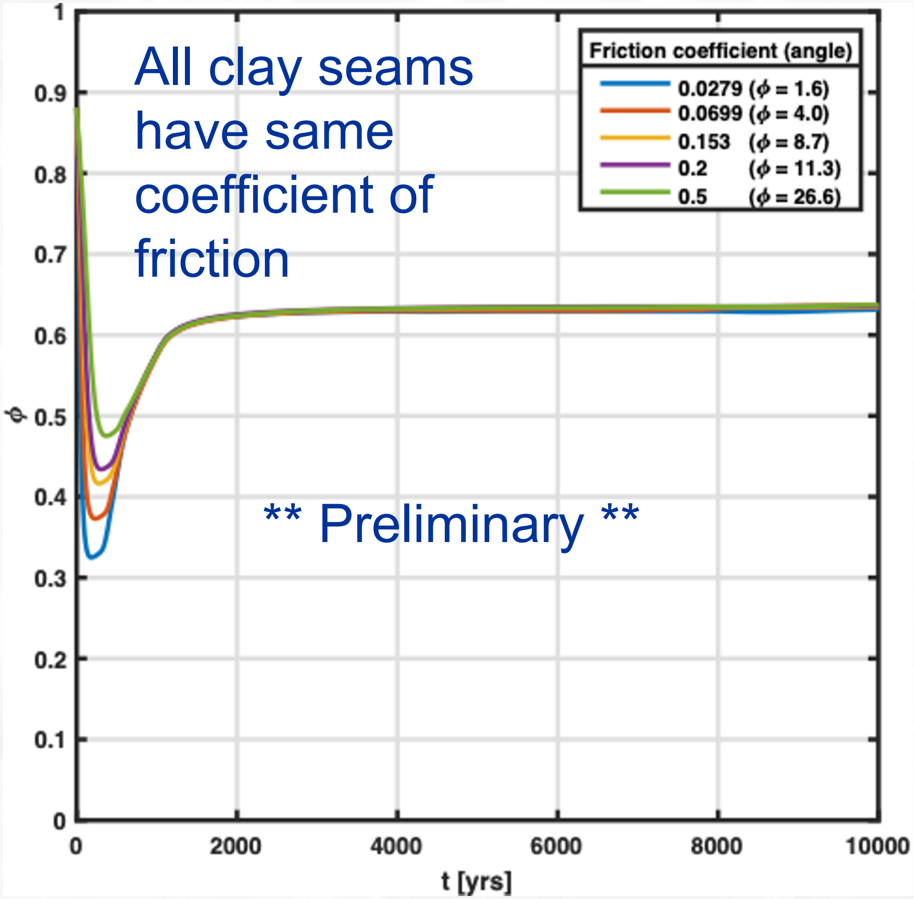
Effect of clay seam on porosity response - zero gas generation

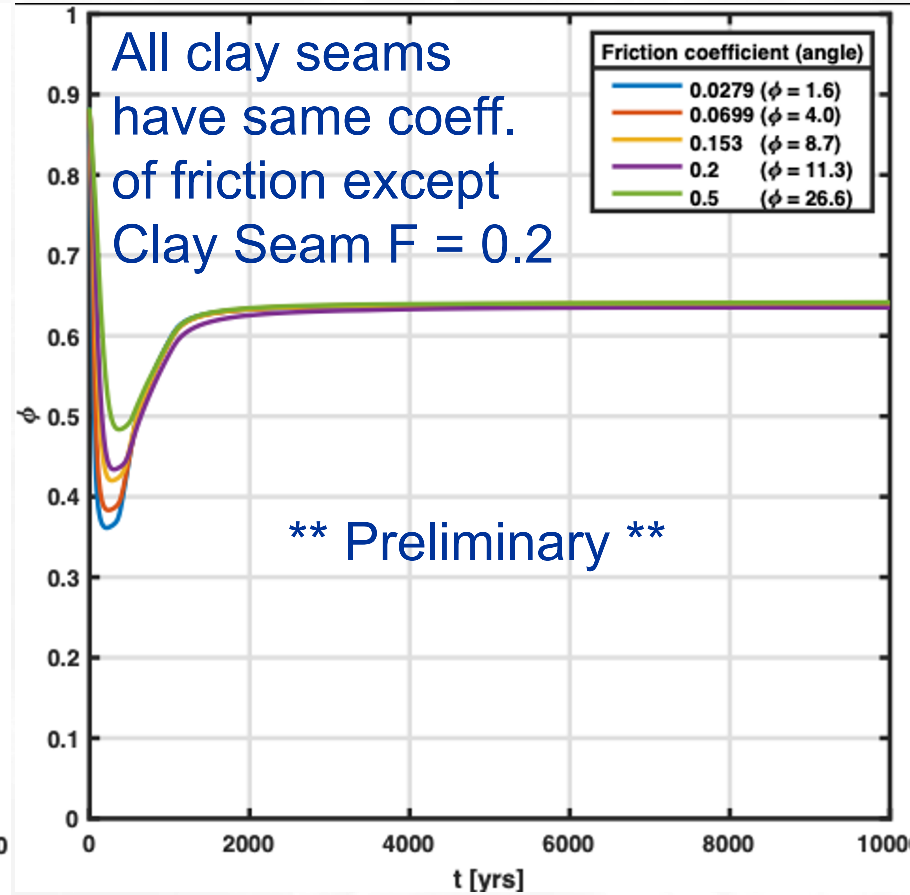




For case of zero gas generation, only clay seams in close proximity to drifts have influence on porosity response surface.

Effect of clay seam on porosity response - gas generation f=0.5





- For case of gas generation, analyses indicate larger sensitivity at short times, and insensitivity at longer times.

Artificial clay seam shear tests – Conclusions

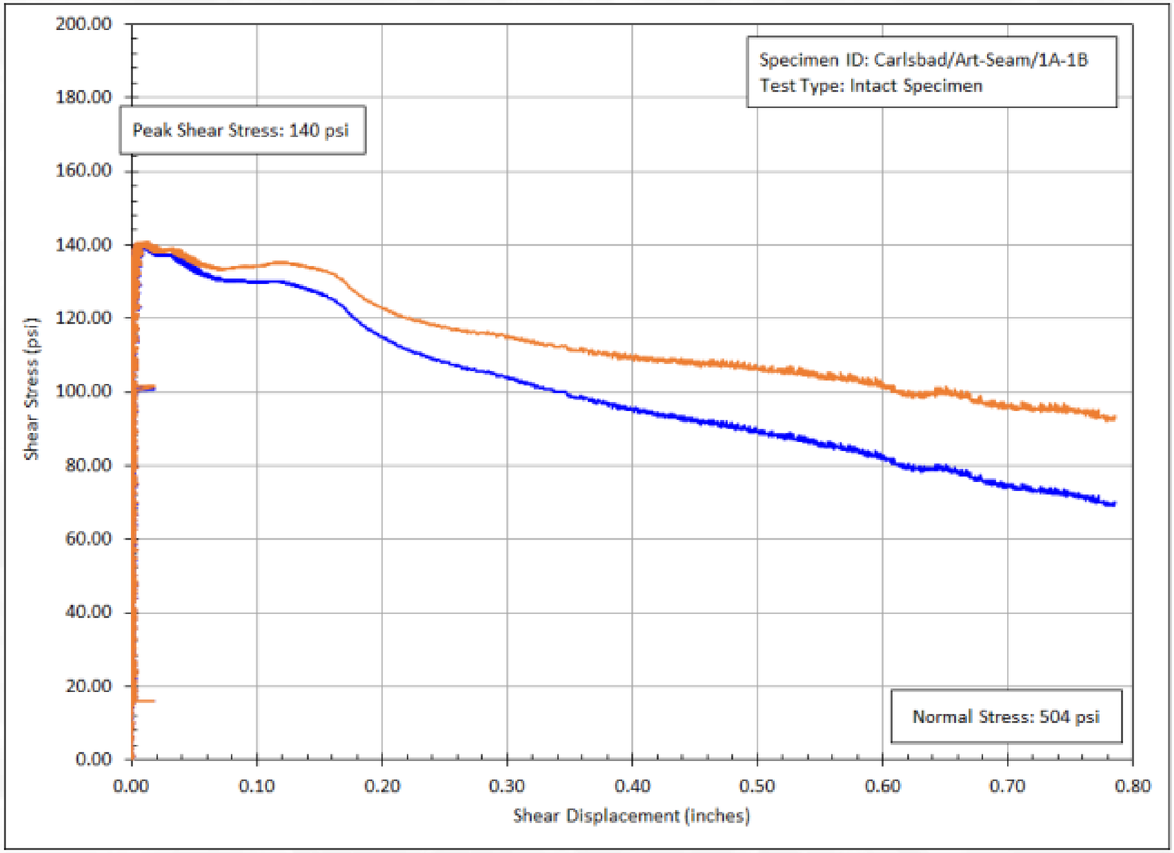
- Eight samples of salt with artificial clay seams of two different thicknesses were subjected to displacement-controlled direct shear tests at three different normal loads.
- Maximum, final shear strength were determined for each test.
- Although none of the tests achieved a true residual stress plateau, the final shear stresses reasonably conformed to Mohr-Coulomb behavior.
- The Mohr-Coulomb parameters were similar to those of a highly consolidated, saturated, clay, which is to say they were quite low.
- In situ WIPP clay seams F, G, others vary significantly in visual, tactile character; relation to artificial seam tests will be unknown until tests on in situ samples can be performed.

Questions?

Thank you for your attention!

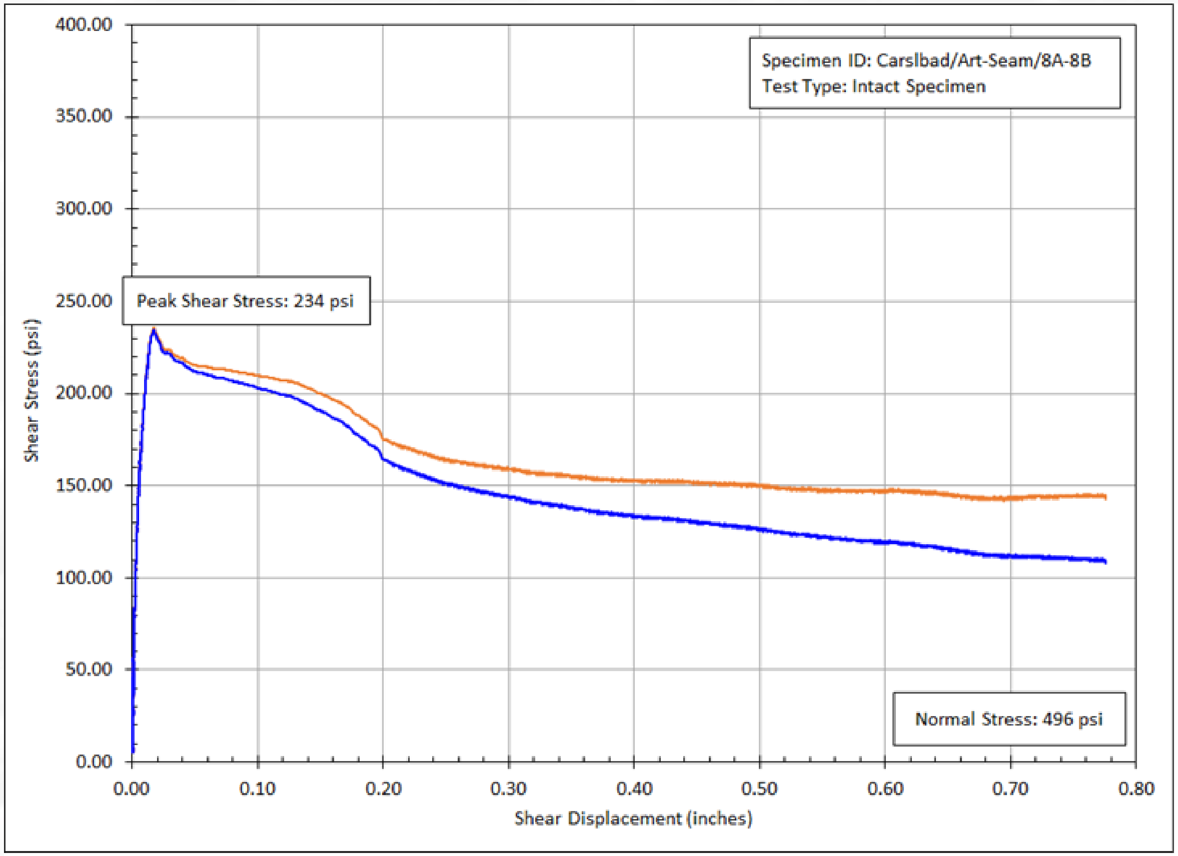
Results of the other artificial seam shear tests

Shear Stress vs. Shear Displacement: Sample #1, ¼” seam pre-consolidation, 500 psi normal stress



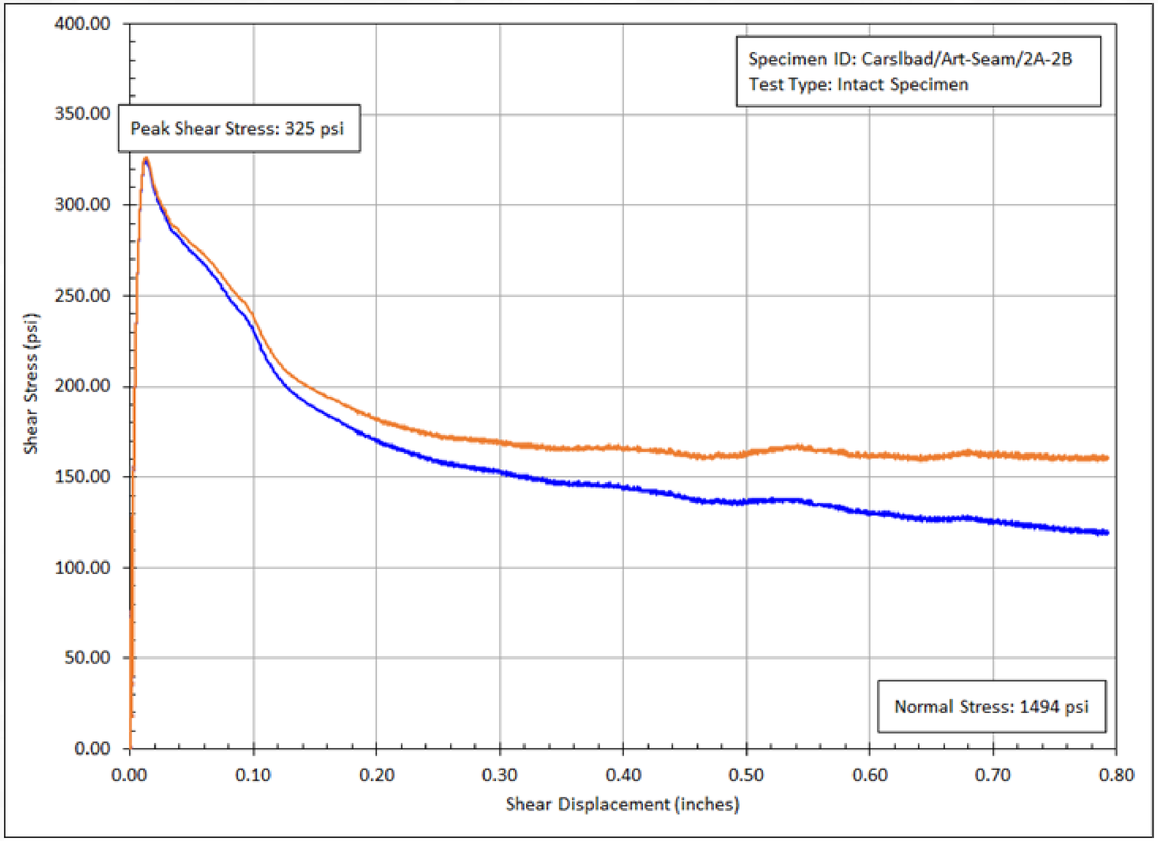
- **Blue: Stress calculated with constant contact area**
- **Orange: Stress calculated with contact area modified by shear displacement**
- **Actual normal stress = 504 psi**
- **Peak shear stress = 140 psi**
- **Never reached residual stress after initiation of shear movement**
- **Test data was very noisy, although probably no effect on main result; Sample #8 tested at same conditions**

Shear Stress vs. Shear Displacement: Sample #8, ¼” seam pre-consolidation, 500 psi normal stress



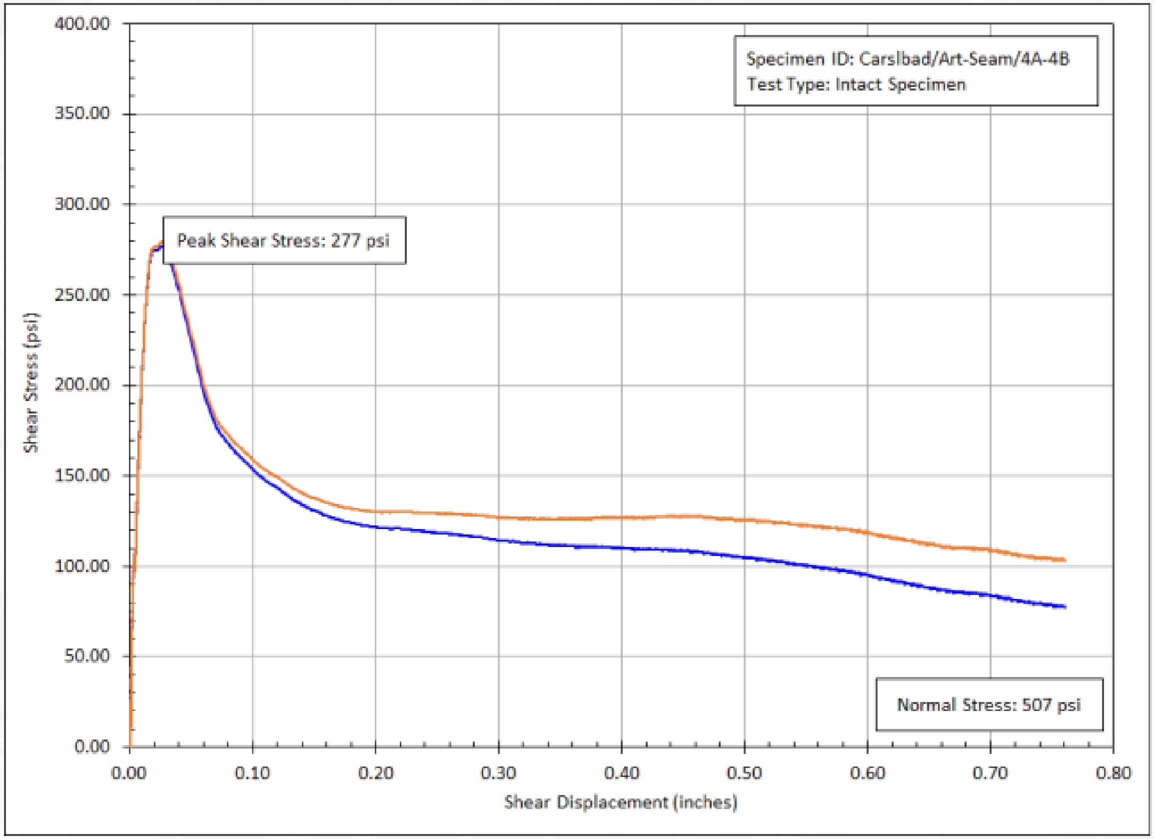
- **Blue: Stress calculated with constant contact area**
- **Orange: Stress calculated with contact area modified by shear displacement**
- **Actual normal stress = 496 psi**
- **Peak shear stress = 234 psi**
- **Reached residual stress of ~150 psi after initiation of shear movement**

Shear Stress vs. Shear Displacement: Sample #2, ¼" seam pre-consolidation, 1500 psi normal stress



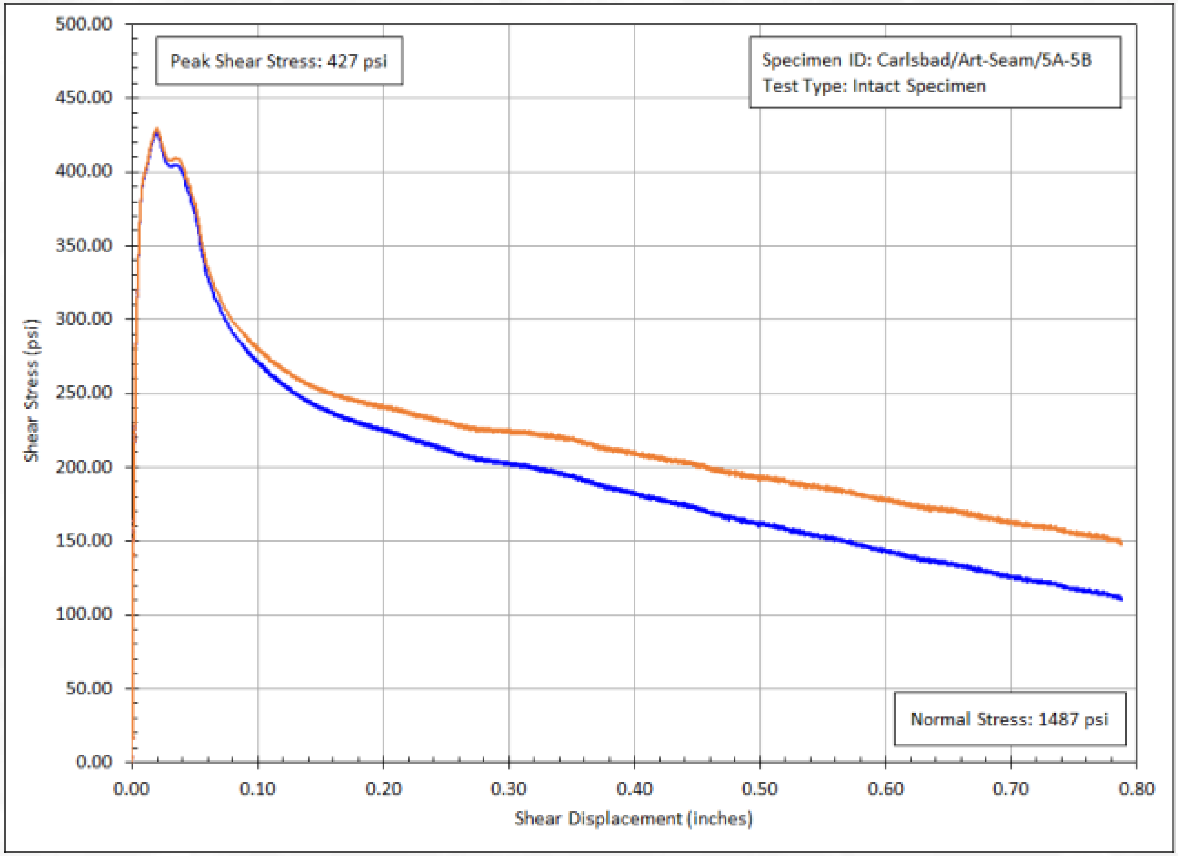
- **Blue: Stress calculated with constant contact area**
- **Orange: Stress calculated with contact area modified by shear displacement**
- **Actual normal stress = 1494 psi**
- **Peak shear stress = 325 psi**
- **Reached residual stress of ~170 psi after initiation of shear movement**

Shear Stress vs. Shear Displacement: Sample #4, ½" seam pre-consolidation, 500 psi normal stress



- **Blue: Stress calculated with constant contact area**
- **Orange: Stress calculated with contact area modified by shear displacement**
- **Actual normal stress = 507 psi**
- **Peak shear stress = 277 psi**
- **Reached residual stress of ~130 psi after initiation of shear movement**

Shear Stress vs. Shear Displacement: Sample #5, ½" seam pre-consolidation, 1500 psi normal stress



- **Blue: Stress calculated with constant contact area**
- **Orange: Stress calculated with contact area modified by shear displacement**
- **Actual normal stress = 1487 psi**
- **Peak shear stress = 427 psi**
- **Never reached residual stress after initiation of shear movement**