Application of Microbial Induced Calcite Precipitation (MICP) to Stabilize Florida High-Organic Matter Soils for Roadway Construction
FDOT Contract No. BDV34 977-06

2017 Geotechnical Research in Progress Meeting
August 17 – 18, 2017

Project Manager:	David Horhota, Ph.D., P.E.
Principal Investigator:	Raphael Crowley, Ph.D., P.E.
Co-Principal Investigators:	Andrew Zimmerman, Ph.D.
Collaborators:	Nick Hudyma, Ph.D., P.E.
	Scott Wasman, Ph.D.
Research Assistants:	Jacob Fuller
	Matthew Davies

UNF FDOT UF

Motivation

- High organic content (OC) soil needs to be stabilized and treated to mitigate settlement
- Previous studies/attempts
  - Surcharging – expensive (Wei et al. 1989)
  - Cut-and-replace – often expensive and not feasible (Mullins 1996)
  - Geogrids and geotextiles tied to cement stabilized columns – excessive differential settlements and column protrusions (Greene et al. 2013)
  - Soil mixing – expensive and causes creep (Mullins and Gunaratne 2014)
  - Dynamic replacement – effective at improving settlement and strength properties (Gunaratne et al. 1997)
  - Large amounts of binder (e.g., cement, lime kiln dust) may be necessary for high OC soil
  - Binder (lime kiln dust) may be a carcinogen (Button 2003)
- Need an effective, economically feasible, and sustainable solution!

Objectives

- Determine Microbial Induced Calcite Precipitation (MICP) feasibility as an environmentally-friendly and sustainable method for treating Florida's OC soil for roadway construction
- Establish procedure to create/test MICP stabilized soil
- Determine procedure and optimal conditions for microbes to stabilize FL OC soil
- Recommendations and guidelines for field test site/application (e.g. pilot project)

MICP – Governing Chemical Reactions

- Governing Reactions (Ureolytic Microbes):
  - $CO(NH_2)_2 + H_2O \rightarrow NH_2COOH + NH_3$
  - $NH_2COOH + H_2O \rightarrow NH_3 + H_2CO_3$
  - $2NH_3 + 2H_2O \leftrightarrow 2NH_4^+ + 2OH^-$
  - $H_2CO_3 \leftrightarrow HC\quad_3^- + H^+$
  - $HC\quad_3^- + H^+ + 2NH_4^+ + 2OH^- \leftrightarrow \boldsymbol{CO_3^{2-}} + 2NH_4^+ + 2H_2O$
  - $\boldsymbol{Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3}$

UNF FDOT UF

Treatment Setup

UF Treatment Cells

- Components:
  - Acrylic test cells that split down the middle
  - Peristaltic pump that pumps feed stock (urea & calcium chloride solution) to the specimens
  - Erlenmeyer flasks for effluent after feeding

UNF FDOT UF

Generalized Treatment Procedure

1. Plate and grow bacteria (*Sporosarcina pasteurii*) using growth media (yeast, ammonium sulfate, and tris)

2. Autoclave fluid and add bacteria

3. Pump bacteria onto soil; wait so that bacteria have time to attach to soil particles

4. Feed bacteria every 6 of hours with nutrient broth (urea solution)

Sand Treatments – Preliminary Testing

- 66 columns tested with varying conditions including different
  - pHs
  - Number of feed times
  - Bacteria strains
  - Pumping methods (top versus bottom of tube)
  - Grain sizes
  - Bacteria attachment times
  - Aeration
  - Bacteria concentrations/volumes
  - Initial growth media

- Once methodology had been determined, 14 additional columns treated for physical property testing

Preliminary Testing – Lessons Learned

- Organism health/vitality appears to play a critical role cementation success
- Attachment time also appears to be critically important
- Aeration appeared to have little effect
- Four feedings per day produces more cementation than two feedings per day
- Much cementation/precipitation variability observed as a function of specimen height; thought to be the result of pore clogging

Treated Sand – Selected Photographs

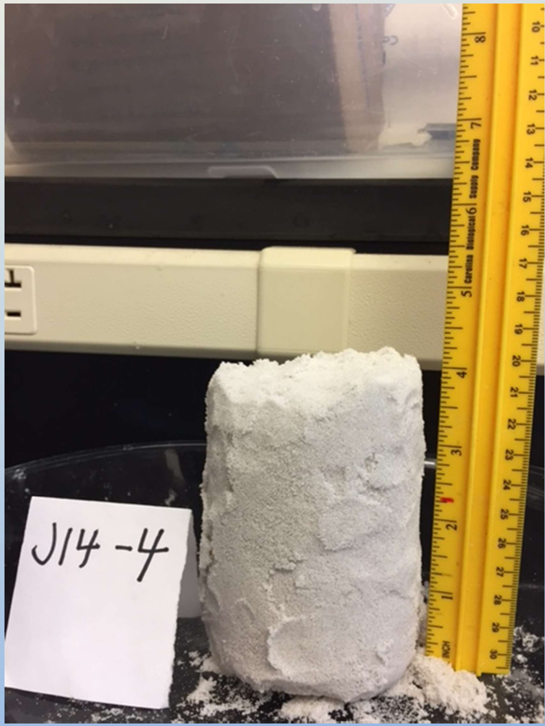
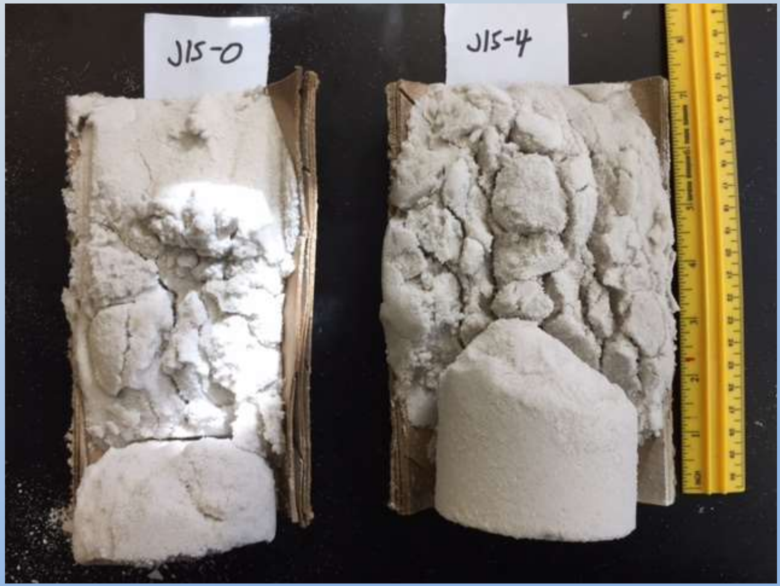
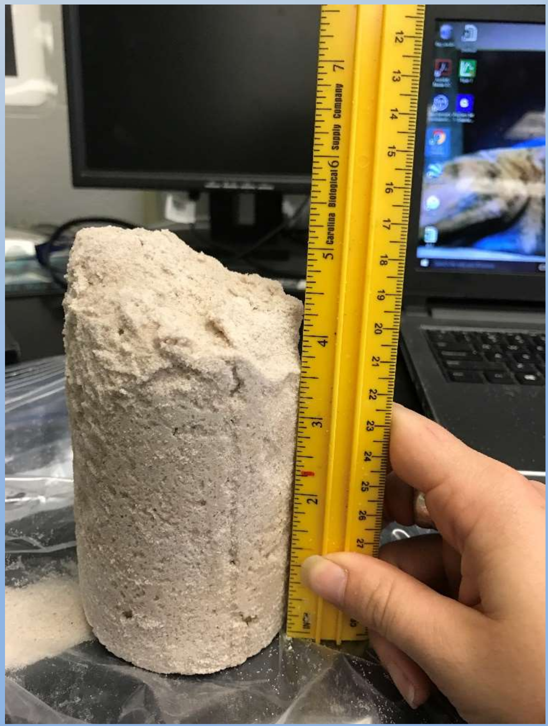


Figure 1-2. Specimen J14-4 after treatment



Specimens J15-0 and J15-4 after treatment



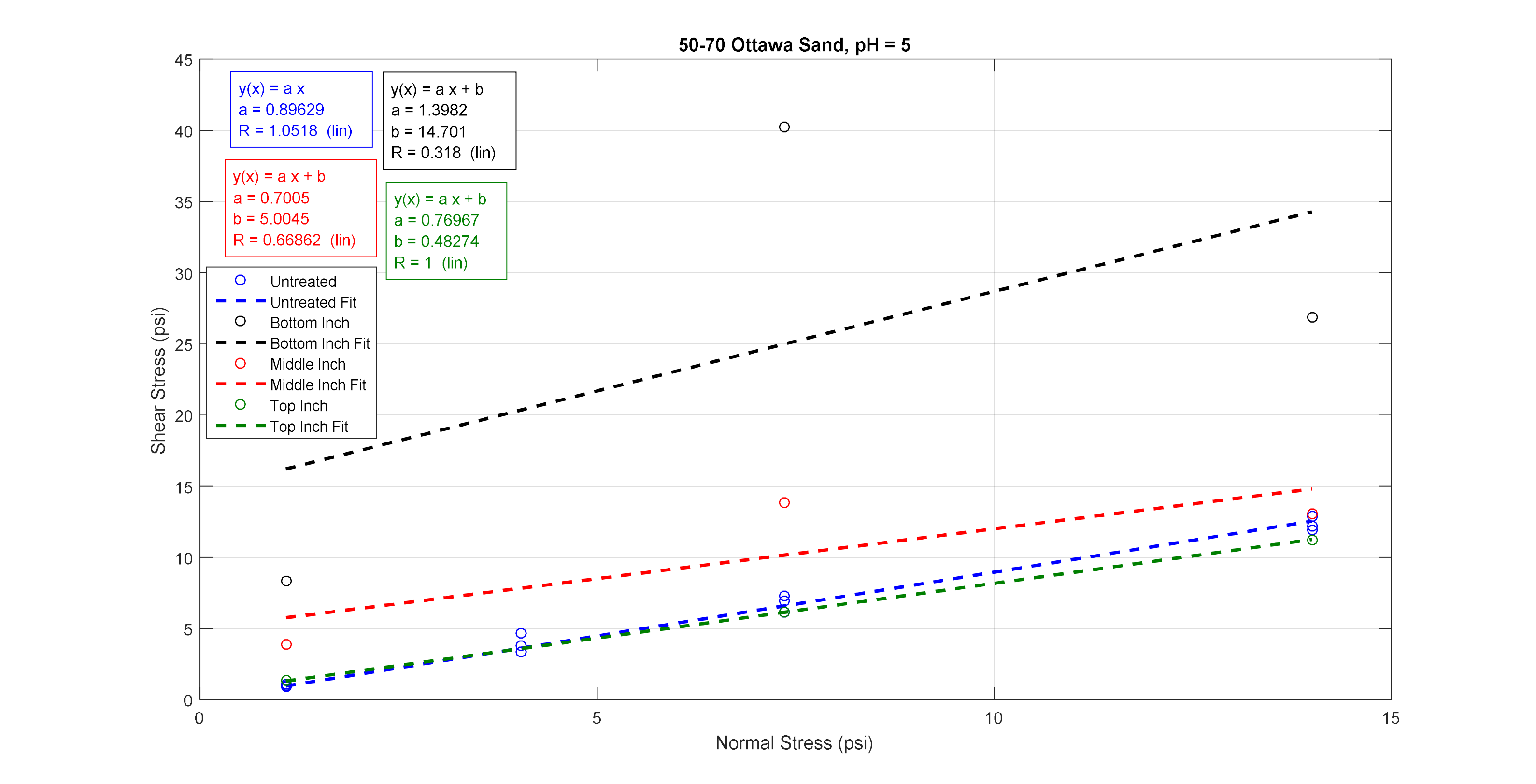
Specimen J11-X after treatment

UNF

FDOT

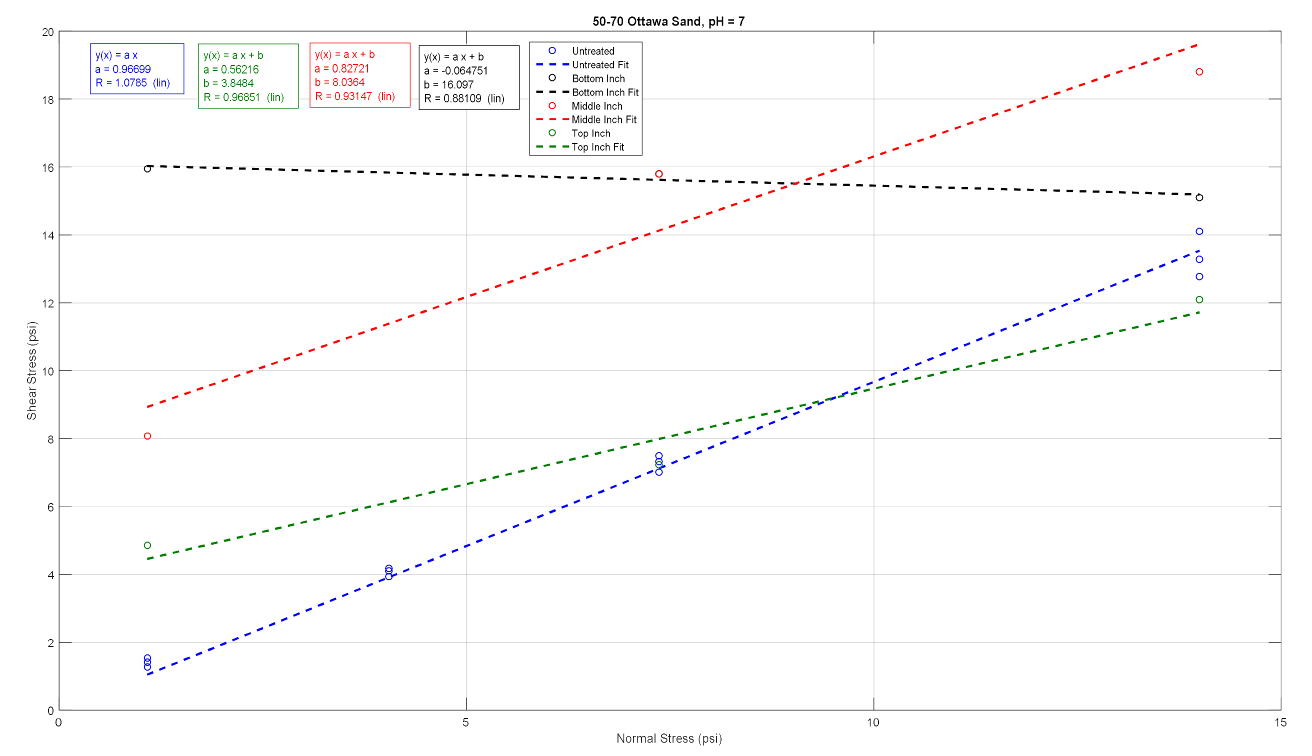
UF

Direct Shear Test Results



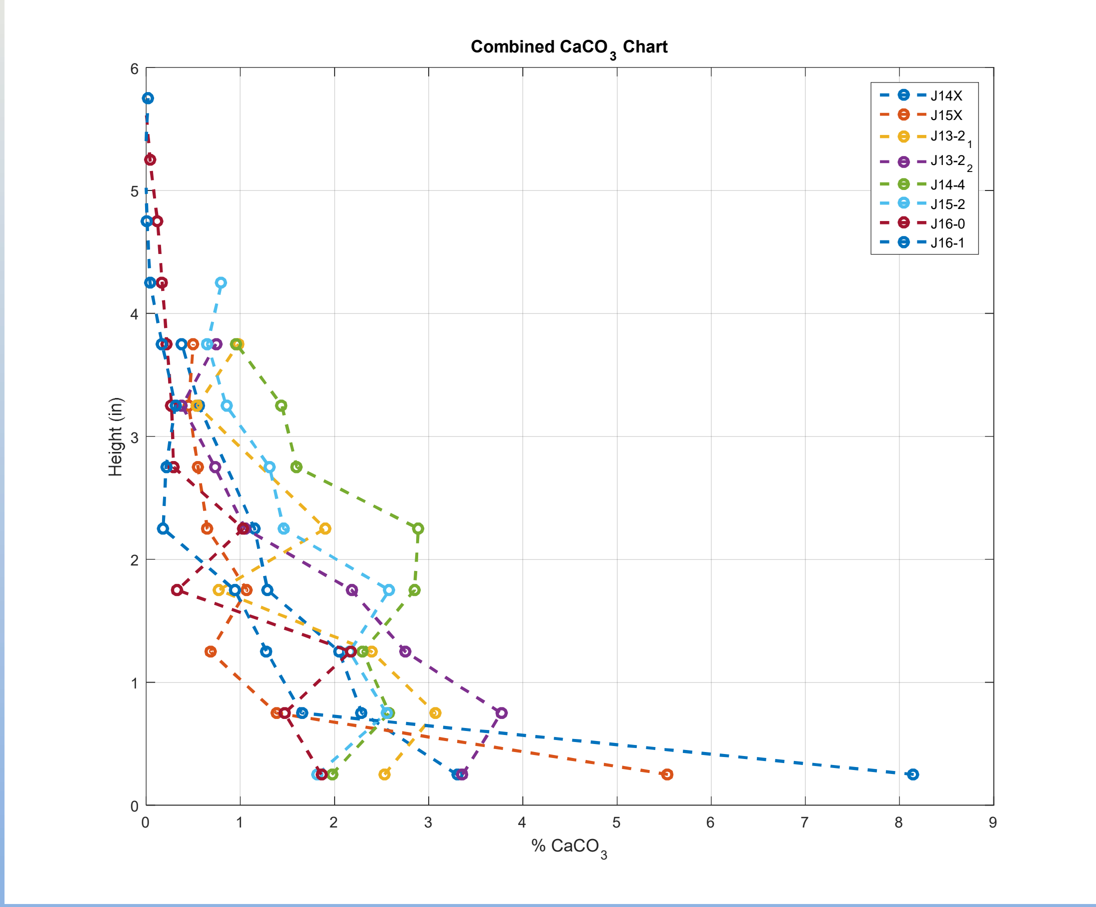
Shear Stress vs. Normal Stress for 50-70 Ottawa Sand, pH = 5

Direct Shear Results



Shear Stress vs. Normal Stress for 50-70 Ottawa Sand, pH = 7

Treated Sand – Variability in Precipitate



% $CaCO_3$ vs. Height for various sand specimens

- Maximum cementation at the bottom of specimens due to pore clogging
- After ~4 inches – very little cementation
- Need to examine physical property tests as a function of specimen height as well

UNF

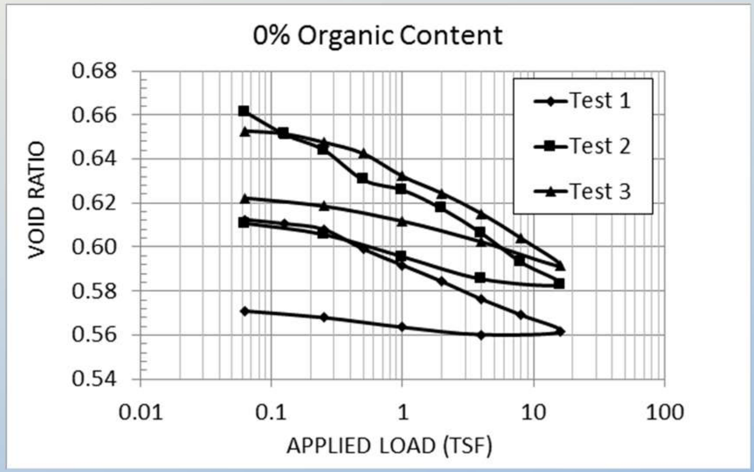
UF

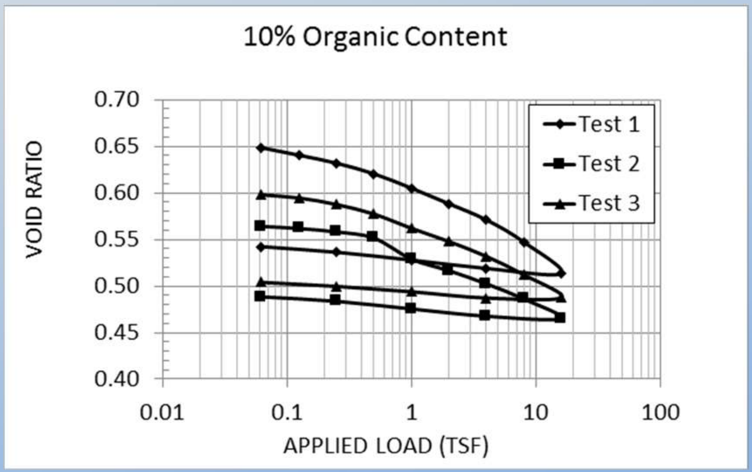
Preliminary Organic Treatment

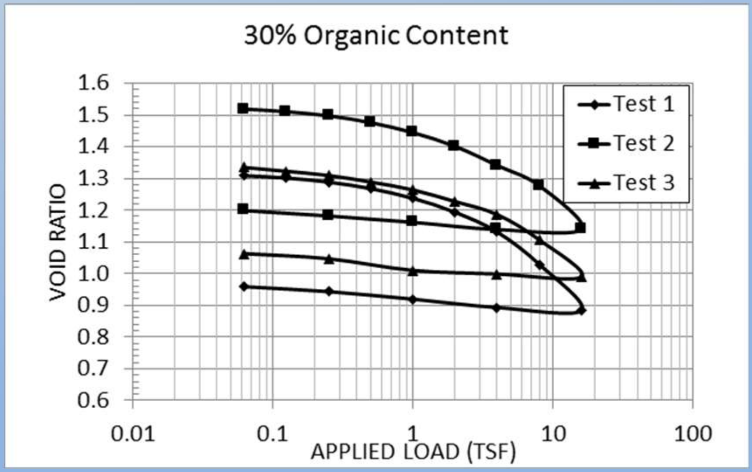
- 27 Columns treated with OC varying 10% to 50%

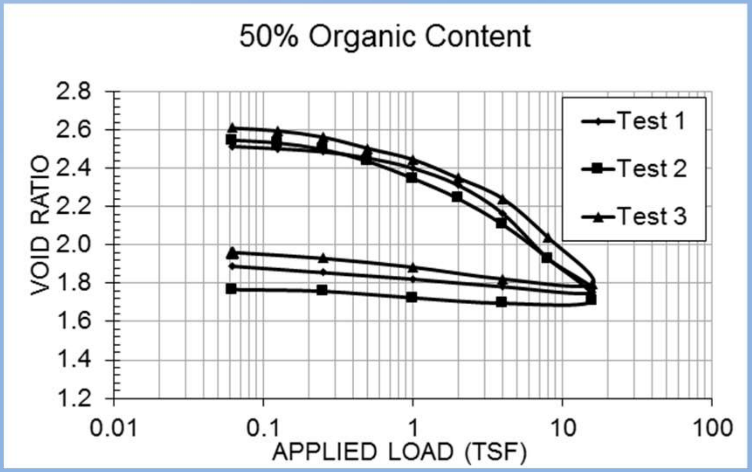
- Results were inconsistent, although experimentation underway to address these issues.

Consolidation: Untreated Soil









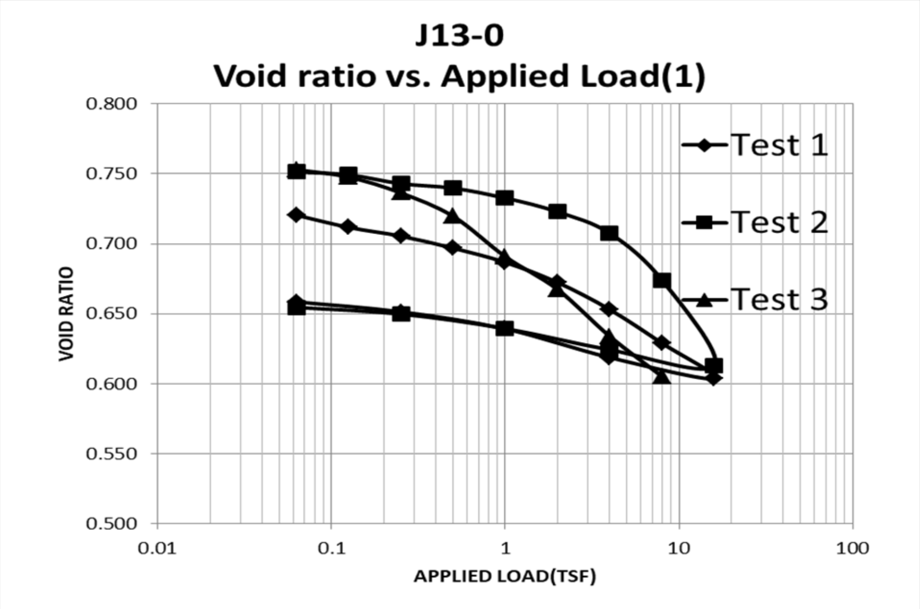
Consolidation, Untreated Soil

Property	0% OC			10% OC			30% OC			50% OC		
	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
Cc	0.025	0.040	0.037	0.095	0.062	0.066	0.41	0.334	0.326	0.679	0.659	0.738
Cr	0.007	0.017	0.017	0.014	0.013	0.011	0.042	0.036	0.018	0.059	0.0523	0.089
e_o	0.614	0.667	0.678	0.66	0.57	0.60	1.33	1.53	1.34	2.52	2.58	2.62
$w_{initial}$ (%)	9.2	9.7	10.05	24.7	30.5	31.3	67.8	67	68.9	88.9	87.8	89.3
γ_w (pcf)	111.49	109.69	108.07	97.9	108.6	106.9	84.0	78.1	84.2	57.2	56.0	56.1
γ_d (pcf)	102.10	99.99	98.20	78.5	83.3	81.4	50.1	46.8	49.9	30.3	29.8	29.6
G_s	2.64			2.09			1.87			1.71		
pH	7			5			5			5		

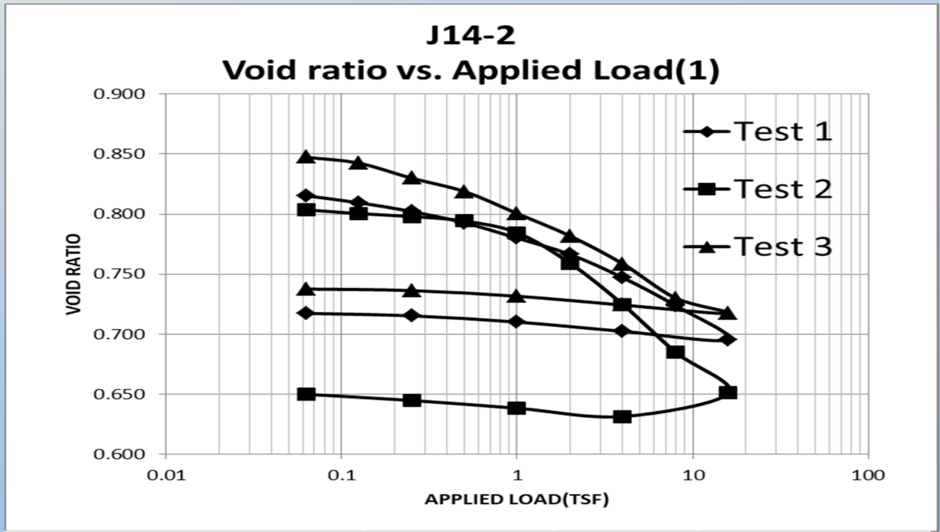
Consolidation: Summary of Results, Untreated 50/70 Ottawa Sand

Properties	Current Research (2017)	Simpson (2014)	Feng and Montoya (2014)	Lin et al. (2015)
Gs	2.64	2.65	2.65	2.65
D_{10}	0.21	0.25	N/A	0.26
D_{30}	0.25	0.26	N/A	0.31
D_{50}	0.27	0.26	0.22	0.44
D_{60}	0.28	0.27	N/A	0.37
C_U	1.33	1.07	1.40	1.43
C_C	1.06	1.02	0.90	1.01
C_C (Compression Index)	0.025, 0.025 (Test 1)	0.05	0.06	0.024
	0.040, 0.040 (Test 2)			
	0.037, 0.039 (Test 3)			
C_R (Recompression Index)	0.007, 0.007 (Test 1)	0.005	0.04	0.0010
	0.017, 0.017 (Test 2)			
	0.017, 0.015 (Test 3)			
Initial Void Ratio	0.614 (Test 1)	0.66	0.75	0.73
	0.667 (Test 2)			
	0.678 (Test 3)			

Consolidation: Treated Sand

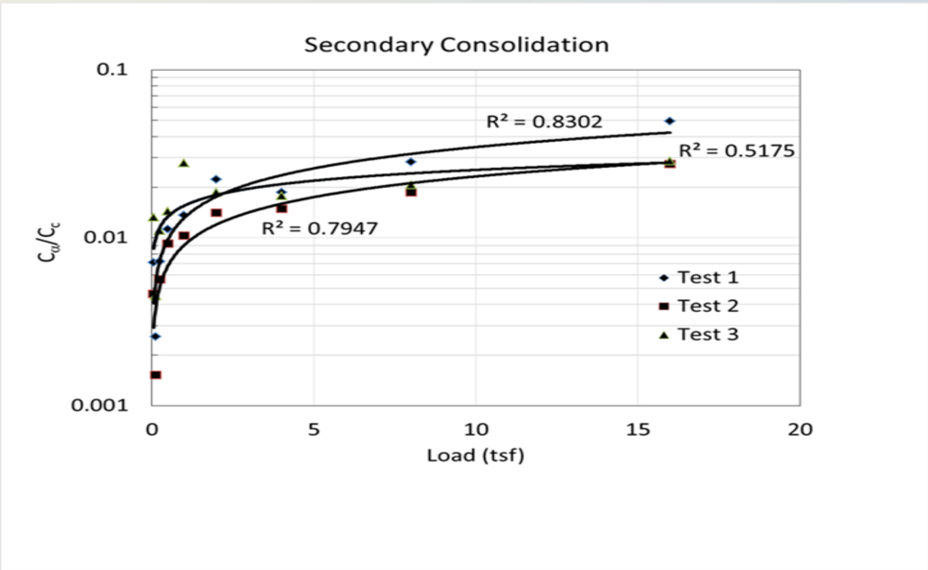


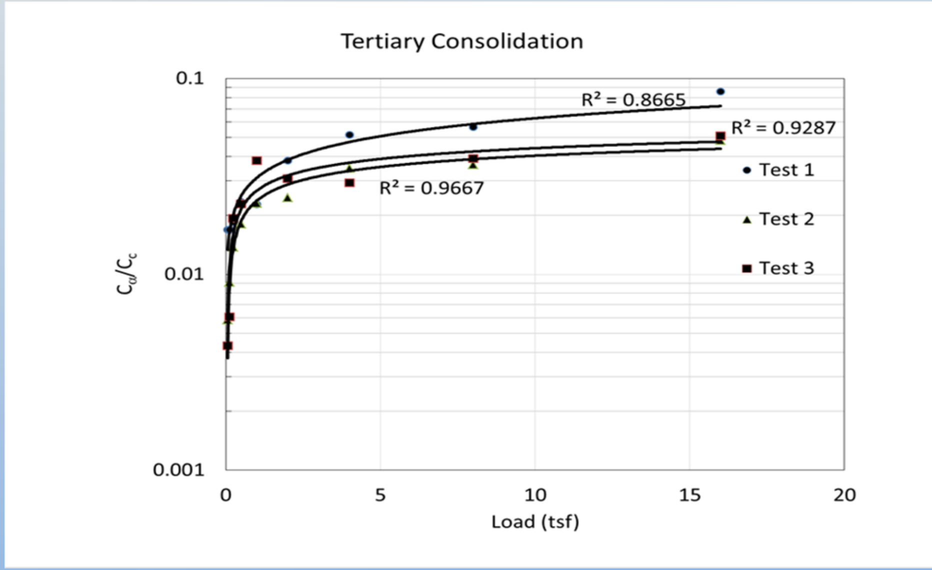
J13-0	Test 1	Test 2	Test 3
C_C	0.077	0.156	0.103
C_R	0.022	0.022	0.020
Initial Void Ratio	0.72	0.75	0.75
pH	7	7	7
Initial moisture content (%)	0.45	0.45	0.44
Wet density (pcf)	96.2	95.0	94.2
Dry density (pcf)	95.7	94.5	93.7



J14-2	Test 1	Test 2	Test 3
C_C (1)	0.071	0.123	0.086
C_R (1)	0.012	0.012	0.125
C_C (2)	0.066	0.116	0.080
C_R (2)	0.013	0.011	0.012
Initial Void Ratio	0.79	0.81	0.85
pH	5	5	5
Initial moisture content (%)	0.75	0.75	0.75
Wet density (pcf)	92.6	91.2	89.1
Dry density (pcf)	91.9	91.2	89.1

Secondary and Tertiary Compression: 10% Organic Content

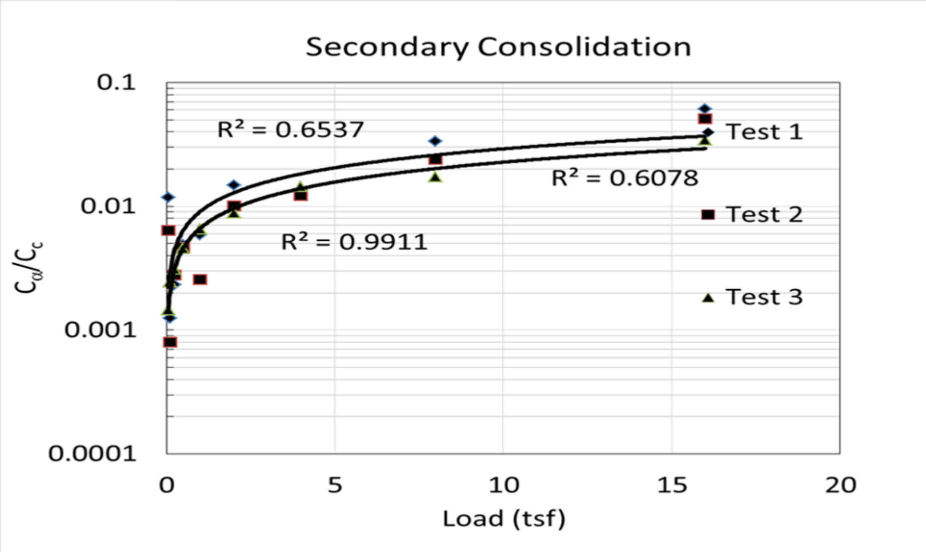


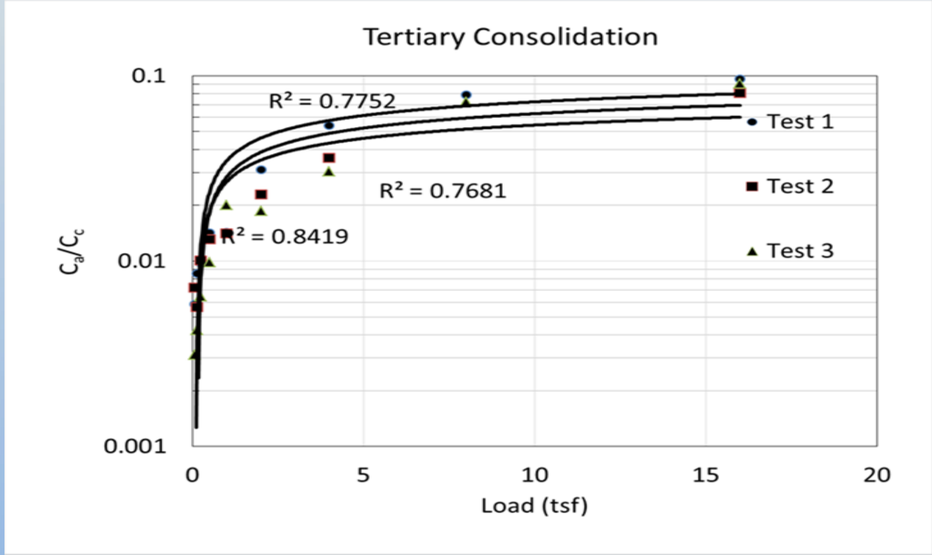


Averages – Secondary Consolidation			
	Test 1	Test 2	Test 3
C_a	0.0014	0.00069	0.0011
C_{ae}	0.00082	0.00044	0.00071
C_a/C_c	0.018	0.011	0.017
C_{ae}/OC	0.0081	0.0044	0.0071

Averages – Tertiary Consolidation			
	Test 1	Test 2	Test 3
C_a	0.0028	0.0013	00016
C_{ae}	0.0017	0.00093	0.0011
C_a/C_c	0.037	0.025	0.027
C_{ae}/OC	0.017	0.0092	0.011

Secondary and Tertiary Compression: 30% Organic Content

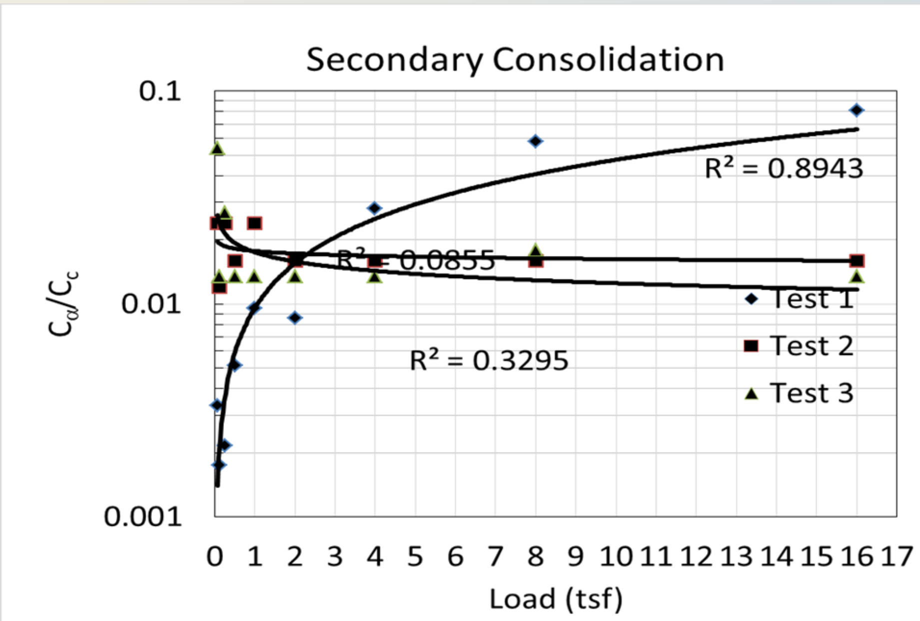


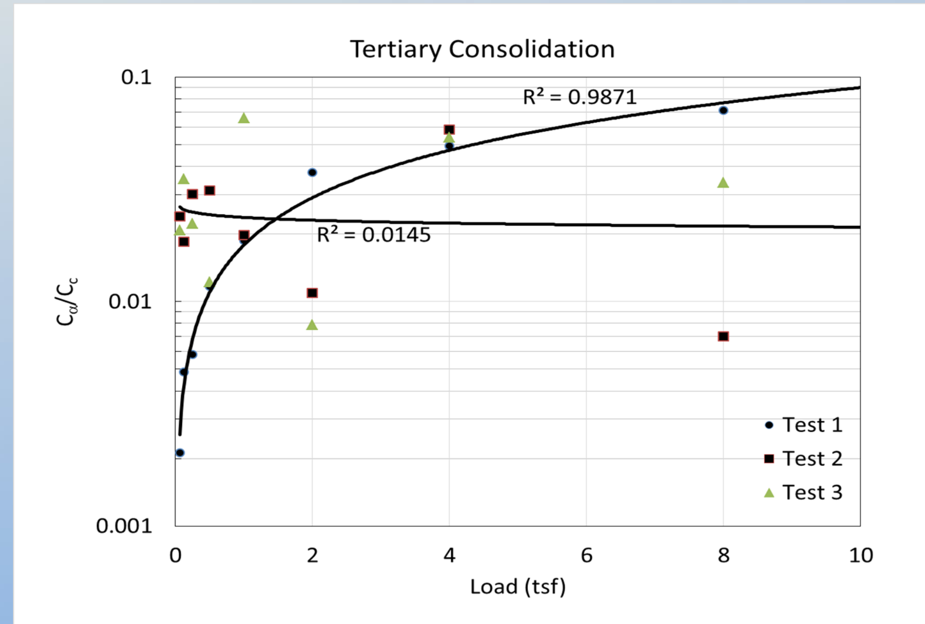


Averages – Secondary Consolidation			
	Test 1	Test 2	Test 3
C_a	0.0058	0.0049	0.0036
C_{ae}	0.0025	0.0019	0.0015
C_a/C_c	0.017	0.013	0.010
C_{ae}/OC	0.0083	0.0064	0.0051

Averages – Tertiary Consolidation			
	Test 1	Test 2	Test 3
C_a	0.012	0.0091	0.0098
C_{ae}	0.0052	0.0036	0.0042
C_a/C_c	0.035	0.024	0.028
C_{ae}/OC	0.017	0.012	0.014

Secondary and Tertiary Compression: 50% Organic Content





Averages – Secondary Consolidation			
	Test 1	Test 2	Test 3
C_a	0.015	0.011	0.013
C_{ae}	0.0042	0.0032	0.0036
C_a/C_c	0.022	0.018	0.020
C_{ae}/OC	0.0080	0.0063	0.0071

Averages – Tertiary Consolidation			
	Test 1	Test 2	Test 3
C_a	0.023	0.015	0.016
C_{ae}	0.0066	0.0042	0.0053
C_a/C_c	0.034	0.025	0.029
C_{ae}/OC	0.013	0.0084	0.011

UNF New Treatment Options

- UNF Treatment Cells

- Were using two strains purchased from ATCC & USDA
- New approaches
  - Strains distributed by USDA Strain
  - New Method: Deep Soil Treatment
  - Possible enzyme treatment option

UNF

UF

Organics – Percolation Method

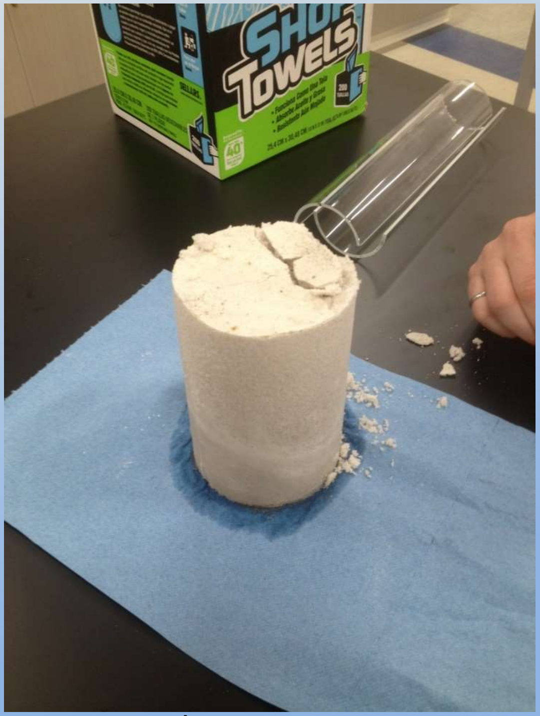
48hr Run

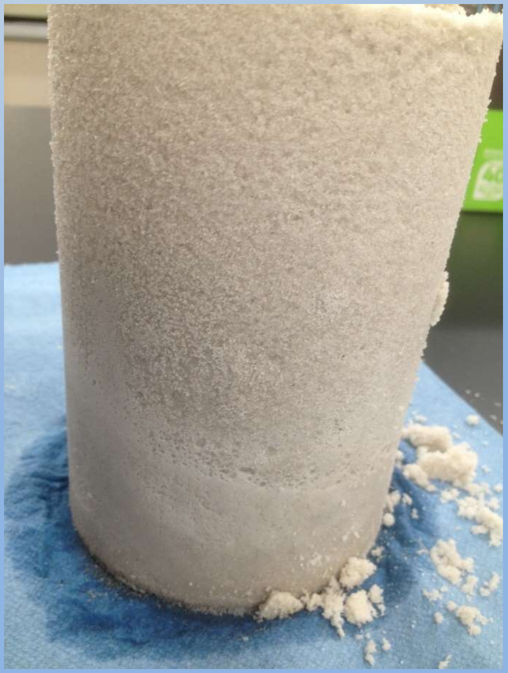
50% OC soil
2.5M Urea 2.5M $CaCl_2$

Post Treatment Wet

Post Treatment Dry

Deep Soil Treatment - New Approach





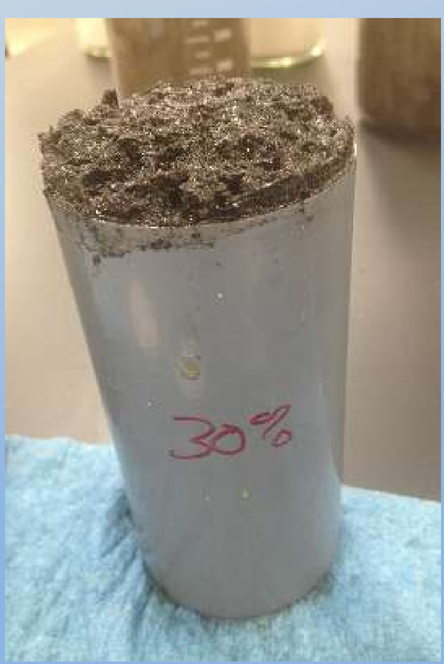
Ottawa Sand – 1.0M Urea, 0.25M $CaCl_2$

24hr Run

Organics – Deep Soil Treatment Approach

Ottawa Sand

10% OC Soil



30% OC Soil

50% OC Soil

Organics – Deep Soil Treatment Approach

Expansion Control

10% OC Soil

30% OC Soil

50% OC Soil

Organics – Deep Soil Treatment Approach

Ottawa Sand | 10% OC Soil | 30% OC Soil | 50% OC Soil

Organics – Deep Soil Treatment Approach

Post Treatment Percolation Method

Organics – Deep Soil Treatment Approach

10% OC Soil 30% OC Soil 50% OC Soil

Organics – Future Direction(s)

- Explain why sporosarcina likes silica more than OC.
  - SEM to look for calcification points and particle bridging
  - Surface area effects to cause a morphological change in the bacteria to induce calcite formation. Use of Surfactants to modify the soil surface tension.
  - CT progressive scans of calcite precipitation in situ.
  - Compression chamber to prevent CO_2 escape thus possibly increasing homogeneity and calcite yield.
  - Enzyme treatment of OC soils with knowledge of above without having to deal with a living orgnaism.

UNF FDOT UF

Summary

- Ottawa treatment
  - Have shown success comparative to previous studies
  - Completed DST
  - Consolidation in progress
  - Beginning triaxial soon
- Organics treatment
  - Underway
  - Preliminary results presented
- More collaborative treatment process
  - Treating at UF/UNF
  - Expanding treatment options
- Increasing productivity/success
  - Introducing more treatment options
  - Multiple treatments at a time

UNF FDOT UF

Thank You!

Questions?