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

2016 Geotechnical Research in Progress Meeting
July 14 – 15, 2016

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Motivation

- High-OM soil needs to be stabilized and treated to stop and prevent roadway settlement
- Previous studies/attempts
  - Ground tire rubber (GTR) – not successful (Cosentino et al. 2014)
  - Soil-mixed vertical columns – expensive (Mullins and Gunaratne 2014)
  - Cut-and-replace – often expensive and not feasible (Mullins and Gunaratne 2014)
  - Lime Kiln Dust (LKD) – 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 high-OM soils for roadway construction

- Establish procedure to create/test MICP stabilized soil

- Determine procedure and optimal conditions for microbes to stabilize FL OM soil

- Recommendations and guidelines for field test site/application (e.g. pilot project)

Microbial Induced Calcite Precipitation

- Governing Reactions (Ureolytic Microbes):
  - $CO(NH_2)_2 + H_2O \rightarrow NH_2COOH + NH_3$
  - $NH_2COOH + H_2O \rightarrow NH_3 + H_2CO_3$
  - $2NH_3 + 2H_2O \leftrightarrow 2NH_4^+ + 2OH^-$
  - $H_2CO_3 \leftrightarrow HCO_3^- + H^+$
  - $HCO_3^- + H^+ + 2NH_4^+ + 2OH^- \leftrightarrow \boldsymbol{CO_3^{2-}} + 2NH_4^+ + 2H_2O$
  - $\boldsymbol{Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3}$

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Project Tasks

- Task 1 – Literature review
- Task 2 – Design/fabricate lab column experiments and test with ureolytic microbes
  - Cells for OM soil treatment/calcium cementation
  - Shear and consolidation tests for influence of treatment
- Task 3 – Optimize ureolytic MICP procedure
- Task 4 – Explore ureolytic and non-ureolytic microbes ability to stabilize FL sand and OM soil
- Task 5 – Final report and closeout meeting

LITERATURE REVIEW

	Test and Methods	Use	Sources
Monitoring			
	Shear Wave Velocity: bender element or accelerometer	Direct relationship between S-wave and mass of calcium carbonate precipitation, void ratio, and confining stress	(DeJong et al. 2006; DeJong et al. 2010)
	Compression Wave Velocity: bender elements, accelerometer, or ultrasonic device	Detect soil deformation behavior	(DeJong et al. 2010; Weil et al. 2012)
	Electrical resistivity	Detect soil density variation and changes in pore fluid composition which allows for the monitoring of hydrolysis	(Klein and Santamarina, 2002; Snieder et al. 2005; Li et al. 2005; Mortensen et al. 2011)
	Hydraulic resistivity: Water pressure transducers and fluid sampling ports	Regulate fluid in/out flow	(Whiffin et al. 2007).
Testing			
	Triaxial	Test shear strength and stiffness	(DeJong et al. 2006; Whiffin et al. 2007; Mortensen et al. 2011; Montoya and DeJong 2015)
	Unconfined Compression	Test stiffness and unconfined strength	Ng et al. (2012)
	Direct Shear	Test shear strength and stiffness	(DeJong et al. 2006; Feng and Montoya 2016)
	Scanning Electron Microscopy (SEM)	Visualize the micro-scale of calcite precipitation	(Stocks-Fischer et al. 1999; Bachmeier et al. 2002; DeJong et al. 2006; Ng et al. 2012; Maleki et al. 2016)
	X-Ray Diffraction (XRD) quantitative analysis	Detect new crystal formations; characterization of precipitate	(Stocks-Fischer et al. 1999; Nonakaran et al. 2015; Vahabi et al. 2015)
	Optical density	Analyze bacterial cell density	(Gat et al. 2011; Rong and Qian 2014)
	X-Ray Tomography	Follow 3D deformation during triaxial test	(Tagliaferri et al. 2011)

Microbe Type	Soil (characteristics)	Source
S. Pasteurii	Sand (quartz)	(Stocks-Fischer et al. 1999)
	Sand: Ottawa 50-70 (D_{50} = 0.12 mm, C_u = 1.6, C_c = 0.8, G_s = 2.65, e_{min} = 0.55, e_{max} = 0.87)	(DeJong et al. 2006)
	Sand: Itterbeck D_{10} = 0.010 mm, D_{50} = 0.165 mm, D_{90} = 0.275 mm; dry density = 1.65 g/cm^3, porosity = 37.8%	(Whiffin et al. 2007)
	Toyoura and No. 3 Silica sand , Edosaki and Kushiro peat	(Inagaki et al. 2011)
	N/A	(Gat et al. 2011)
	Silica, calcite, iron oxide, feldspar	(Mortensen et al. 2011)
	Fractured rock	(Cuthbert et al. 2013)
	Sandy soil, sand = 95%, Silt = 5%, pH = 8	(Maleki et al. 2016)
	Sand: Ottawa 50-70	(Feng and Montoya 2016)
	Uniformly Graded Sand, saturated hydraulic conductivity = 1.5 × 10^{-3} cm/s, specific gravity = 2.65, coarse sand = 0.6 %, medium sand = 31.9 %, fine sand = 67.5 %, D_{10} = 0.24 mm, D_{30} = 0.3 mm, D_{60} = 0.4 mm, C_c = 0.94, C_u = 1.67.	(Salifu et al. 2016)
E. Coli HB101 (studied with plasmids pBU11 and pBR322)	N/A	(Bachmeier et al. 2002)
Bacillus Sphaericus	Silica sand	(Cheng and Cord-Ruwisch 2012)
B. Diminuta CP16, S. soli CP23 and B. lentus CP28		(Wei et al. 2015)
Bacillus Megaterium	Gravel = 0%, sand = 29%, silt = 55%, clay = 16%	(Ng et al. 2012)
Pseudomonas Stutzeri	n/a: synthetic homogeneous pore network	(Singh et al. 2015)

Highlights

- S. *Pasteurii proven thus far to be most successful*
  - *Combined or competing bacterium has shown promise in recent research*
- *Injection rates greater than 10 ml/min produce higher cementation rates, but less uniformity (Mortensen et al. 2011)*
- *Alternating percolation in unsaturated conditions produces three times higher local strength per mass than traditional saturated techniques* (Cheng and Cord-Ruwisch 2012)
- DeJong et al. (2013) applied MICP to gravel to enable horizontal directional drilling for a gas pipeline treating a 100 cubic meter (131 cubic yards) volume between depths of 3 and 20 meters which proved successful
- Inagaki et al. (2011) successfully treated small scale peat samples using MICP
- *Organics and calcite permanence require more research*

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LABORATORY EXPERIMENTS

Task 2	Soil Type	Soil pH	No. Soil Columns	No. Direct Shear Tests	No. Consolidation Tests
Baseline (In Progress)	Ottawa Sand	-	1	1	1
	50% OC	-	1	1	1
Untreated	Ottawa Sand	5.0	1	3	3
	Ottawa Sand	7.0	1	3	3
	50% OC	5.0	1	3	3
	50% OC	7.0	1	3	3
	30% OC	5.0	1	3	3
	30% OC	7.0	1	3	3
	10% OC	5.0	1	3	3
	10% OC	7.0	1	3	3
Treated	Ottawa Sand	5.0	1	3	3
	Ottawa Sand	7.0	1	3	3
	50% OC	5.0	1	3	3
	50% OC	7.0	1	3	3
	30% OC	5.0	1	3	3
	30% OC	7.0	1	3	3
	10% OC	5.0	1	3	3
	10% OC	7.0	1	3	3
		Totals	18	50	50

Materials

0% Organic Content (Ottawa 50-70), G(s): 2.64

- Silica sand purchased from…

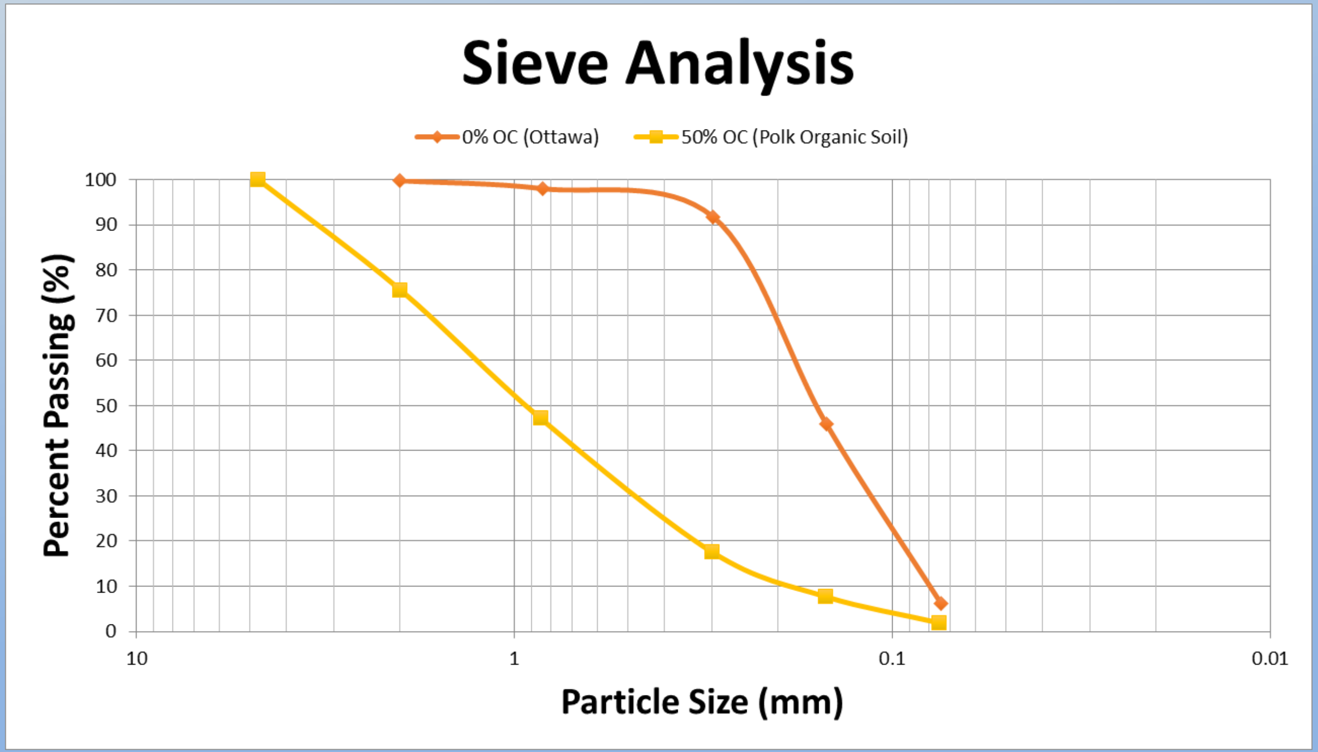
50% Organic Content (Polk City Organic Material SR-33), G(s):

- 100 % passing No. 4 sieve (4.75 mm)

Index and Classification Properties

	Organic Soil			Ottawa Sand		
Moisture Content (%)	60.4	58.4	59.1	0	0	0
Organic Content (%)	49.7	49.2	45.2	na	na	na
Specific Gravity	1.71	1.71	1.74	2.64	2.64	2.64

	Ottawa	Organic
D(10)	0.08	0.19
D(30)	0.12	0.49
D(60)	0.19	1.30
Cu	2.3	6.8
Cc	1.0	1.0



MICP-Treatment Processes

Untreated

- Aerated solution of urea medium pumped through sample at 20 mL/minute

Treated

- Enriched urea-culture of Sporosarcina *pasteurii* pumped through samples at 20 mL/minute for 20 minutes
- Urea solution pumped through until maximum cementation reached

Treatment Setup

Full treatment setup

OTTAWA SAND
IN CHAMBER

PERISTALTIC PUMP

INCUBATION CHAMBER 2.8 IN ID,
7 IN LENGTH, ACRYLIC SPLIT MOLD

Bacterial Solution

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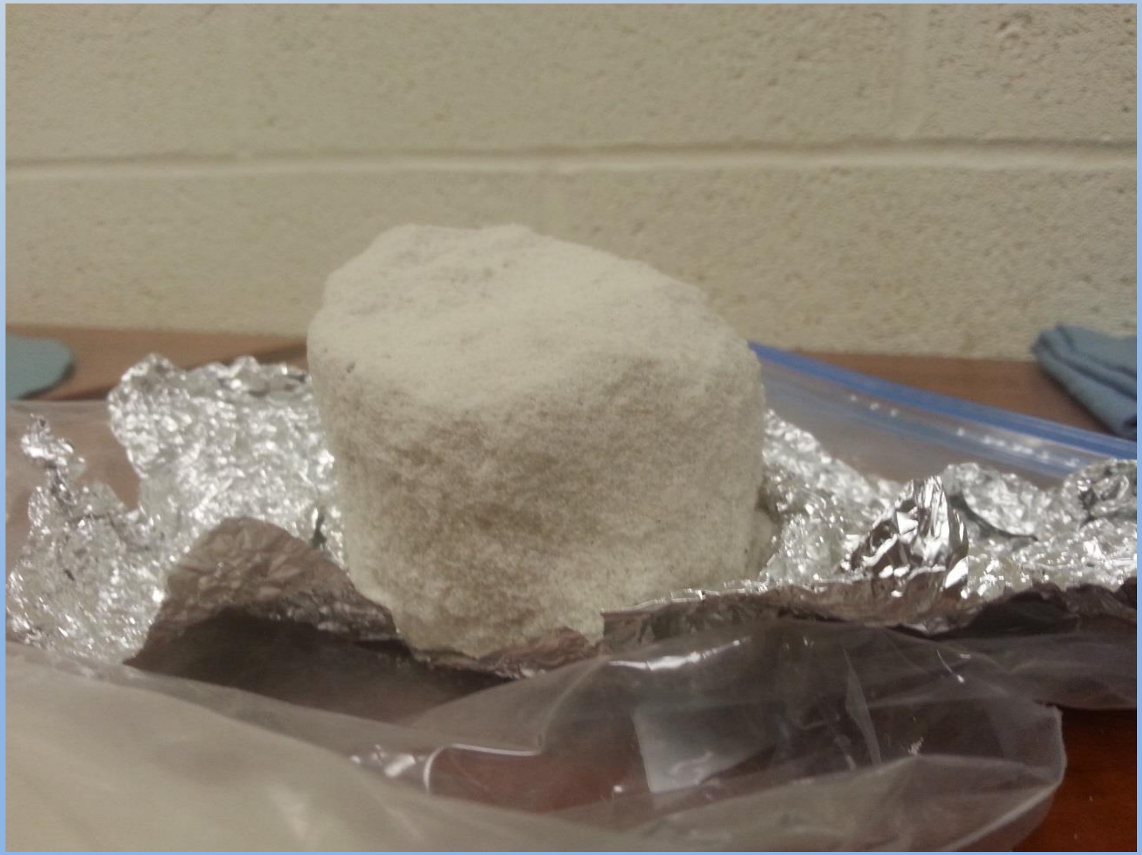
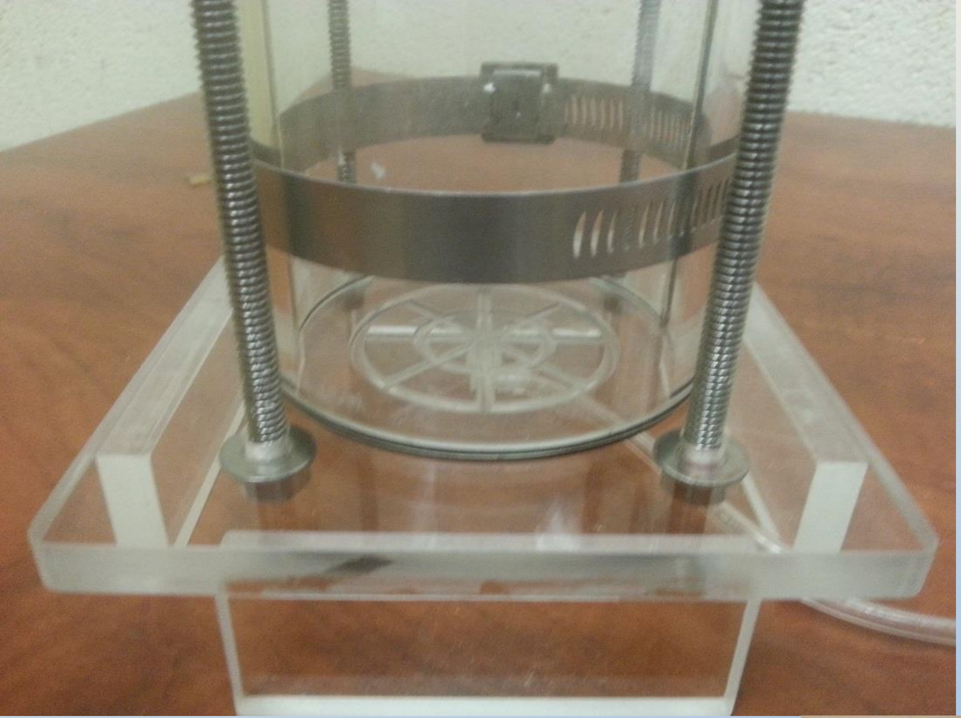
Preliminary Cementation of Ottawa Sand

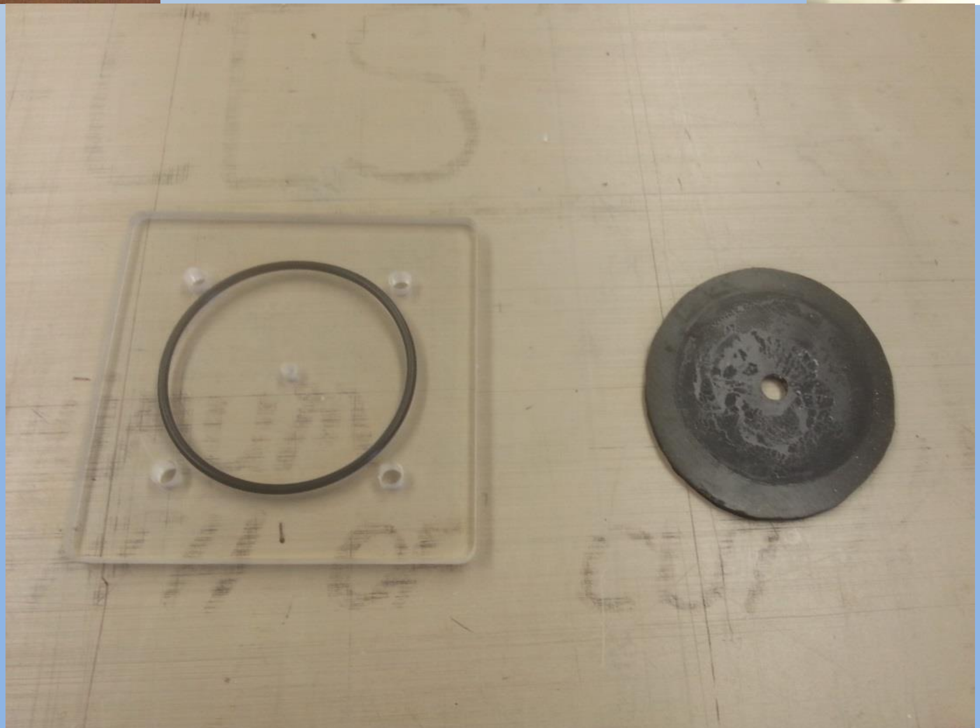


Chamber Modification

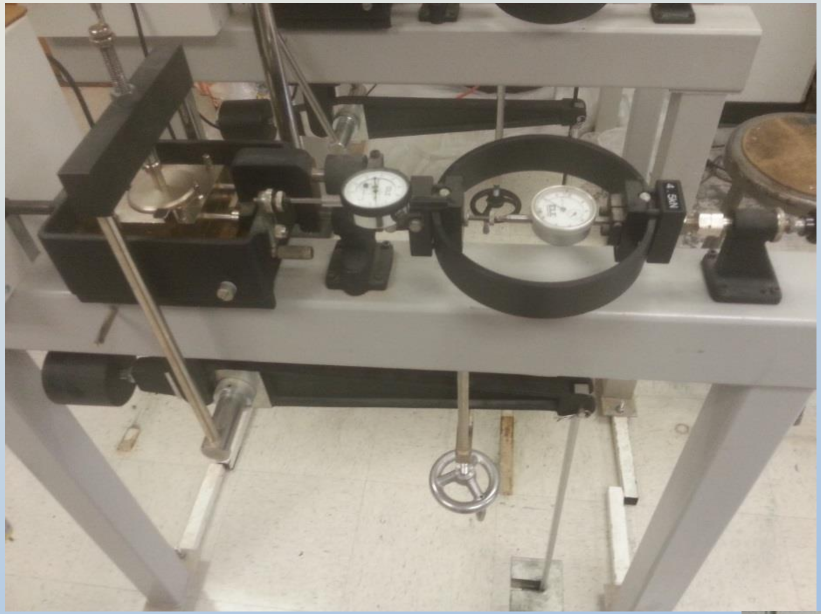

New Chamber (sideview)


New chamber (topview)

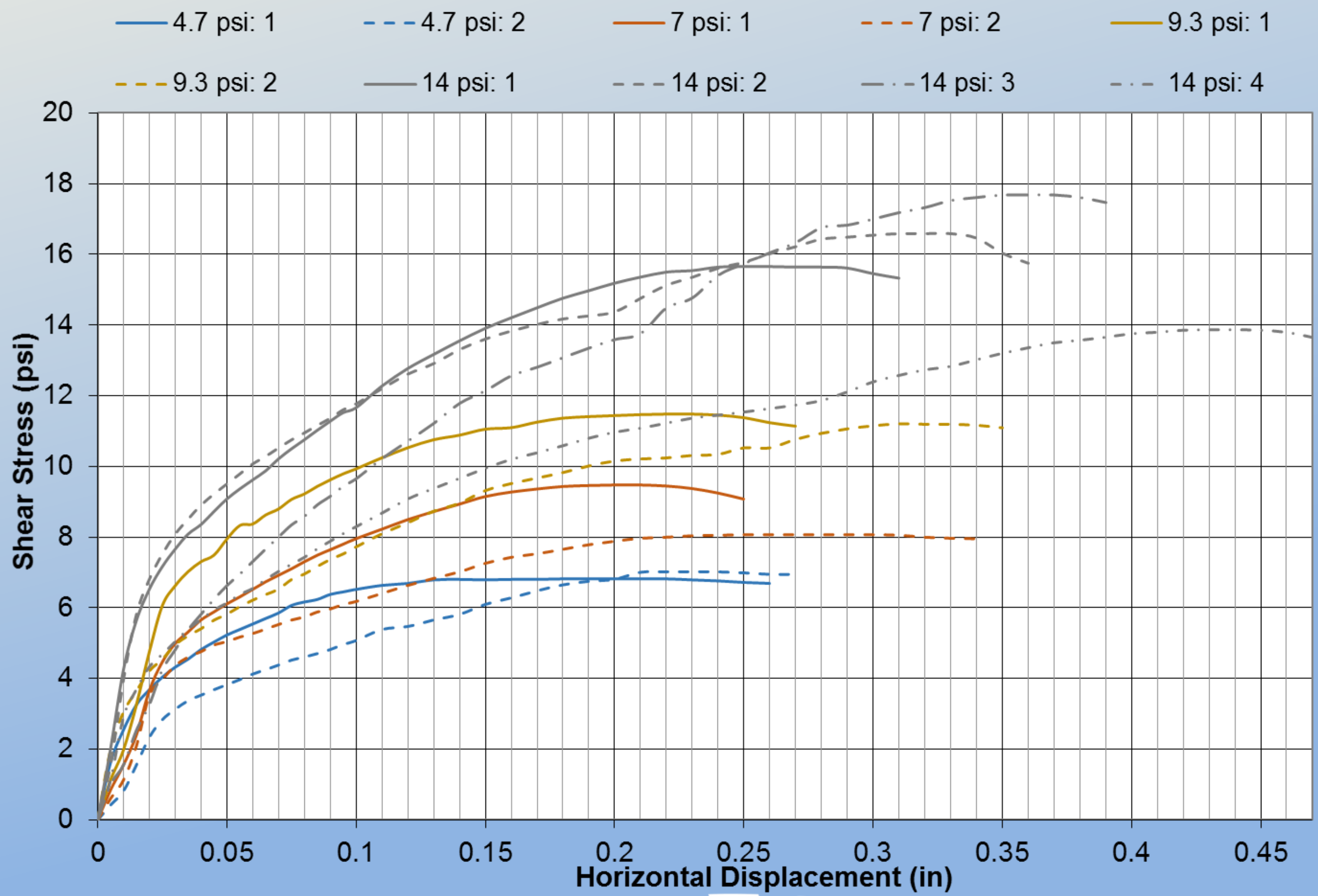
Old bottom plate w/
sealing comparison



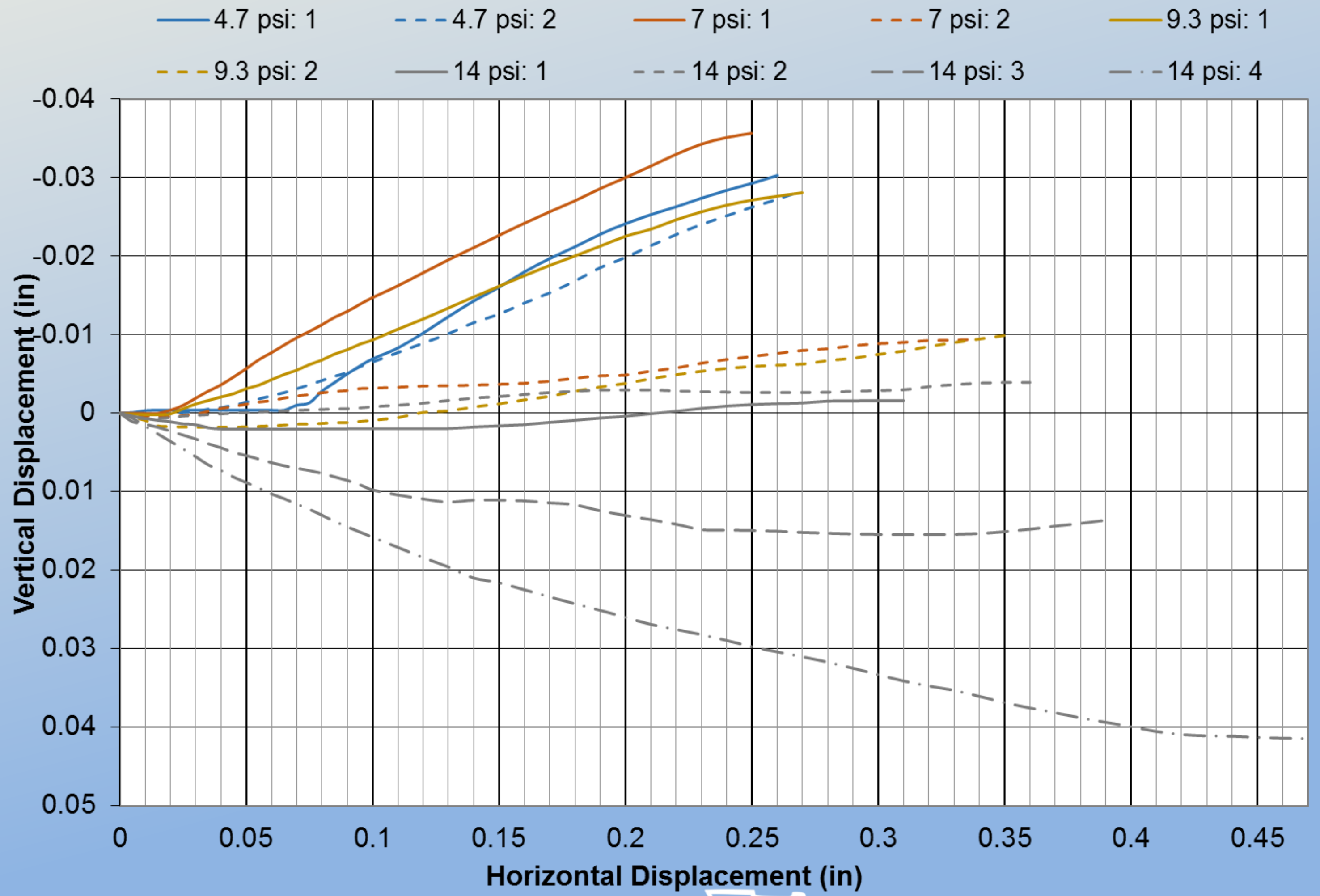
Soil Testing Equipment



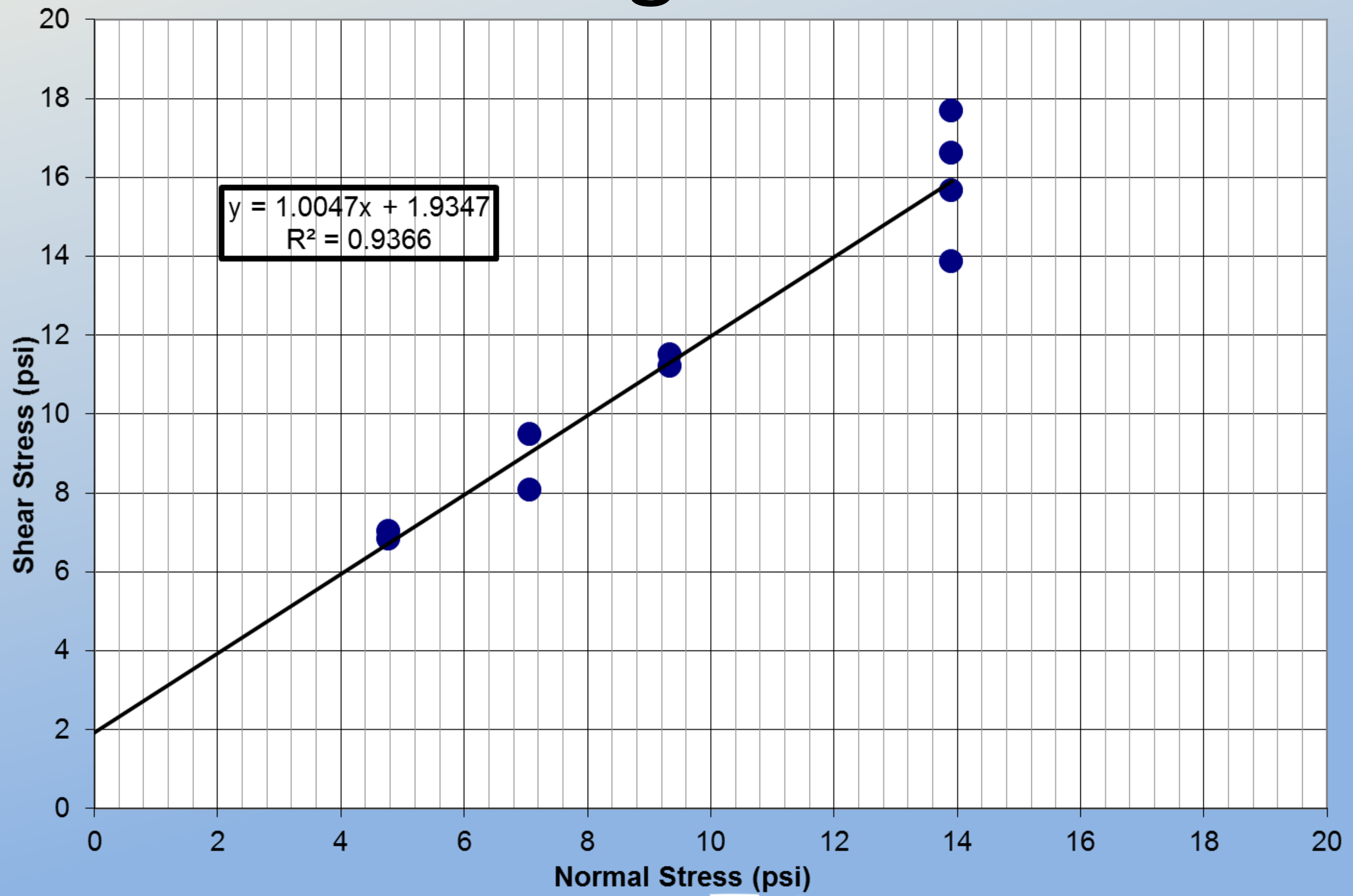
DST Organic Soil



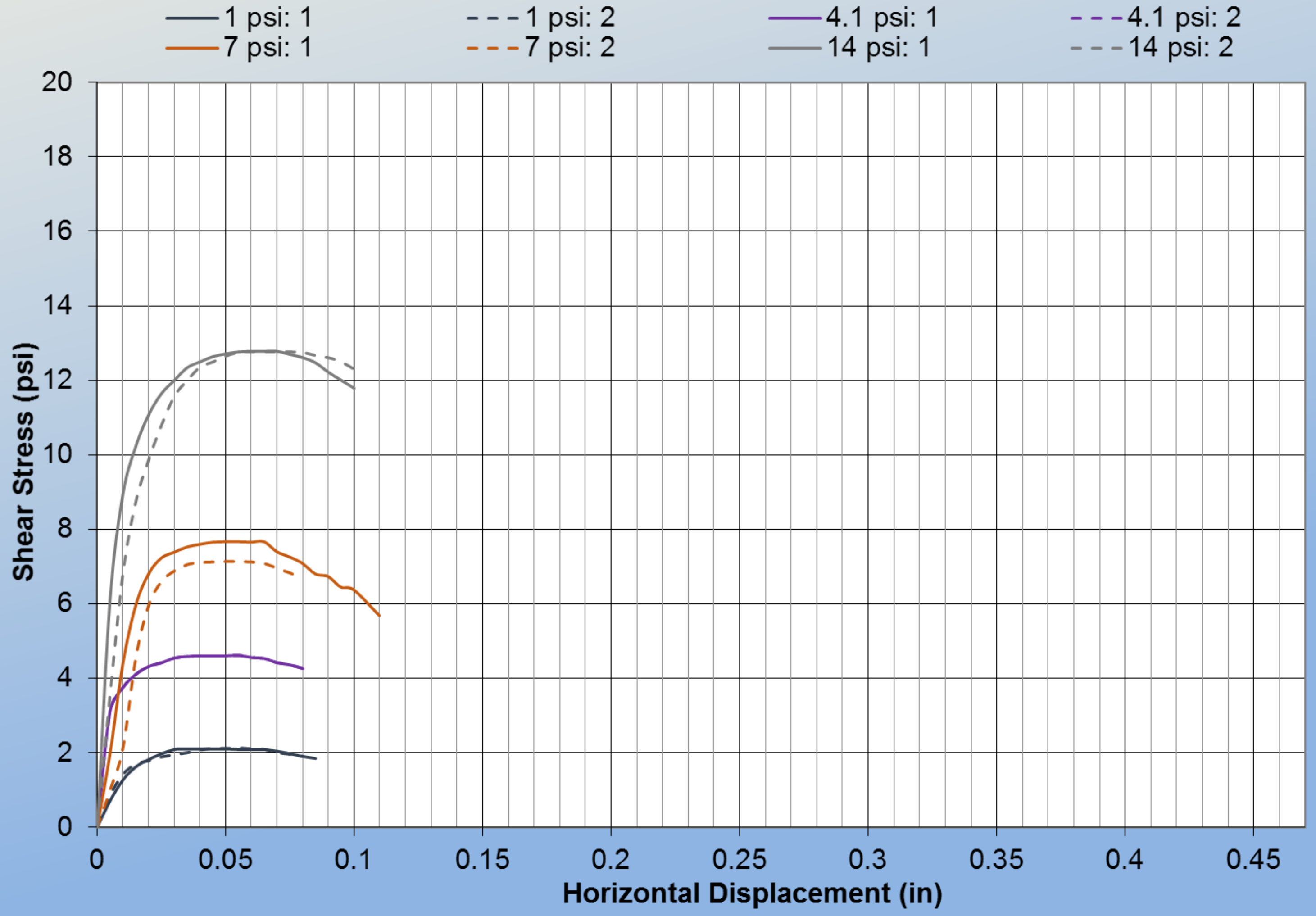
DST Organic Soil



DST Organic Soil



DST Ottawa Sand



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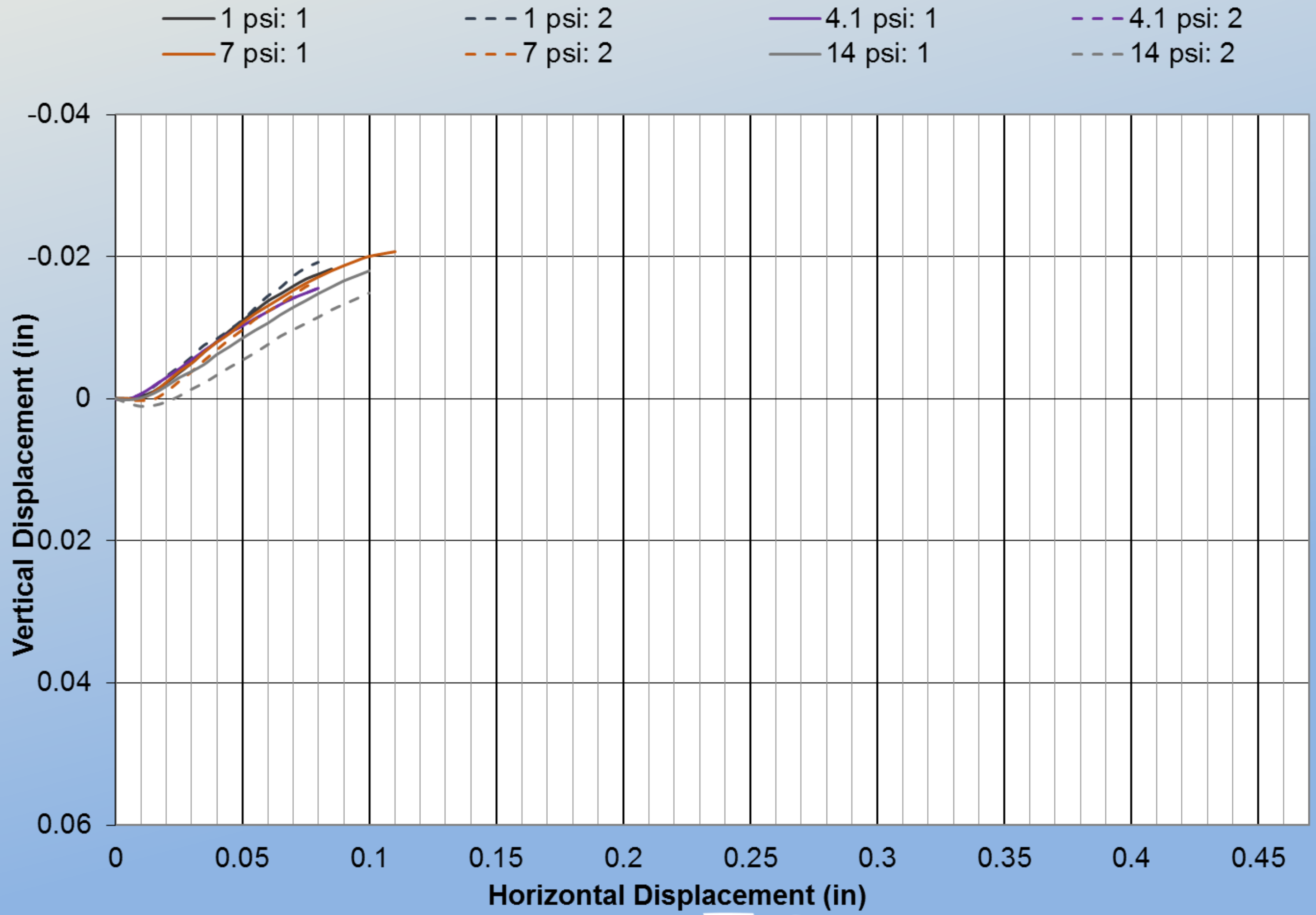
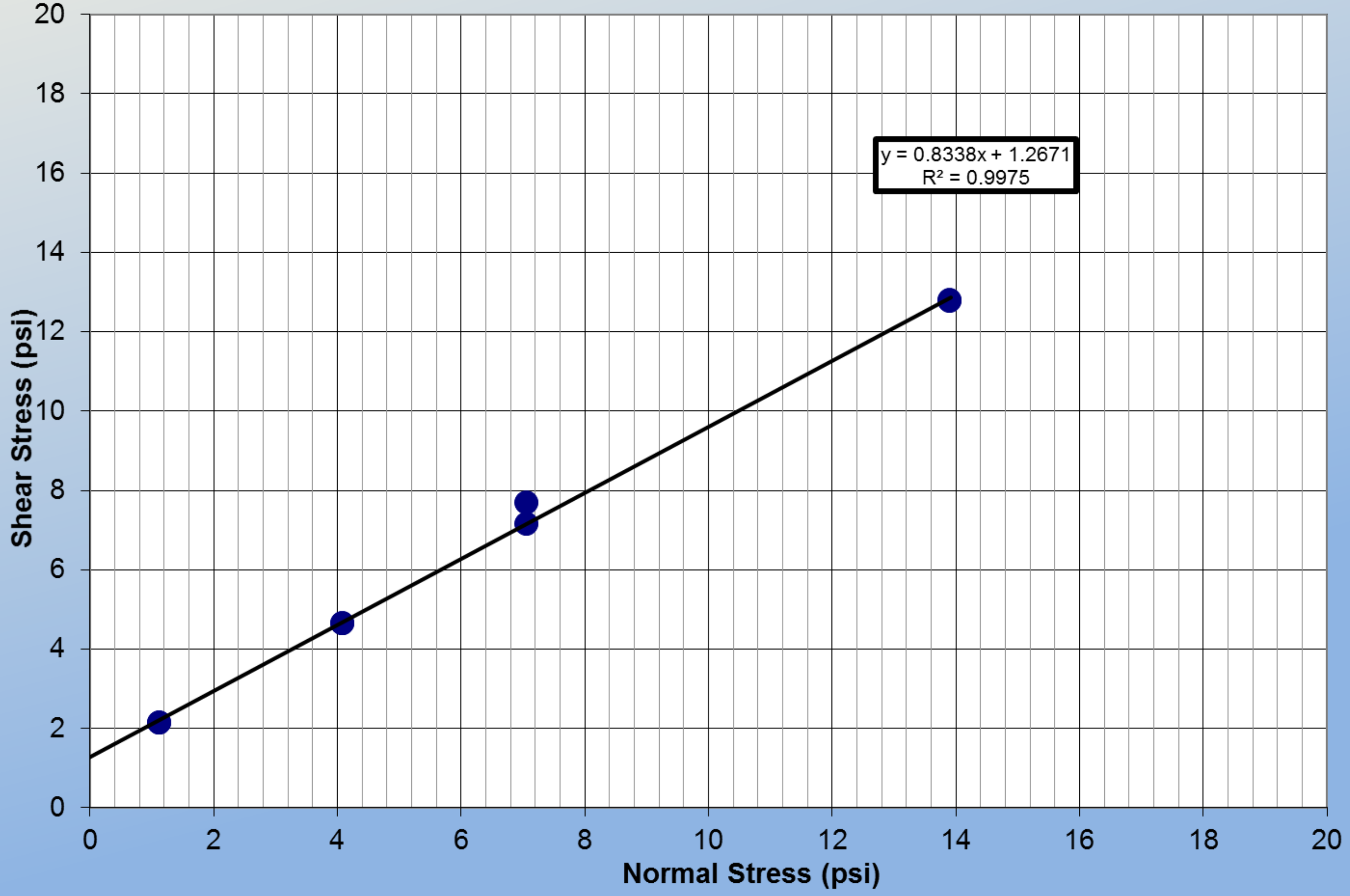


DST Ottawa Sand



Specimen Unit Weights

	Test	1		4		4.7		7		9.3		14				21	
	Run	1	2	1	2	1	2	1	2	1	2	1	2	3	4	1	2
Ottawa	Unit Weight pcf	107	106	107	107	-	-	108	106	-	-	106	106	-	-	108	107
Organic	Unit Weight (wet) pcf	45	45	45	45	48	43	45	46	46	45	46	45	46	46	46	48
	Unit weight (dry) pcf	29	29	29	29	30	28	29	29	29	28	29	28	29	29	29	30

DST Treated Ottawa Sand

DST Ottawa Sand

DST Treated Ottawa Sand

Timeline

- Task 1 – Literature review (COMPLETED)
- Task 2 – Design/fabricate lab column experiments and test with ureolytic microbes
  - Cells for OM soil treatment/calcium cementation (present – Aug. 2016)
  - Shear and consolidation tests for influence of treatment (present – Dec. 2016)
- Task 3 – Optimize ureolytic MICP procedure (Dec. 2016 – Apr. 2017)
- Task 4 – Explore ureolytic and non-ureolytic microbes ability to stabilize FL sand and OM soil (Apr. 2017 – Aug. 2017)
- Task 5 – Final report and closeout meeting (Nov. 2017)

Questions?

References

- Consentino, P. J., Bleakley, A. M., Armstrong, A. T., Misilo, T. J., Sajjadi, A. M. (2014). Ground Tire Rubber as a Stabilizer for Subgrade Soils. FDOT Contract Number BDK81 977-03
- Mullins, G. and Gunaratne, M. (2014). Soil Mixing Design Methods and construction Techniques for Use in High Organic Soils. FDOT Cotnract Number BDV25-977-14
- Button, J. W. (2003). Kiln Dust for Stabilization of Pavement Base and Subgrade Materials. Texas Transportation Institute
- See Technical Memorandum: Application of Microbial Induced Calcite Precipitation to Stabilize Florida High-Organic Matter Soils for Roadway Construction, FDOT Contract No. BDV34 977-06 for rest

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