Strength Envelopes for Florida Rock and Intermediate Geomaterials

FDOT BDV31-977-51

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Tasks

Task 1 – Equipment setup
Task 2 – Field rock acquisition
Task 3 – Laboratory testing
Task 4 – Test results and analyses
Task 5 – Numerical modeling
Task 6 – Final report draft and closeout teleconference;
Task 7 – Final report.

Literature Review

Geology of Florida Surface Rocks:

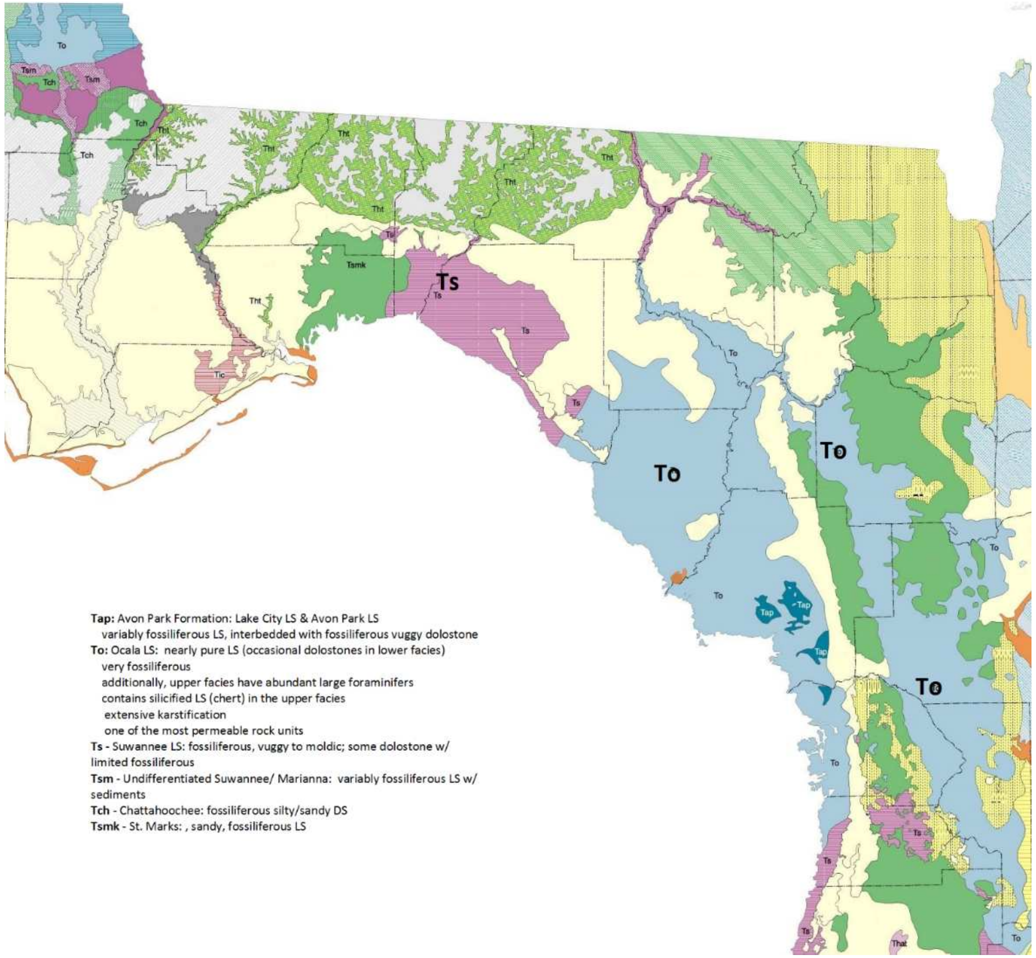
Limestones → Calcite mineral (Rhombohedral structure – cube of rhombi faces)
Limestones → Aragonite mineral (Orthorhombic structure)

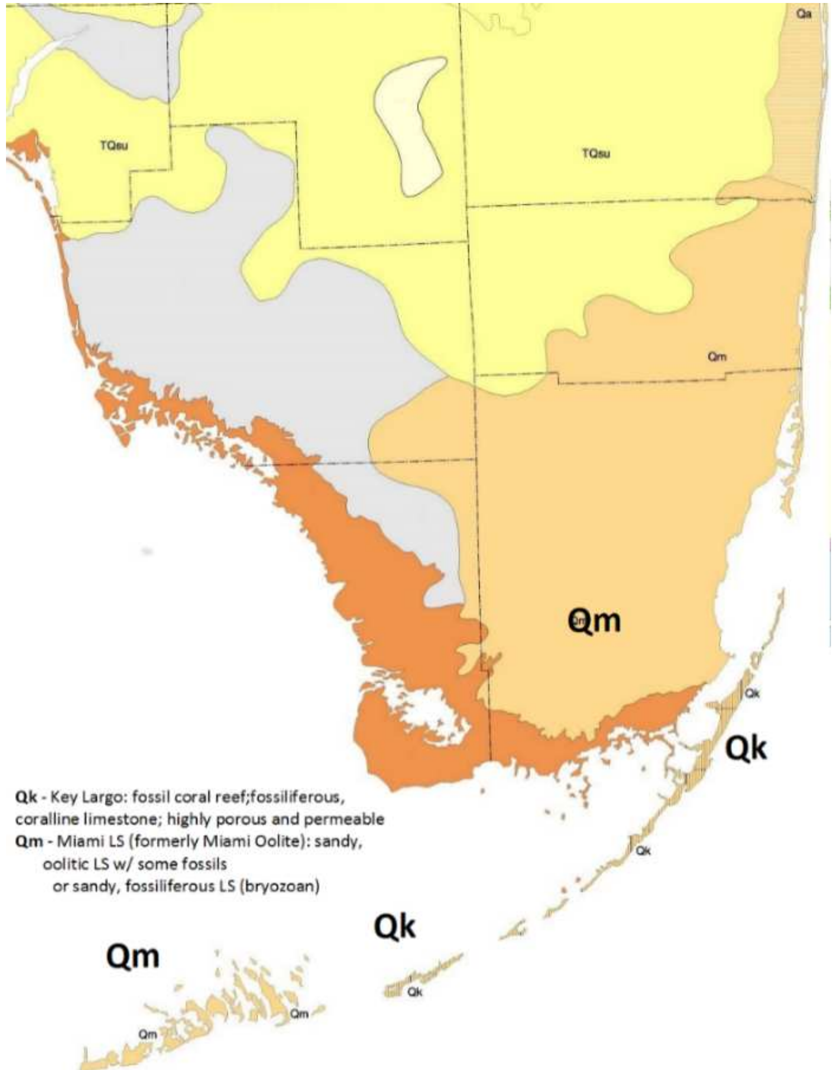
Dolostones: Dolomite mineral

Marl or marlstone: Calcite mixed with soils and other earthy substances

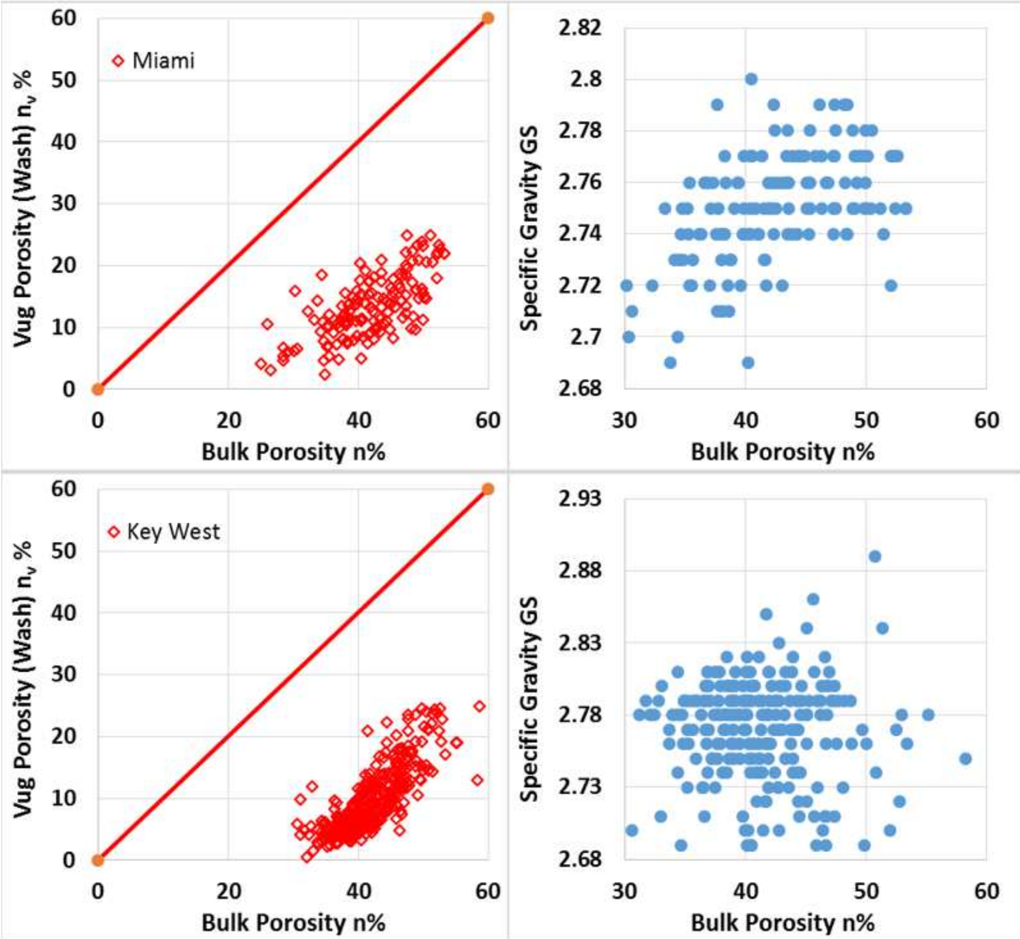
Calcarenite (for example Anastasia formation)

Literature Review





Literature Review



South Florida limestone:
Hester & Schmoker (1985)

Other limestone in the world:

Solenhofen limestone:	n = 0.05
Great Britain limestone:	n = 0.06
Salem/ Bedford limestone:	n = 0.12 to 0.13

Literature Review

Table 3-3. Mineral specific gravities from literature

	Jumikis, 1983	Goodman, 1989	Lambe & Whitman, 1969	Hester & Schmoker, 1985
Calcite	2.71 - 3.72	2.7	2.72	2.71
Aragonite				2.94
Dolomite	2.80 - 3.00	2.8-3.1	2.85	
Quartz		2.65	2.65	2.65

Table 3-6. Florida rock strengths with regards to strength engineering classification

Strength Class	Q_u (ksi)	RMR_{str} Rating	Florida Rocks
A – Very high	> 32	15	
B – High	16-32	8-12	
C – Medium	8-16	5-7	Isolated Avon Park
D – Low	4-8	3-4	Avon Park, Ocala LS, Ft. Thompson,
E – Very low	<4	2-3	Ocala LS, Miami LS, Ft. Thompson, Key Largo LS, etc.

Literature Review

SHALLOW FOUNDATION – BEARING CAPACITY:

Carter and Kulhawy (1988):

$p_u = \left[\sqrt{s} + \sqrt{m\sqrt{s} + s}\right] q_u$ for medium to strong rocks

$p_u = mq_u$ for soft rock (s=0 for soft rock)

$s = e^{(GSI-100)/(9-3D)}$

$m = m_i\, e^{(GSI-100)/(28-14D)}$;

D = disturbance factor caused by the rock removal methodology.

D=0 if no disturbance (typical for shallow foundation excavation).

D=1 for disturbance due to blasting techniques.

ROCK STRENGTH ENVELOP:

Hoek – Brown criteria:

$$\sigma'_1 = \sigma'_3 + q_u\,(m\sigma'_3/q_u + s)^a$$

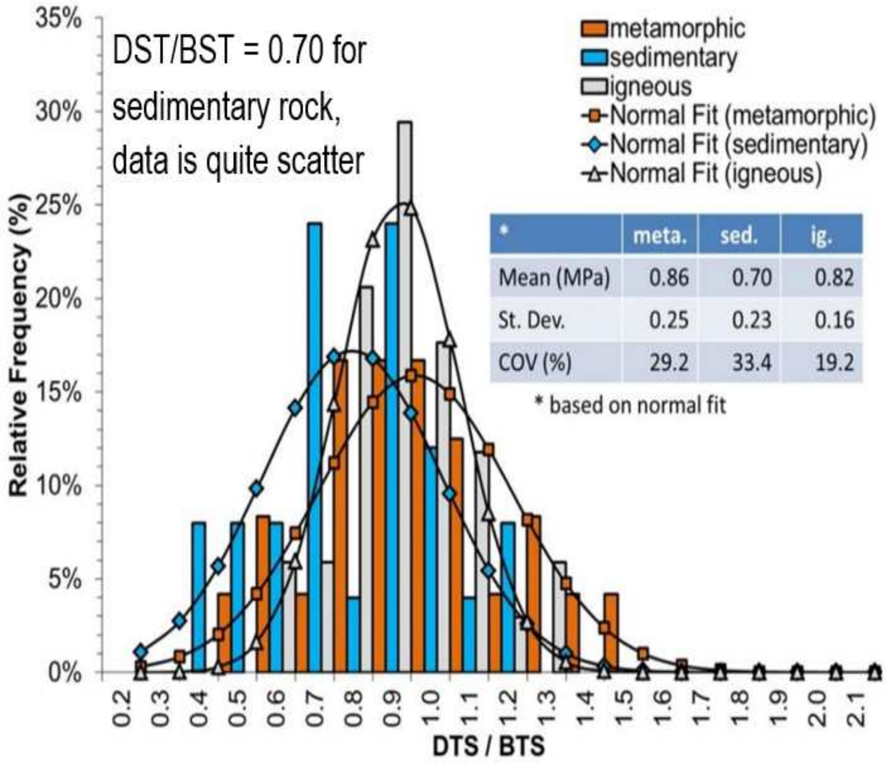
s and m: see equations 4 and 5.

$a = 0.5 + (e^{-GSI/15} - e^{-20/3})\,/6$; Typically, $a = 0.5$

Literature Review

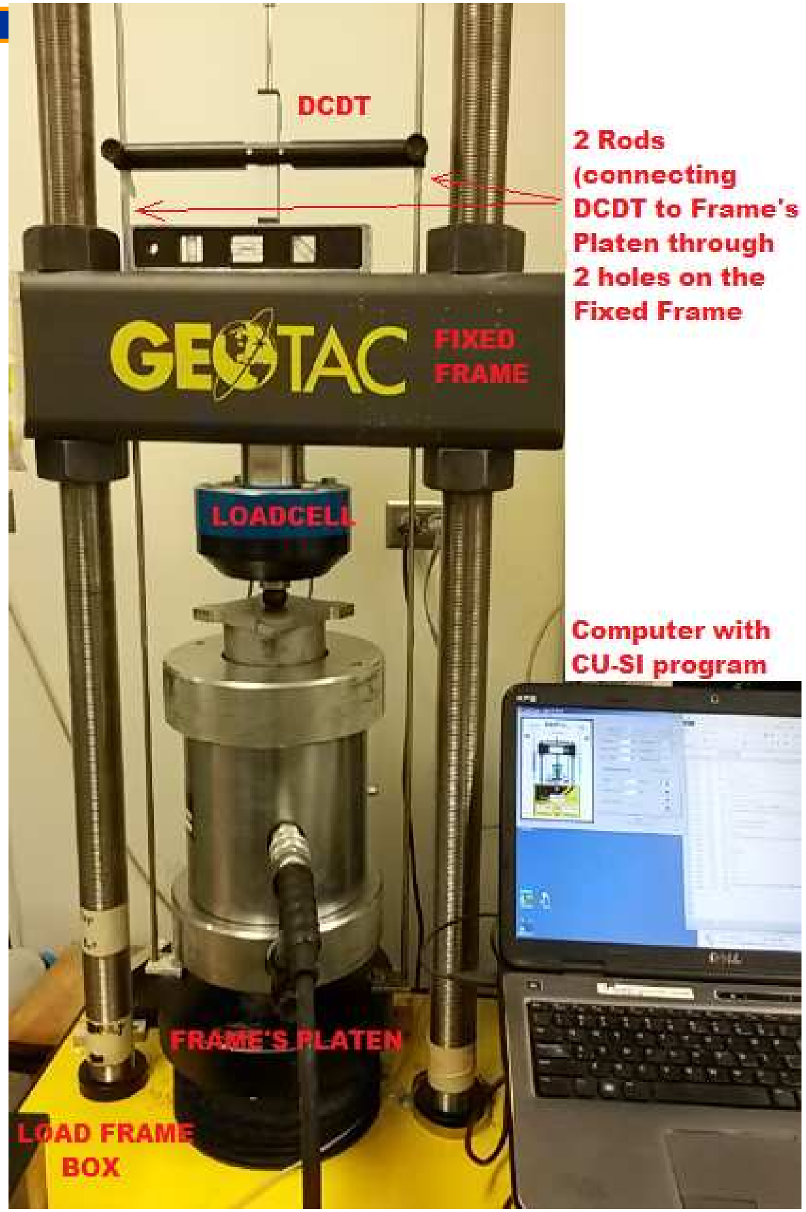
Lab tests:

- QU Tests
- BST (Brazilian Splitting Tension)
- Triaxial Tests
- Index Tests
- Carbonate Content Tests
- X-Ray Diffraction (XRD) tests

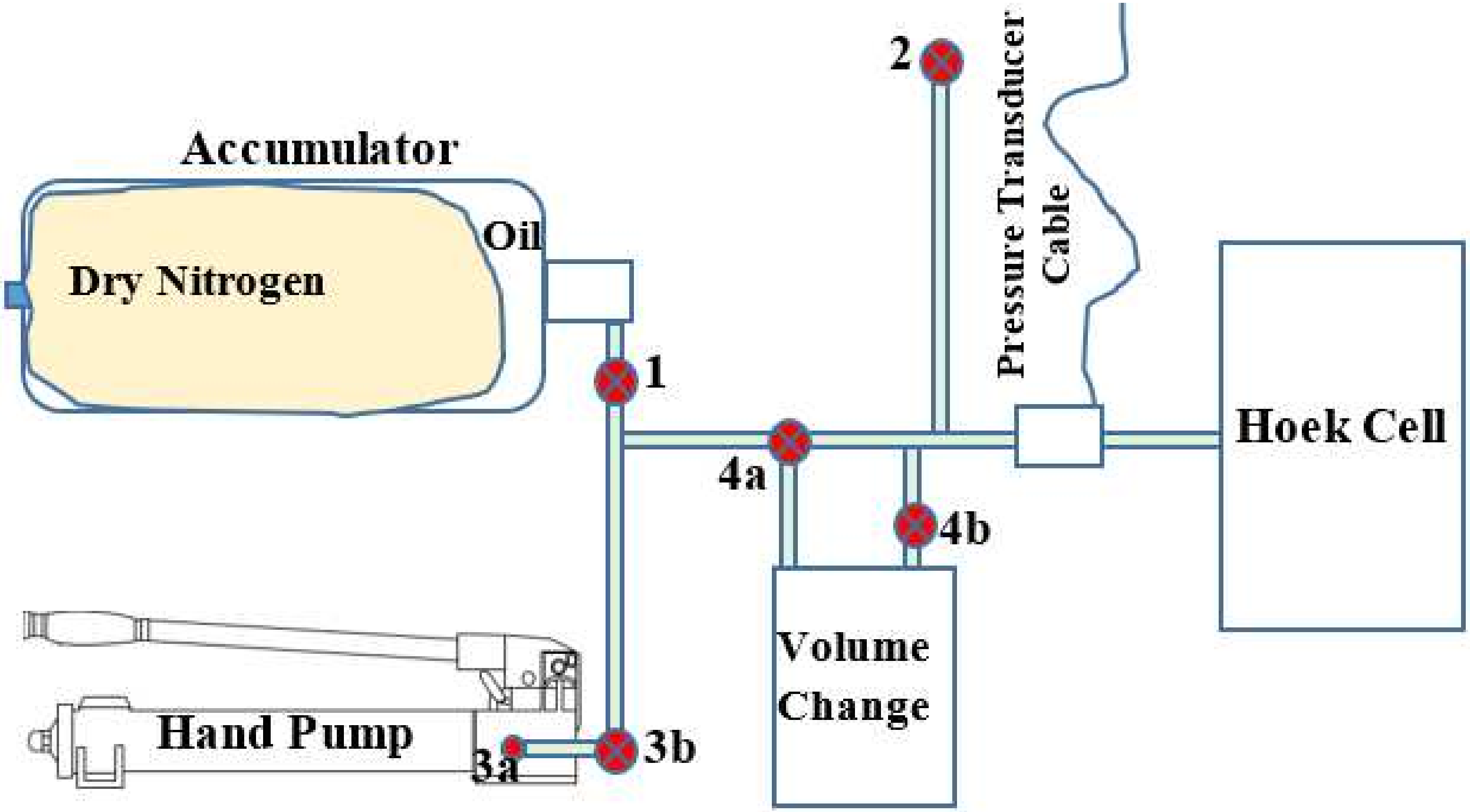


Task 1 - Triaxial Equipment

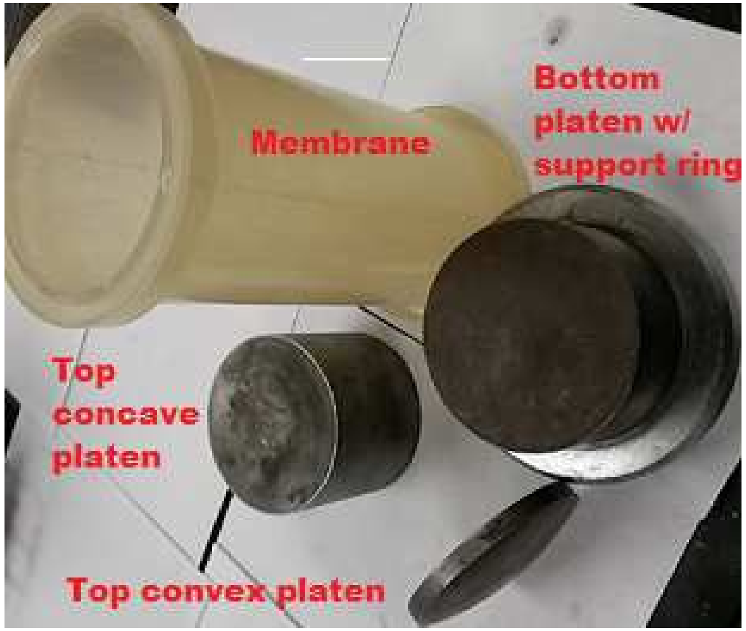
- 40-K load-frame
- 50-K load cell
- Displacement transducer (DCDT)
- Hoek cell with platens
- Hydraulic pump
- Oil pressure transducer
- Accumulator
- Volume Change Unit (VCU)



Triaxial Equipment



Triaxial Equipment



Task 2 - Field Rock Acquisition

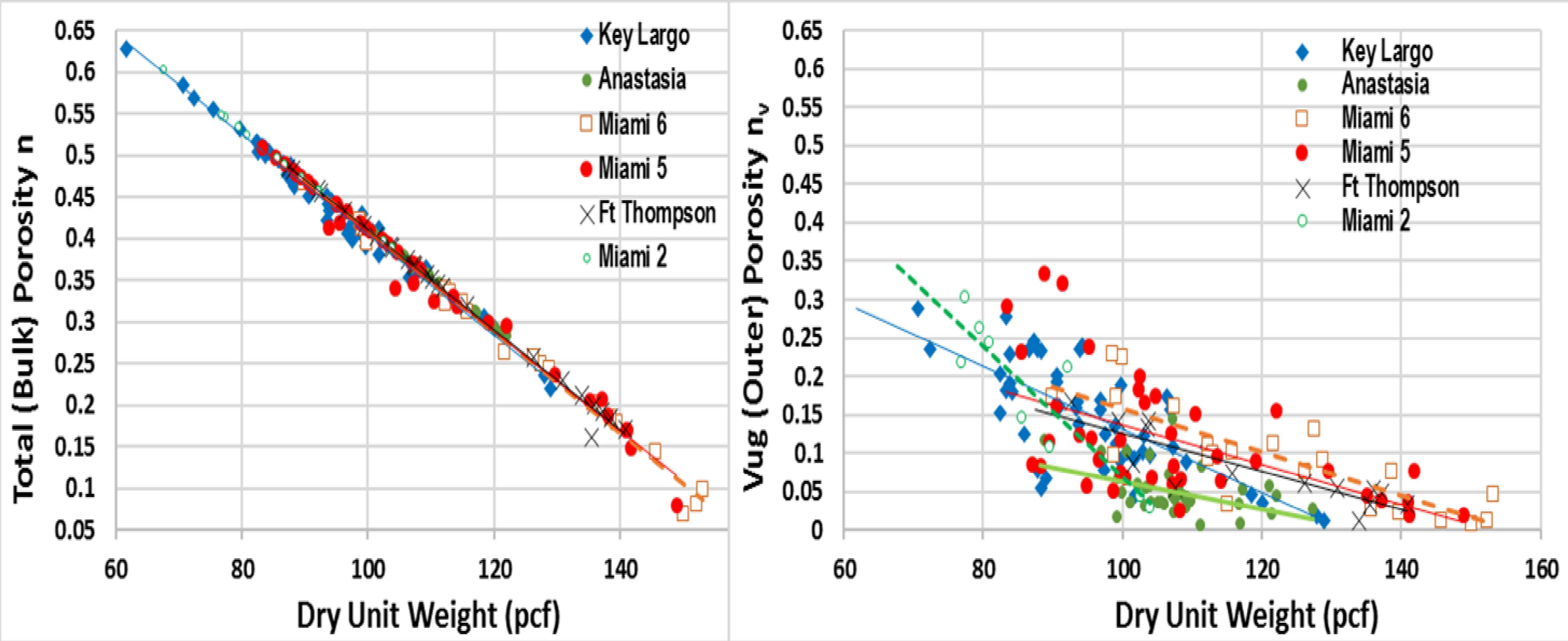
Site	Address	Area	Geology
1	I-75/ I-595	Davie (Broward)	Qm overlays Tqsu; Rocks cored typically below 8-ft, identified as Tqsu (Ft Thompson)
2	SW 13th St	Miami	Qm (Miami); 0.5 miles from Ocean
3	SR80 Bingham Island	West Palm	Qa (Anastasia)
4	SR 5-Marvin Adams Way	Key Largo	Qk (Key Largo)
5	SR 836 Ext - NW 12 St-MDX	Miami	Qm (Miami), poor induration
6	SR 997-Krome Avenue		Qm (Miami), poor to moderate induration

Historical qu – BST FDOT database

District	Project Name
1	I-75 over Manatee River
1	I-75 over Golden Gate Canal
1	Edison Farm
2	SR-20 @ Lochloosa Creek, Alachua Co.
2	SR-25 @ Santa Fe River
2	SR-10 @ CSX RR (Beaver St. Viaduct), Duval Co.
2	SR-9 (I-95) Overland
2	SR-9 (I-95) Overland Bridge
2	CR-326 @ Waccasa River
2	I-295 Dames Point Bridge
2	I-295 Buckman Bridge
2	I-95 @ I-295 Cloverleaf
2	Acosta Bridge Research (Modulus)
2	I-95 Fuller Warren Bridge
3	US-98 / SR-30 @ Wakulla River
3	BRIDGE #530022 US 98 OVER WAKULLA
3	Rob Forehand Road Over Little Creek
3	Lost Creek Bridge #590048
3	I 10, SR 8 over Ochlockonee River
3	I 10, SR 8 over Ochlockonee River1
3	SR 63, US 27 Ochlockonee Relief Bridge
3	SR 8 over Choctawhatchee River
3	SR-10 Bridge over Choctawhatchee River
3	I 10, SR 8 Over Apalachicola River
3	I 10, SR 8 over Chipola River
3	SR-20 over Chipola River

District	Project Name
3	Merritts Mill Pond US-90 SR-10
3	SR-166 Rock Slope Design
3	Fisher Creek Bridge CR 2203
3	CR 166 Alligator Creek Bridge
3	SR-8 (I-10) @ CR-286 High Mast
3	Holmes Creek - Cr 166 Bridge
3	CR 12A (Kemp Road Bridge)
3	Natural Bridge over St. Marks River
3	SR-10 (US-90) over Yellow River
3	SR 71 over Rocky Creek
3	SR-20 @ BLOUNTSTOWN (APALACHICOLA RIVER)
3	US-90 Victory Bridge
3	SR-2 Cowarts Creek
3	SR-2 Marshall Creek Jackson Co.
3	SR-2 Spring Branch Jackson Co.
3	SR-261 Capital Circle
3	US-98 / SR-30 @ ST. MARKS RIVER
3	I-10 TOWER SITE @ SNEAD'S WEIGH STATION
6	NW 36th Street Bridge
6	NW 12th Ave (SR 933) Miami River Bridge
6	MIC- People Mover Project
6	Verona Ave Bridge over Grand Canal
6	HEFT / SR 874 PD&E
6	Wall @ Service Rd. South of Snake Creek
6	17th St. Causeway
6	96th St. & Indian Creek (Pump Station @ Bal Harbour)
6	Jewfish Creek
6	NW 5th Street Bridge
6	Radio Tower Everglades Academy (Florida City)

Lab Tests: Index Tests



- Apparent Dry Unit Weight and Apparent Mineral Unit Weight are obtained from Bulk Specific Gravity A/(B-C) and Apparent Specific Gravity A/(A-C) of the AASHTO T-85/ ASTM D6473/C97 for Rocks or Aggregates
- Bulk (True) Dry Unit Weight γ_{dt} = Dry weight/ Total cylinder volume, which includes vug volume

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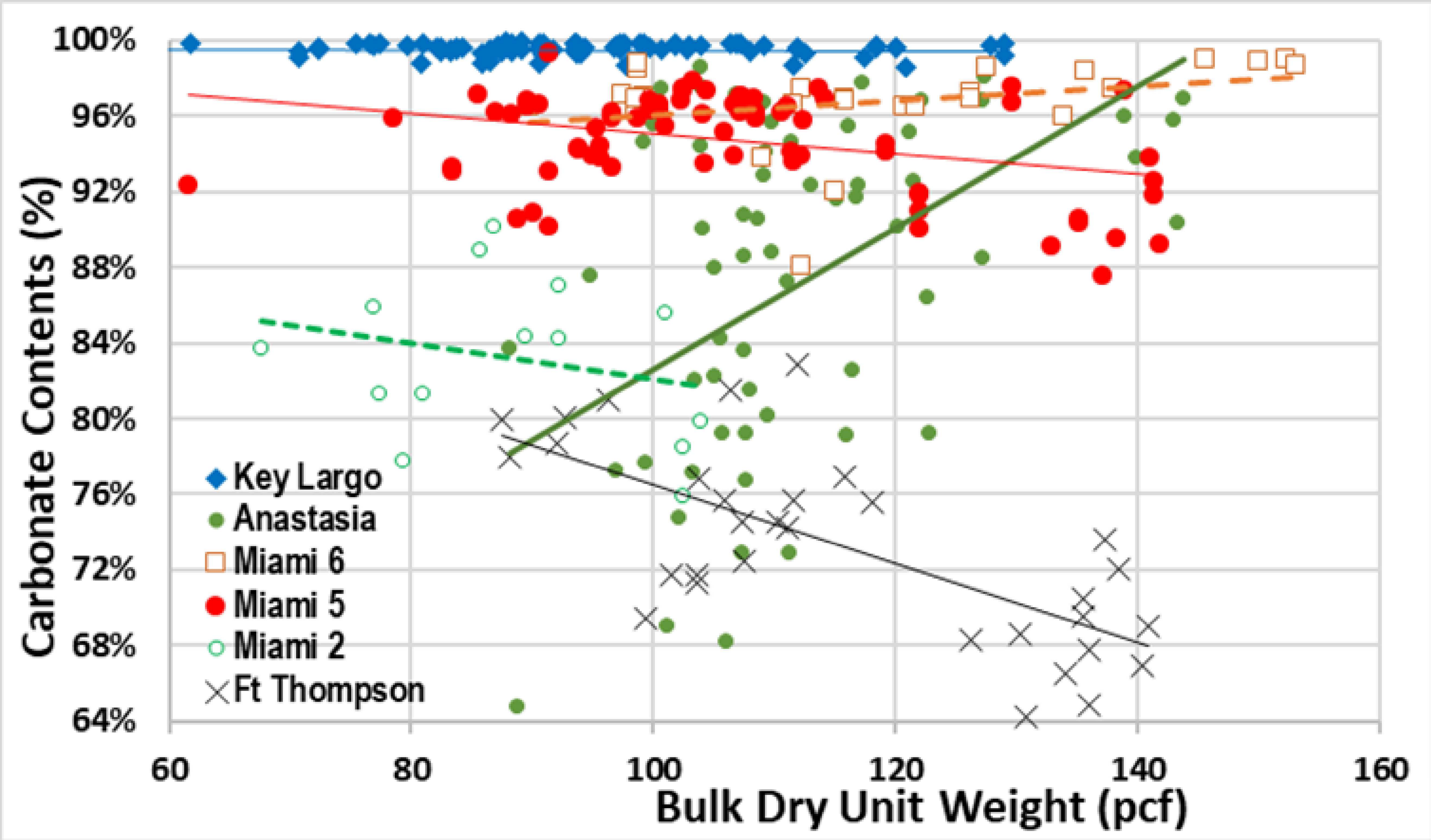
Lab Tests: Carbonate Content Tests

Florida method FM 5-514 :



Lab Tests: X-Ray Diffraction (XRD)

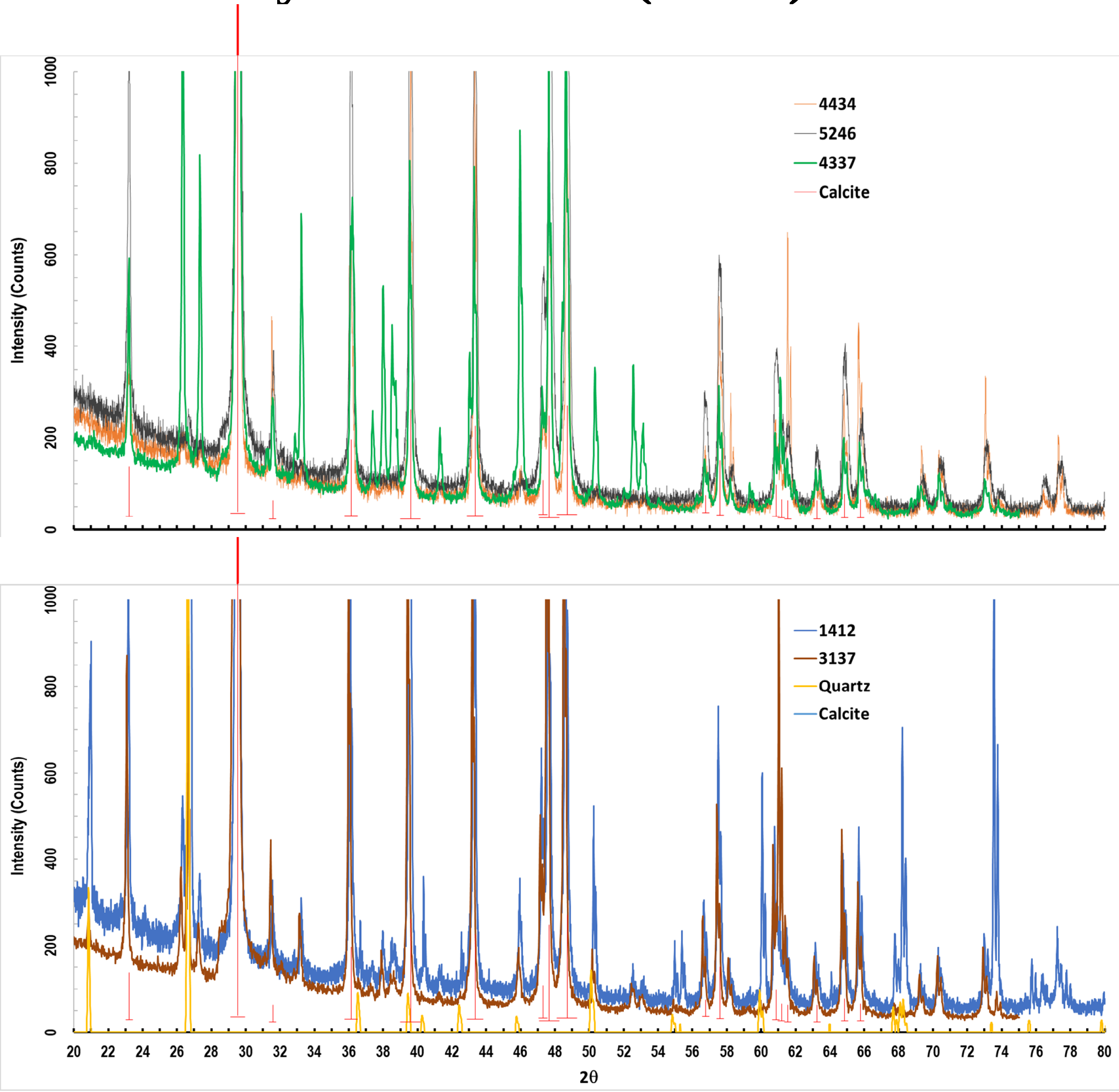
Typical Minerals:

*Miami: Calcite

*Key Largo: Calcite, mixed with Aragonite

*Ft. Thompson: Calcite (roughly 70-75%) and Quartz

*Anastasia: Calcite (roughly 85-90%) and Quartz



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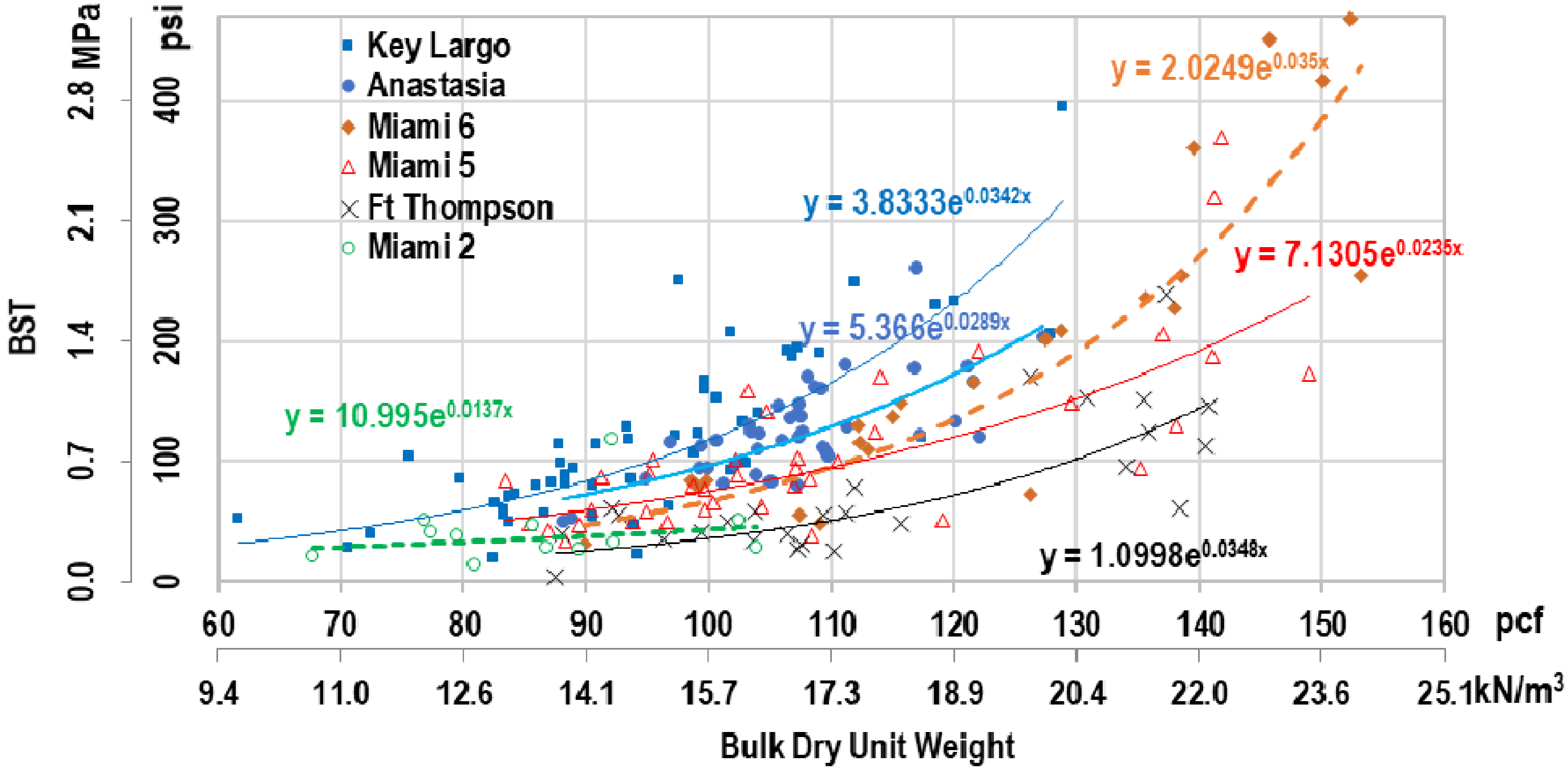
Lab Tests: BST



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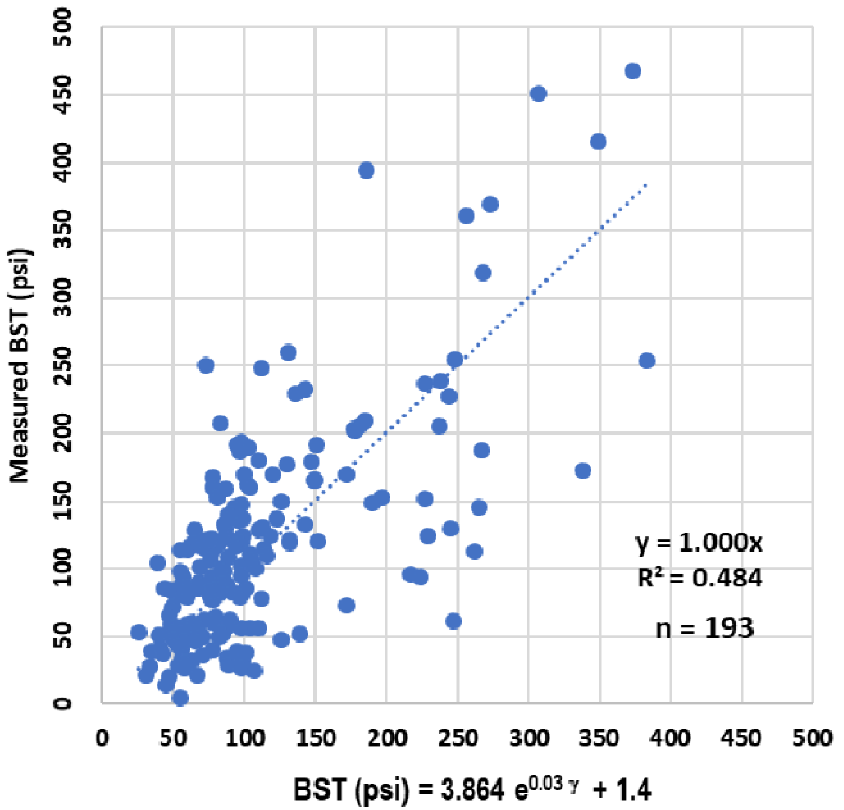
Lab Tests: BST

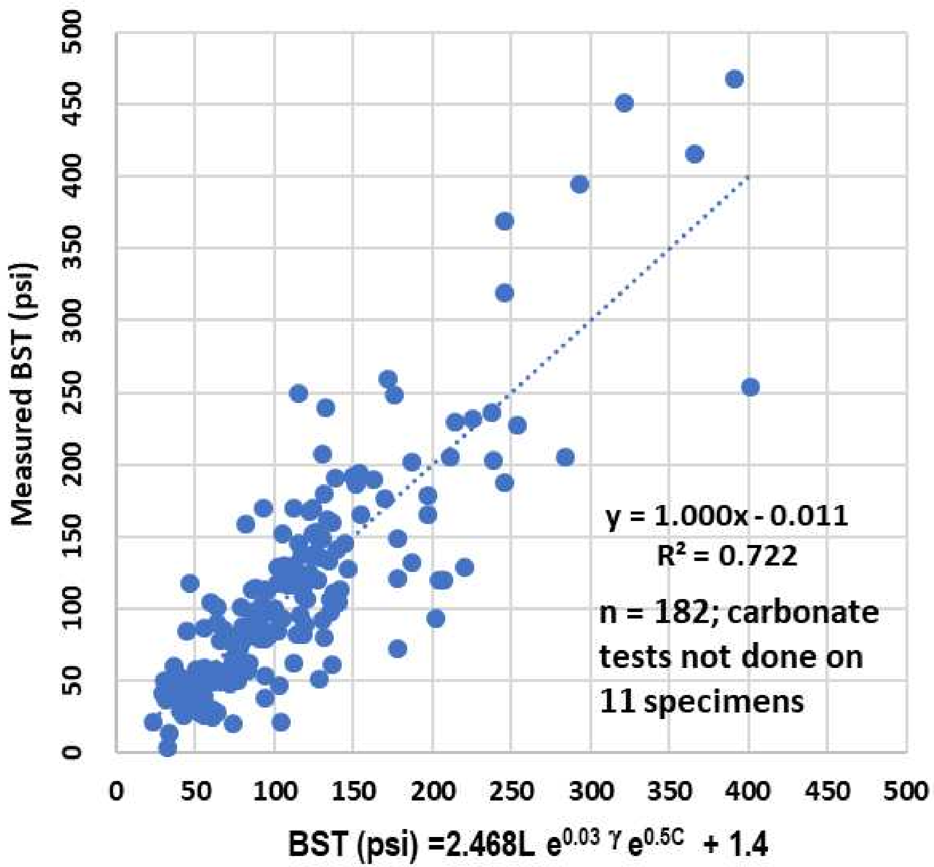


- Correlation based on only 1 parameter: Bulk Dry Unit Weight γ_{dt}
- $R^2 = 0.48$

Lab Tests: BST

- Correlation based on 3 parameters:
  1. Bulk Dry Unit Weight γ_{dt}
  2. Carbonate Content C:
     $e^{0.5C}$ ranges from 1.35 to 1.65 for typical carbonate content
  3. Mineral bond link strengths; Suggested bond modification:

Formation	L
Ft. Thompson	0.60
Anastasia	1.30
Key Largo	1.50
Miami, poor induration	0.75
Miami, moderate induration	0.90
Miami, moderate/well induration	1.00



- Significant correlation improvement $R^2 = 0.72$ vs previously 0.48

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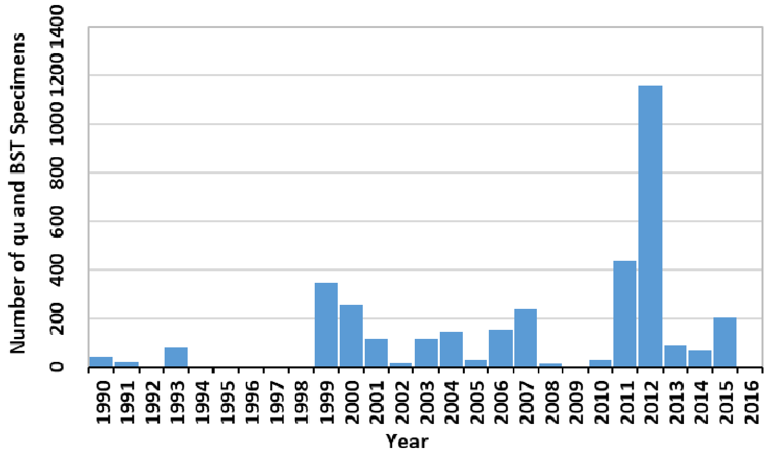
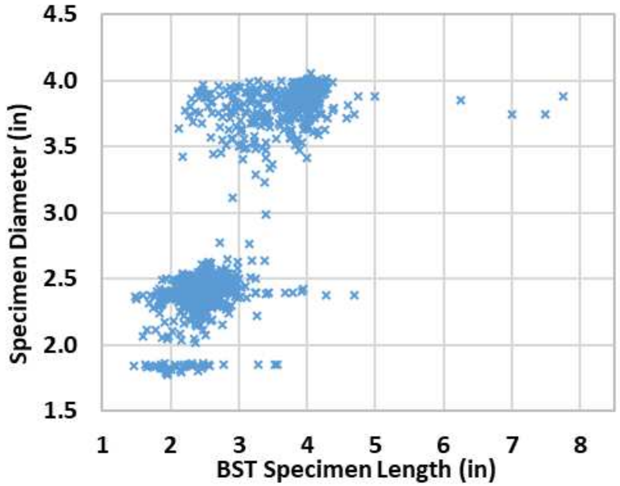
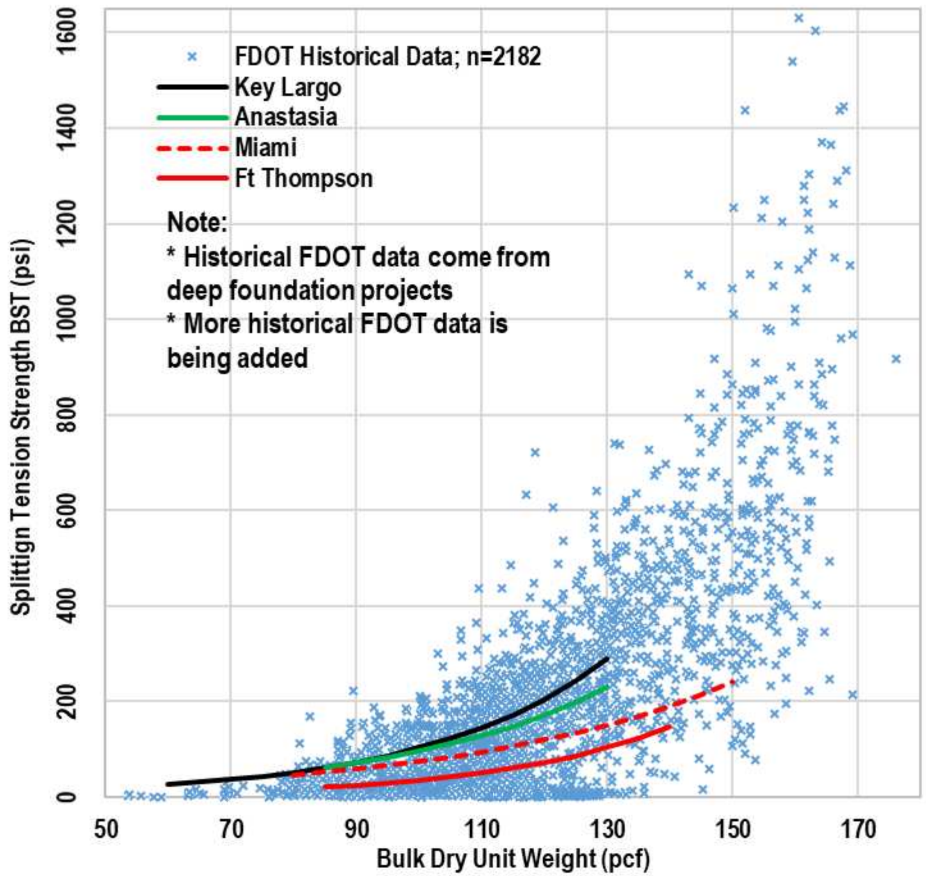
Lab Tests: FDOT Historical BST







Extend the correlation to FDOT Historical Data:

$BST = 2.468L\, e^{s\gamma}\, e^{0.5C} + 1.4$ with $s = 0.03$ for $\gamma_{dt} < 140$ pcf

and $s = 0.0328$ for $\gamma_{dt} > 140$ (higher power for the denser rocks encountered at historical deep foundation projects)

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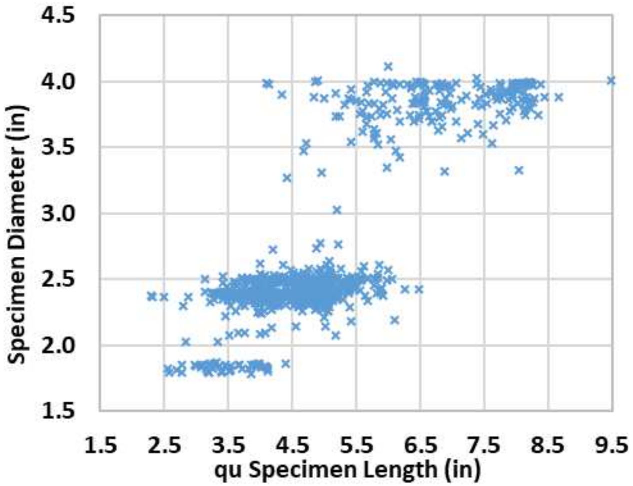
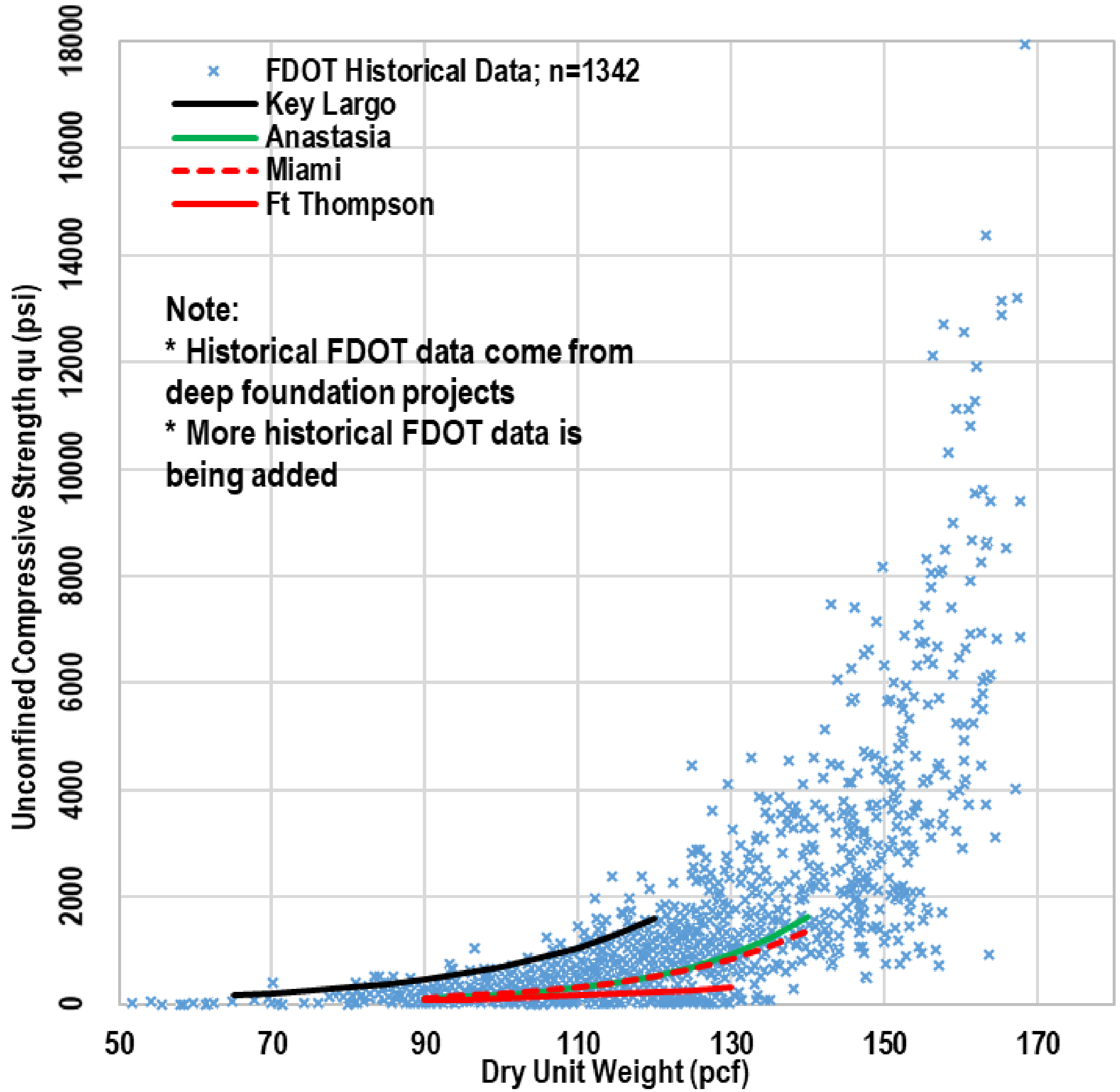
Lab Tests: q_u





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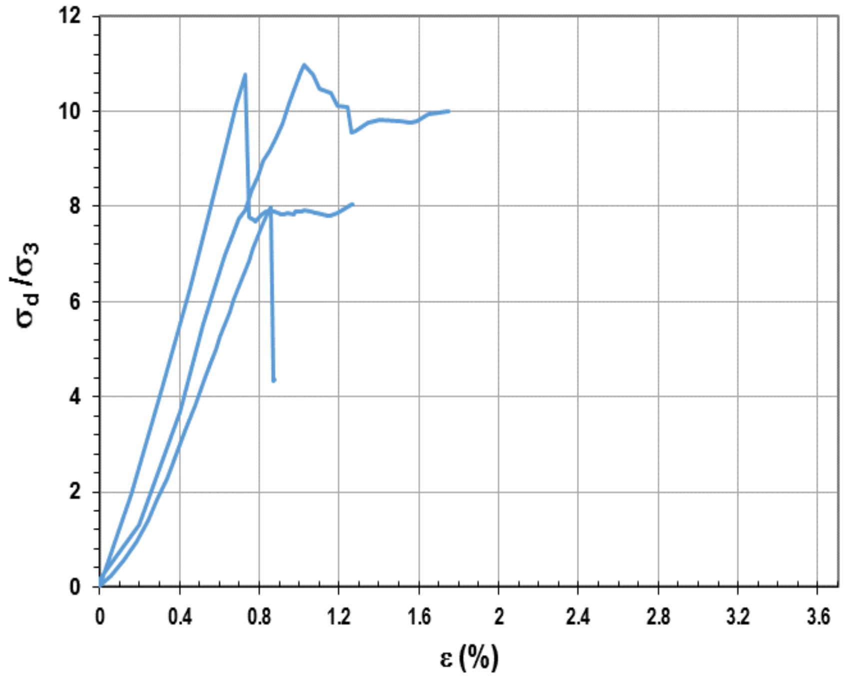
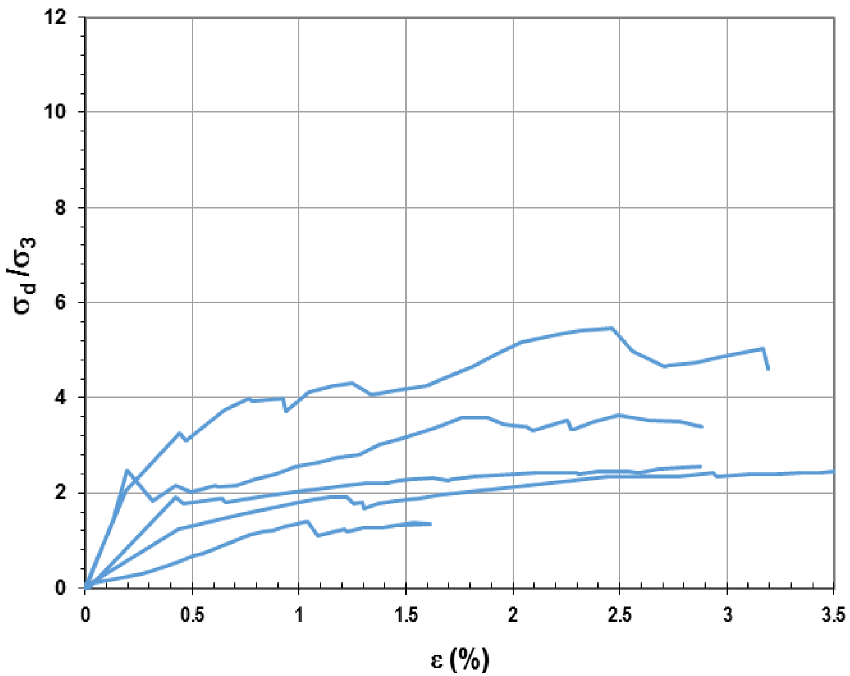
Lab Tests: Triaxial





σ_3 (psi)	Dry Unit Weight Range (pcf)				
	60 – 65	66-85	86-110	111-120	121-130
0 – 10	Ductile	Brittle	Brittle	Brittle	Brittle
25 – 50	Ductile	Brittle	Brittle	Brittle	Brittle
130-150	Ductile	Ductile	Ductile	Brittle	Brittle
200	Ductile	Ductile	Ductile	Ductile	Brittle
>300	Ductile	Ductile	Ductile	Ductile	Ductile

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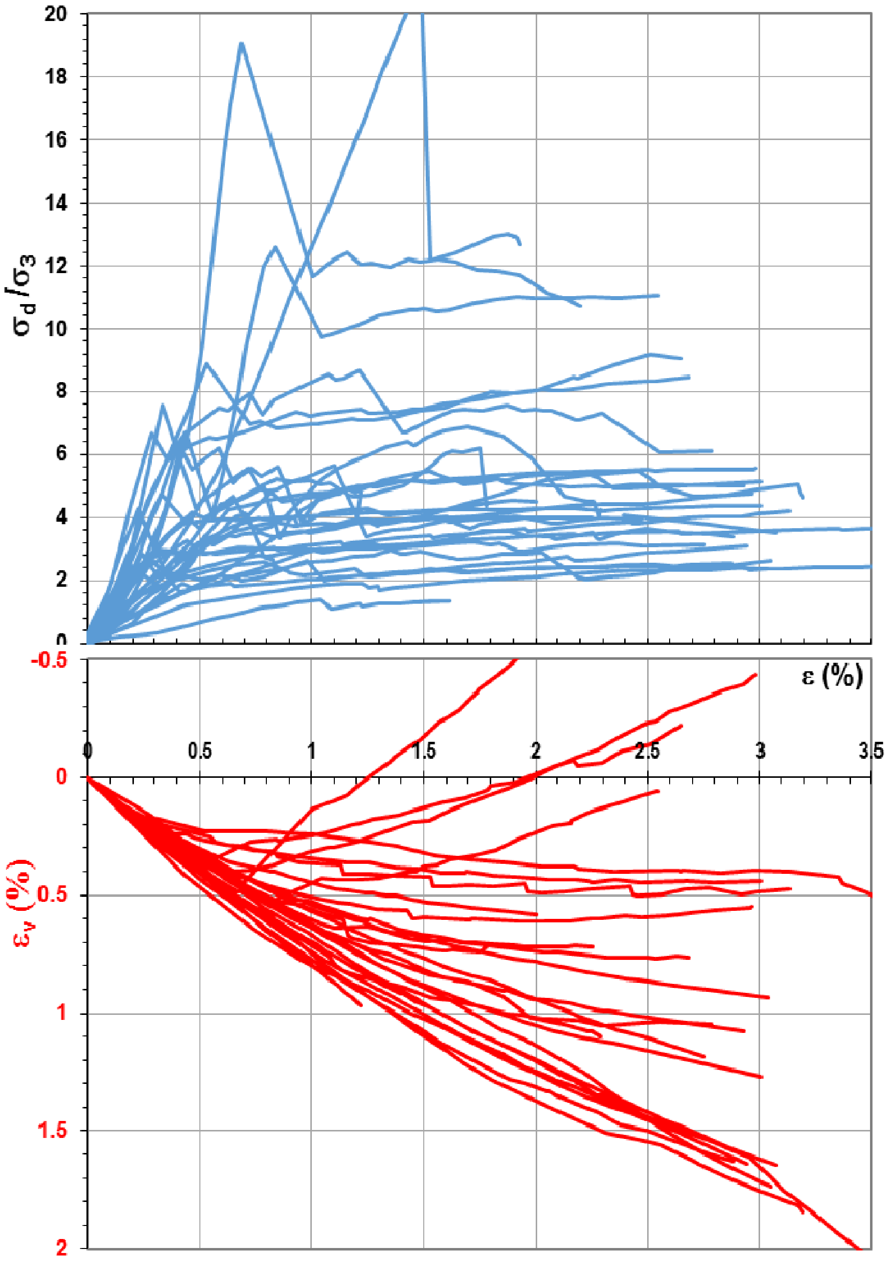
Lab Tests: Triaxial

Volumetric behavior:
Typically contractive, as most of our rocks are porous and low strength.

Some higher strength rocks / higher density rocks experience initial contraction, then dilation as the rock specimens fail in shear



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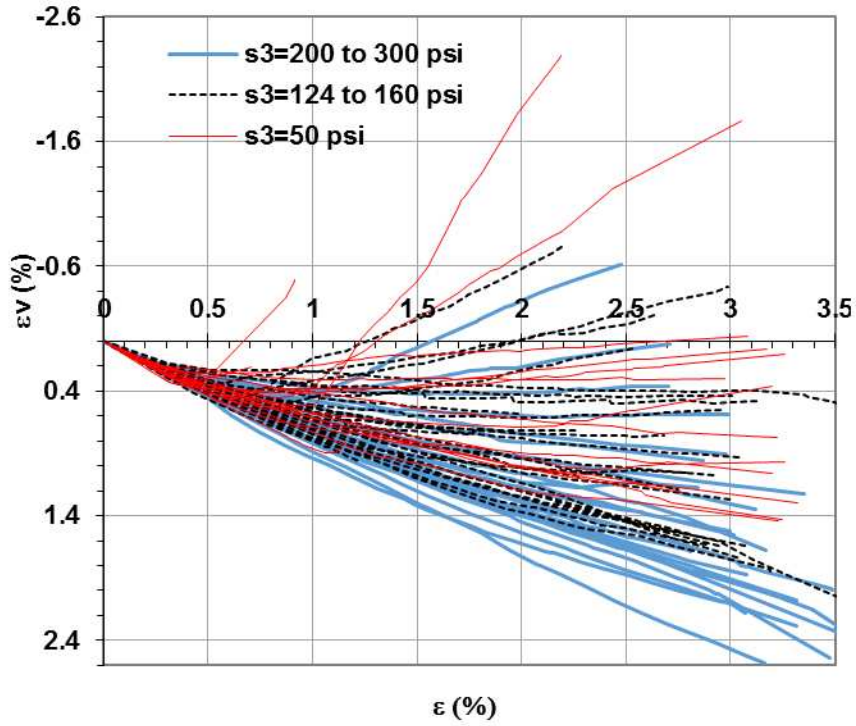
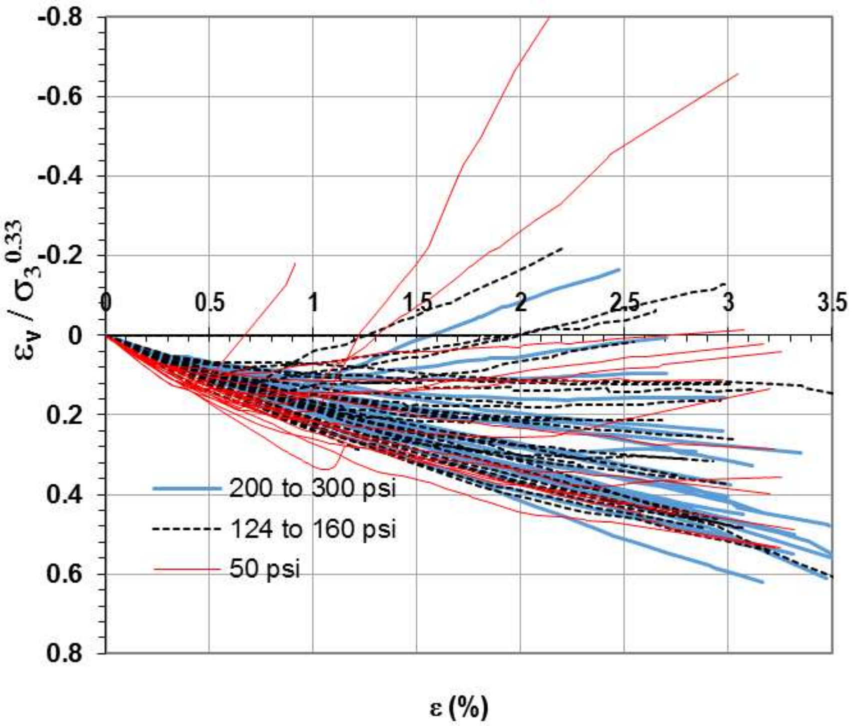
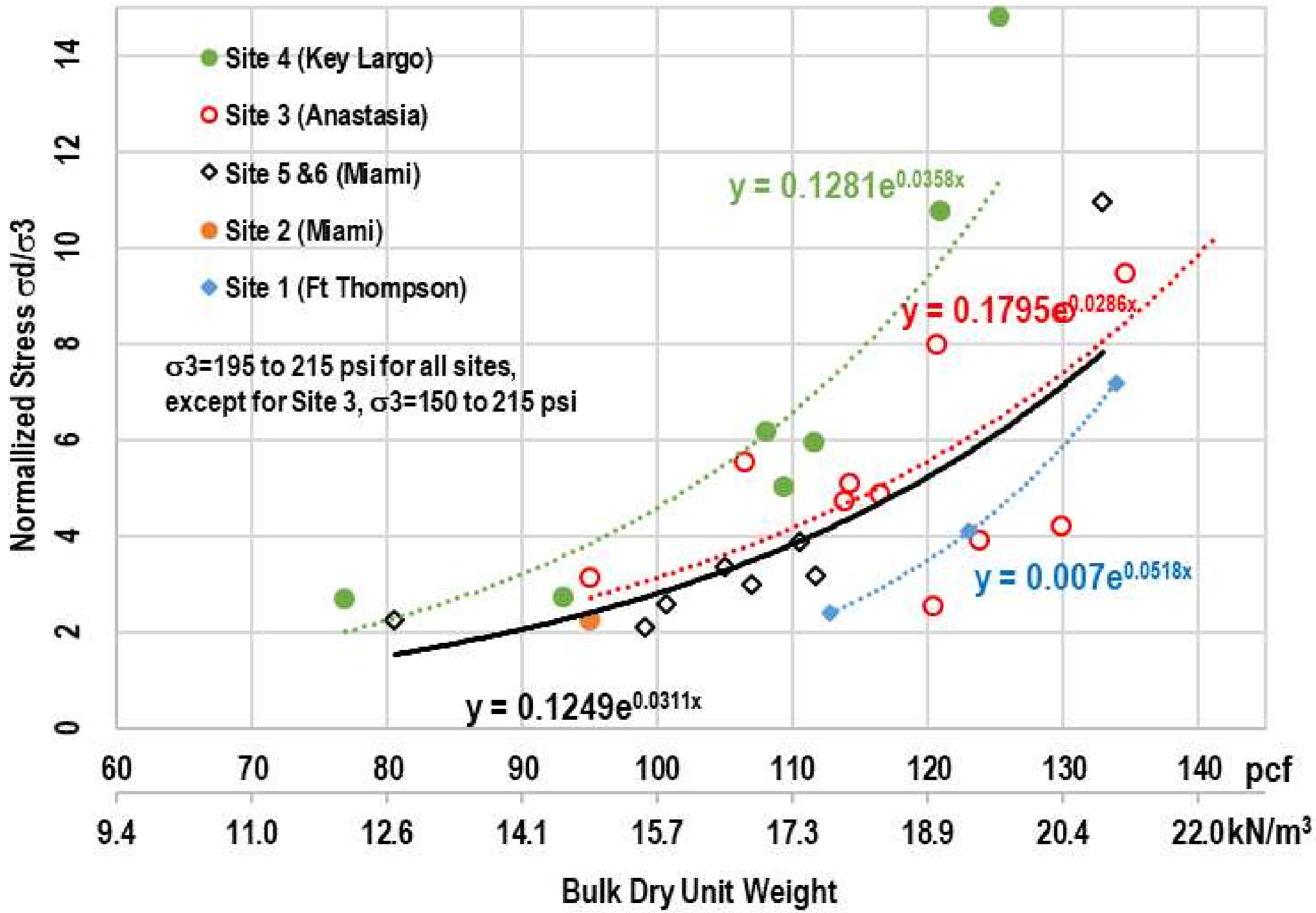
Lab Tests: Triaxial





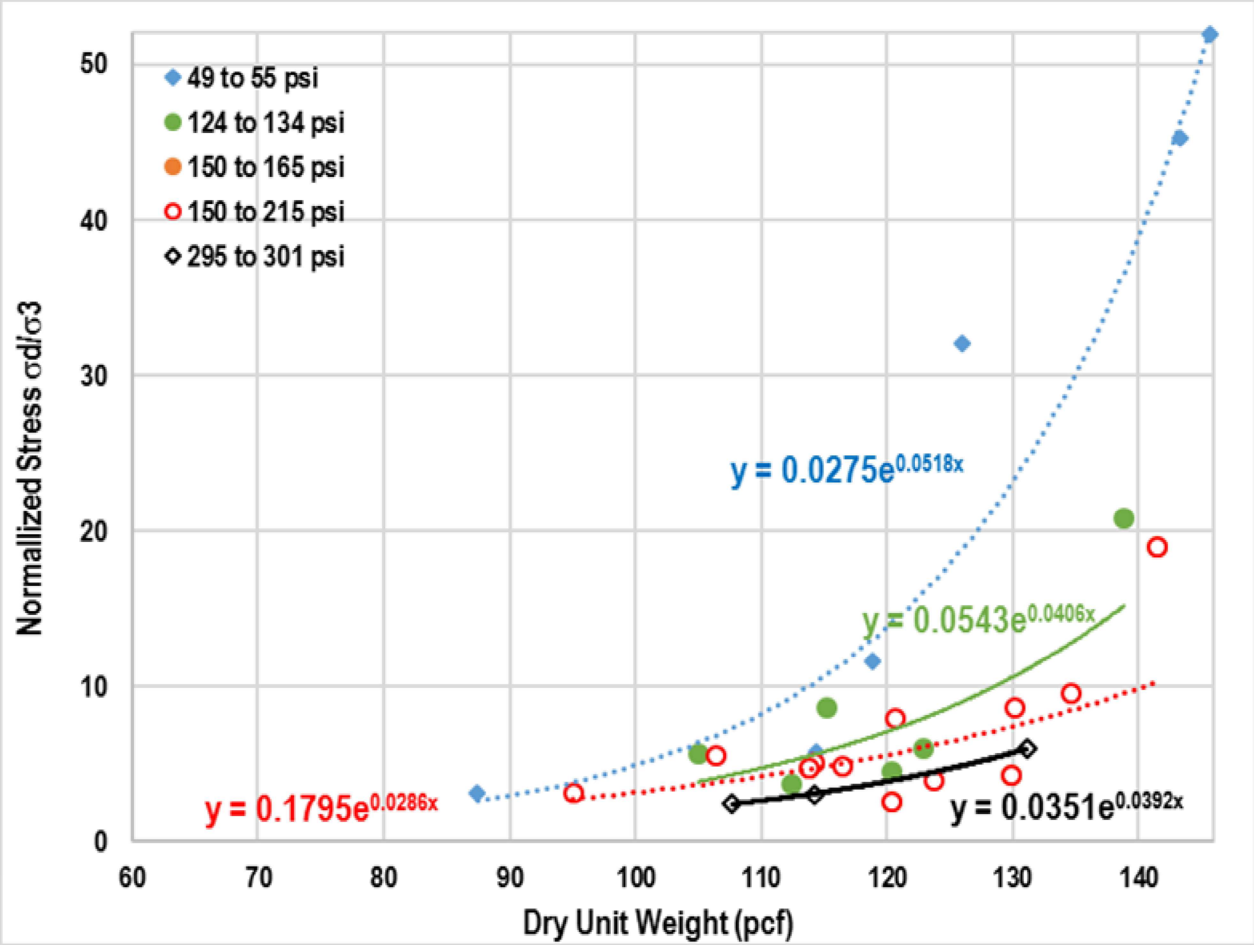
Lab Tests: Triaxial

Example: 4 South Florida formations,
tested at approximately 200 psi chamber pressure



Lab Tests: Triaxial

Example: Anastasia with Chamber Pressures = 50 to 300 psi



Lab Tests: All triax results to date (4 formations)

Log space:

Standard Dev: $\sigma_{mLN} = 0.8242$

$\sigma_{pLN} = 0.7949$

Parameter: $b = 0.9722$

$a = 0.0342$

Coef of Determ.: $R^2 = 0.8790$

Method error:

$\sigma_{\varepsilon LN}^2 = \sigma_{mLN}^2 (1 - R^2)$

$= 0.8242^2 (1 - 0.8790) = 0.0822$

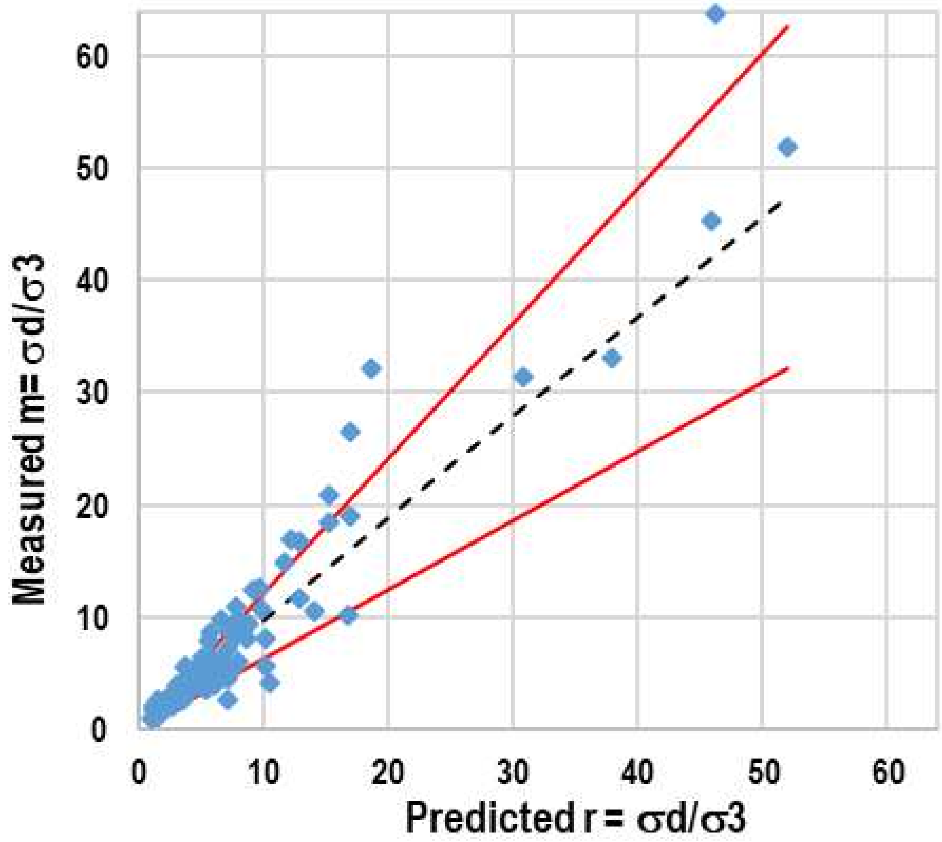
Coef of Variation of Error

$CV_\varepsilon = [\exp(\sigma_{\varepsilon LN}^2) - 1]^{0.5}$

$= [e^{0.0822} - 1]^{0.5}$

$= 0.2927$

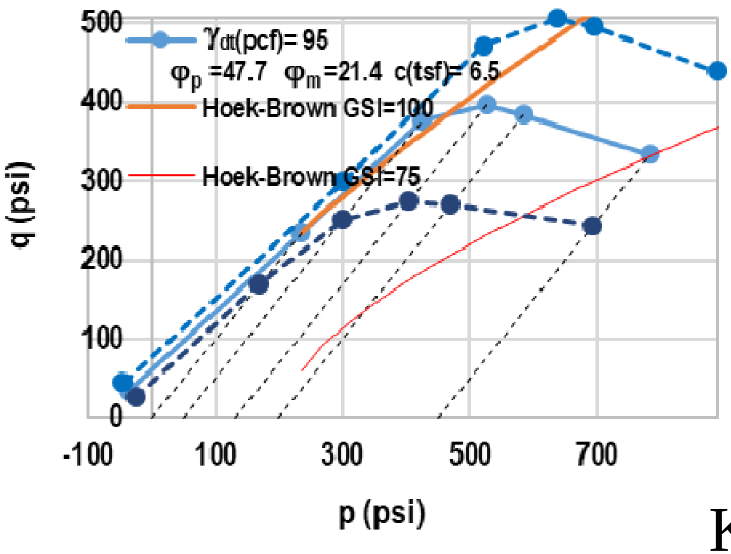
$\sigma_\varepsilon = CV_\varepsilon * r$

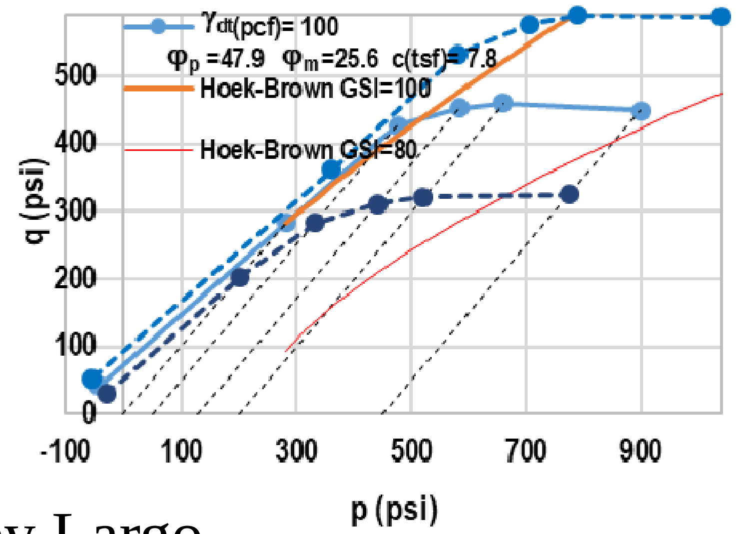


Regression back in Normal Space:

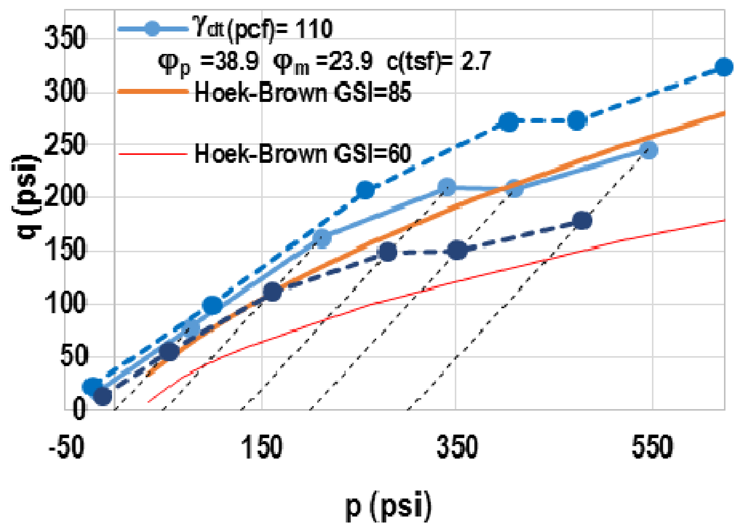
$\ln(m) = b\ln r + a$ thus $m = e^a r^b \pm CV_\varepsilon r = 1.035 * r^{0.9722} \pm 0.2927 * r$

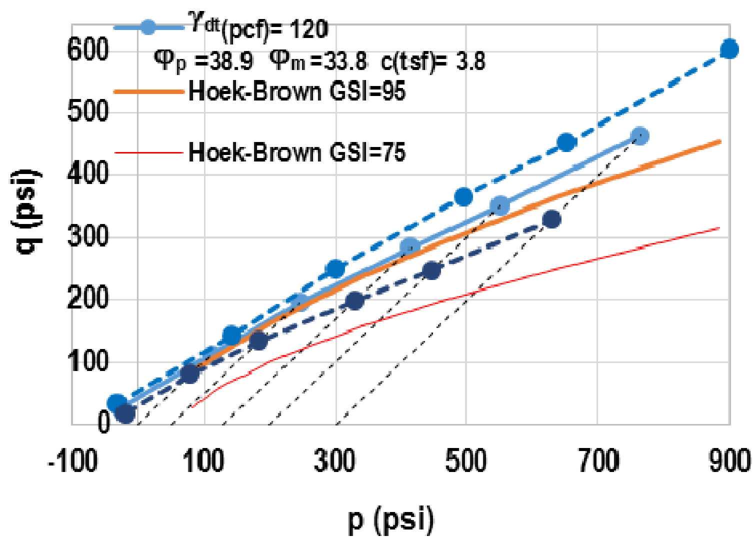
Lab Tests: Triaxial





Key Largo





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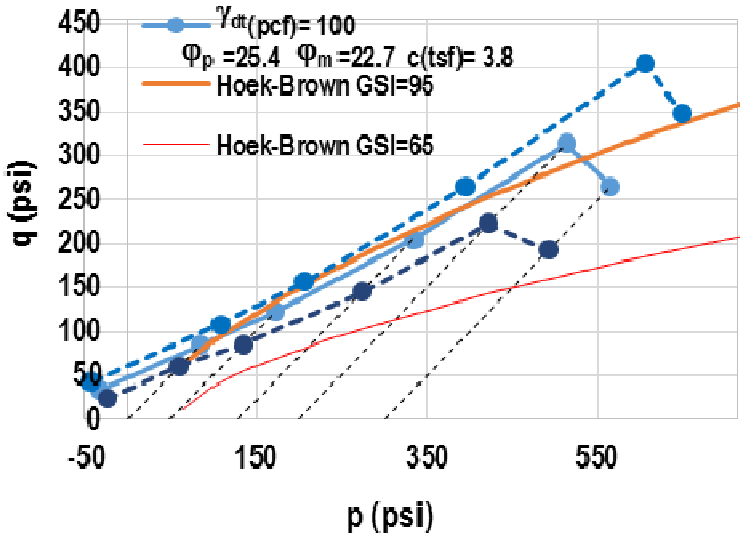
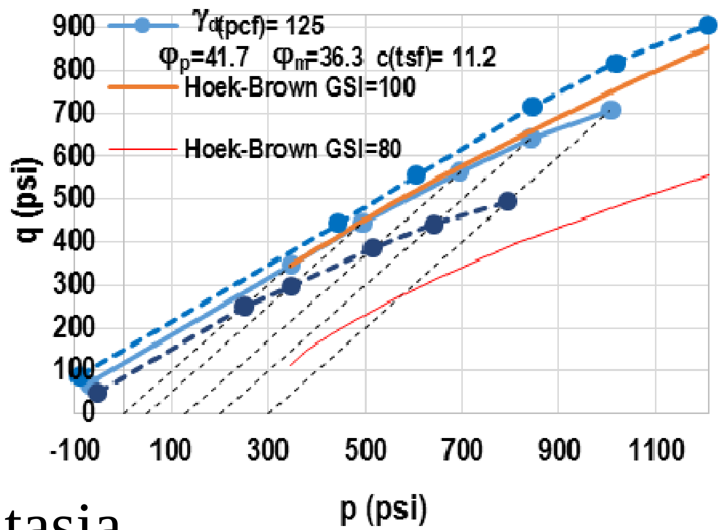
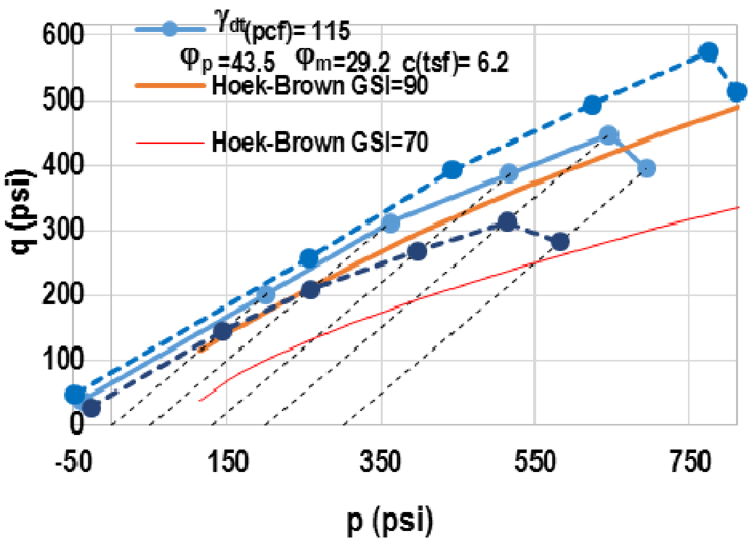
Ft. Thompson

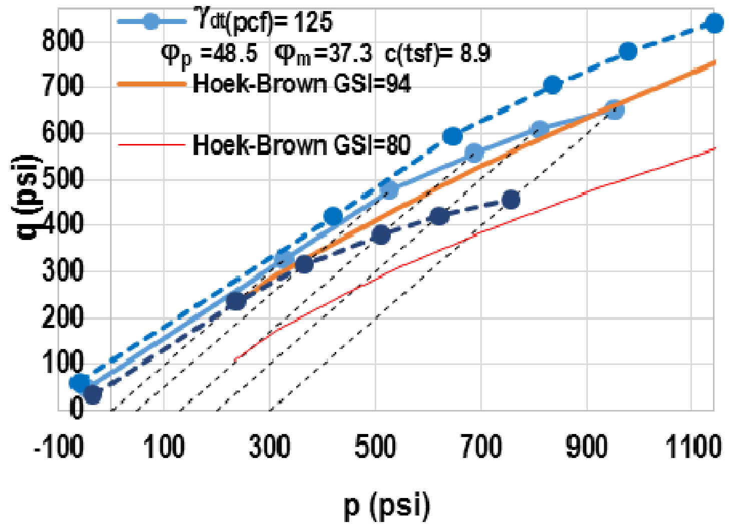
Lab Tests: Triaxial





Anastasia





Miami

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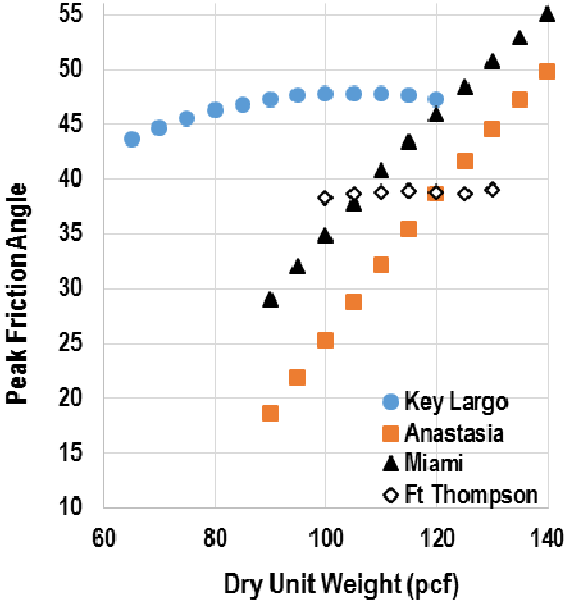
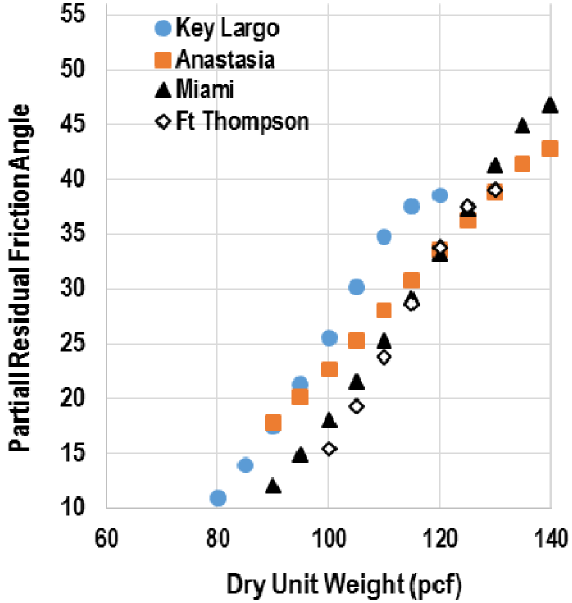
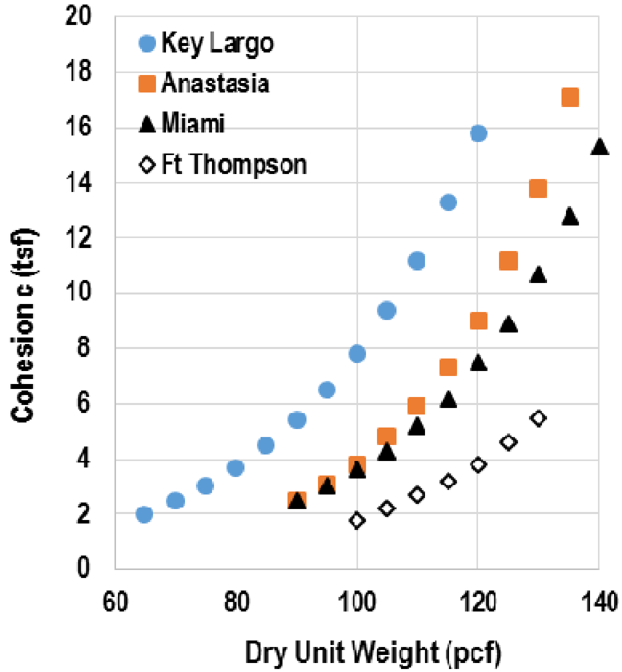
Lab Tests: Triaxial





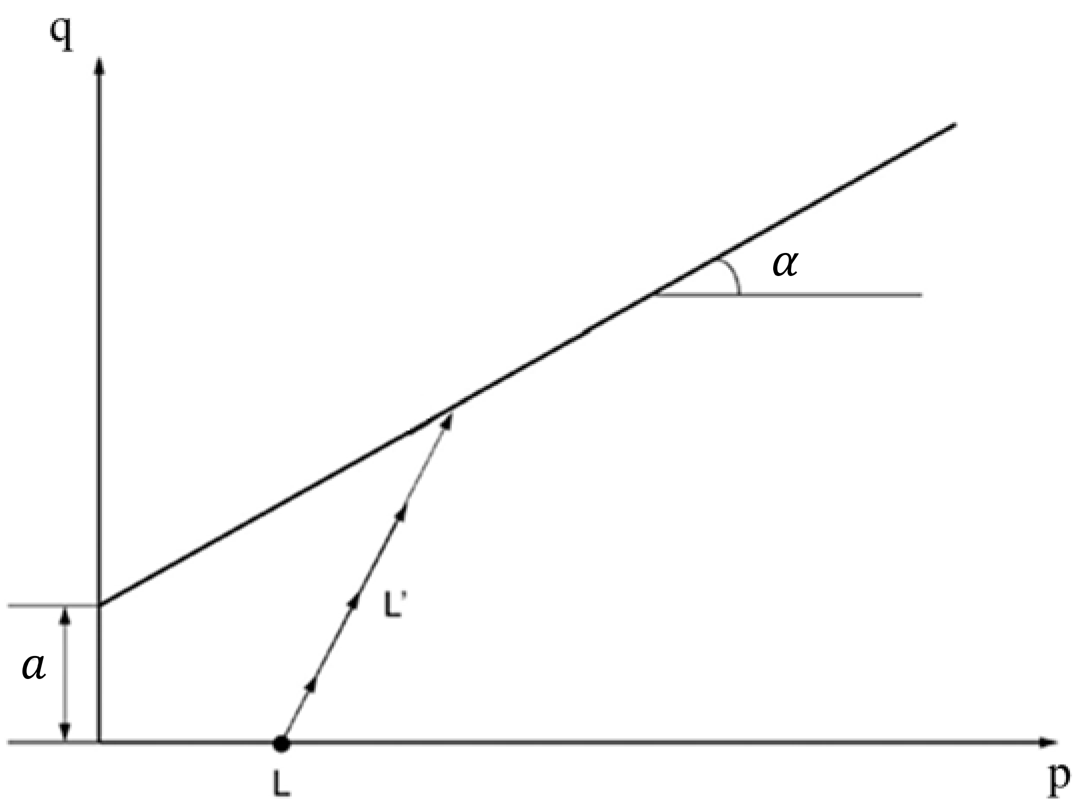


Preliminary suggested ϕ and c values (pending 25 additional future tests for South Florida).

Additional note: Results reduced from testable core pieces (L/D, etc.). Engineers should exercise conservative judgement with regards to rock core pieces that are not suitable for testing.

Numerical modeling

Drucker Prager model



$$\alpha = \tan^{-1}(\sin\phi)$$

$$a = c \cdot \cos\phi$$

$$q = \frac{\sigma_1 - \sigma_3}{2}$$

$$p = \frac{\sigma_1 + \sigma_3}{2}$$

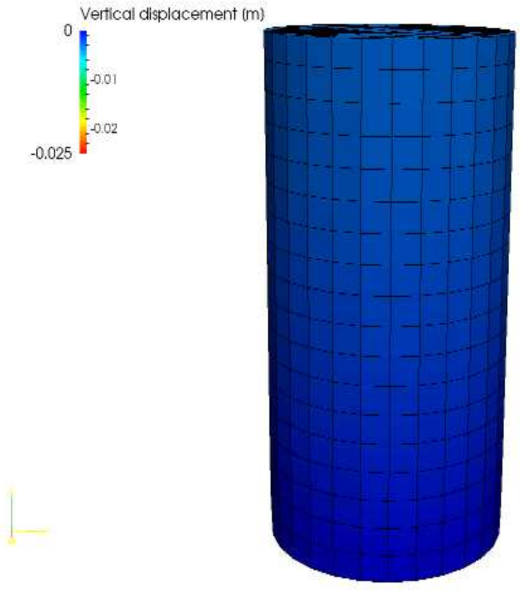
Numerical modeling

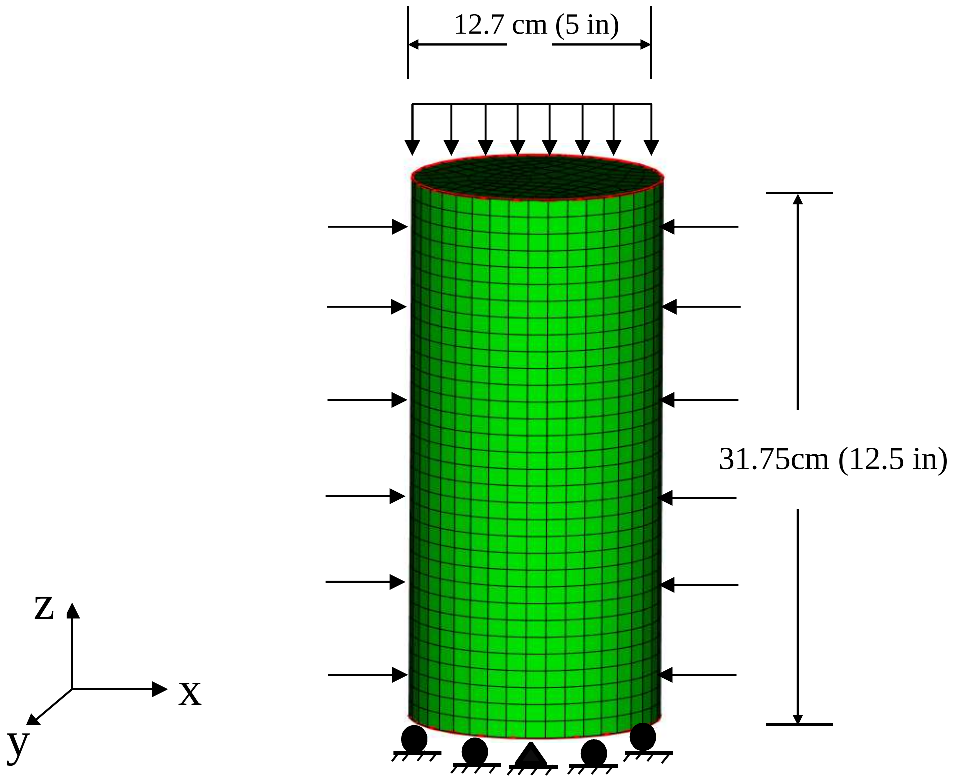
Triaxial testing simulation

Parameters Table of triaxial test					
Loading steps		Initial Conditions		Boundary conditions	
Start Time	0	x_displacemnt	0 cm	fixed_surface	bot_surface
End Time	1000	y_displacement	0 cm	displacement	top_surface
Steps	50	confining pressure	1379kPa (200psi)		
Material parameters					
Dry unit weight	15.71 kN/m^3 (100pcf)	Bulk Modulus	7660kPa (1111psi)		
Porosity	0.4	Poisson	0.2		
Cohesion	383.04 kPa (4tsf)	Friction Angle	35 dgree		

Numerical modeling

Triaxial testing simulation

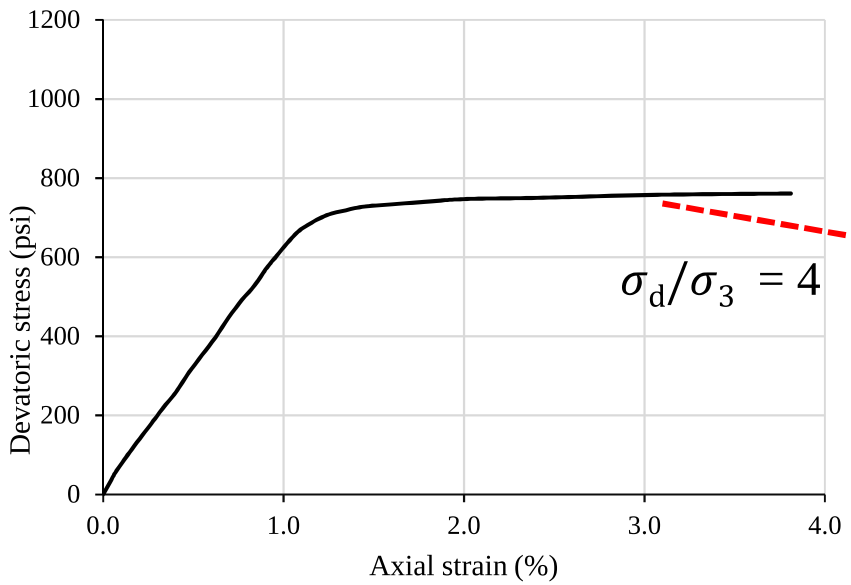




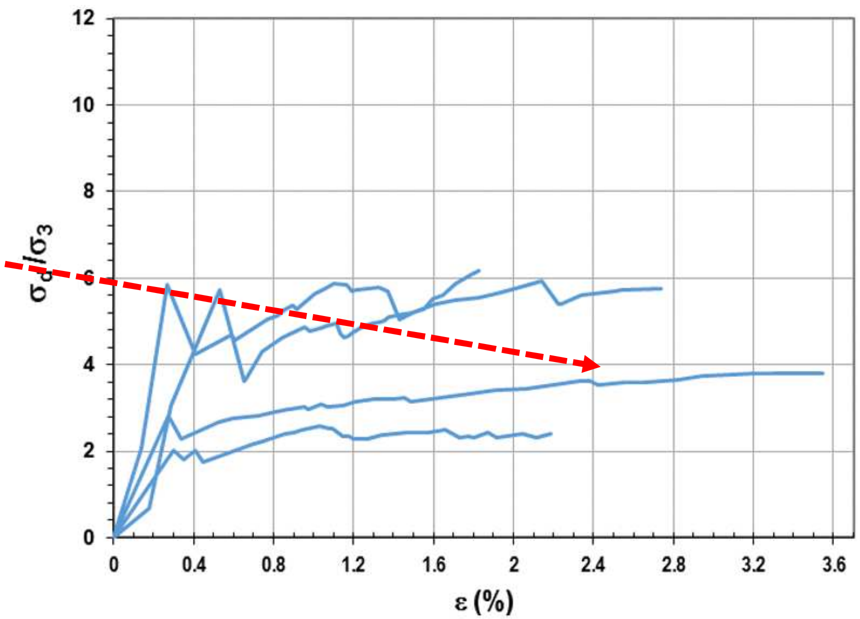
Numerical modeling

Triaxial testing simulation

Simulation results



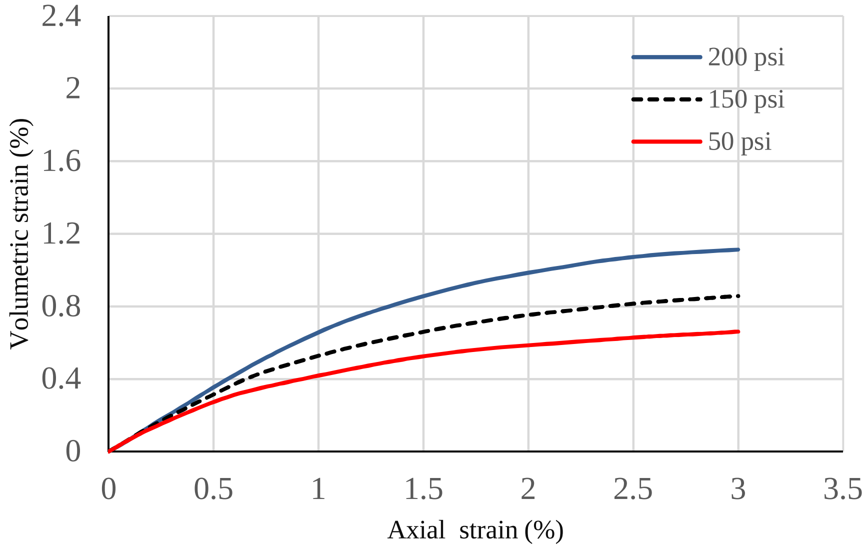
Laboratory testing results



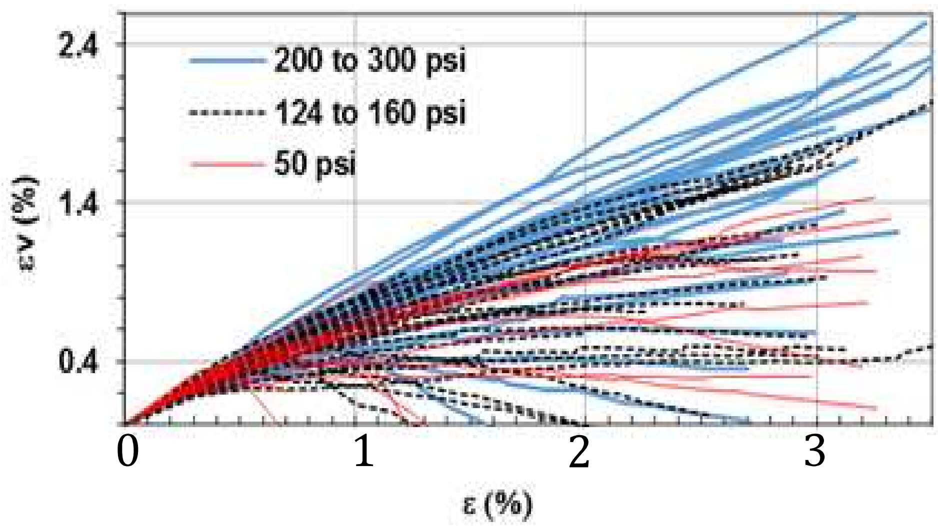
Numerical modeling

Triaxial testing simulation

Simulation results



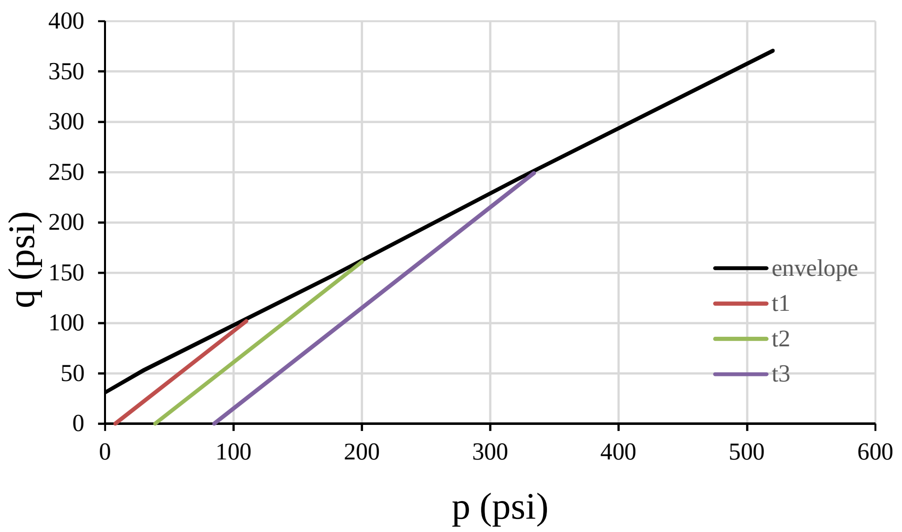
Laboratory testing results



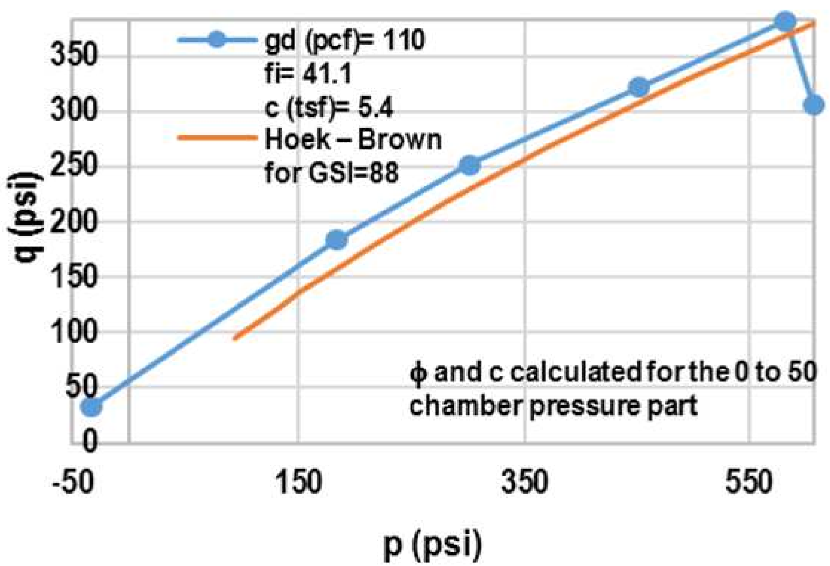
Numerical modeling

Triaxial testing simulation

Simulation results



Laboratory testing results



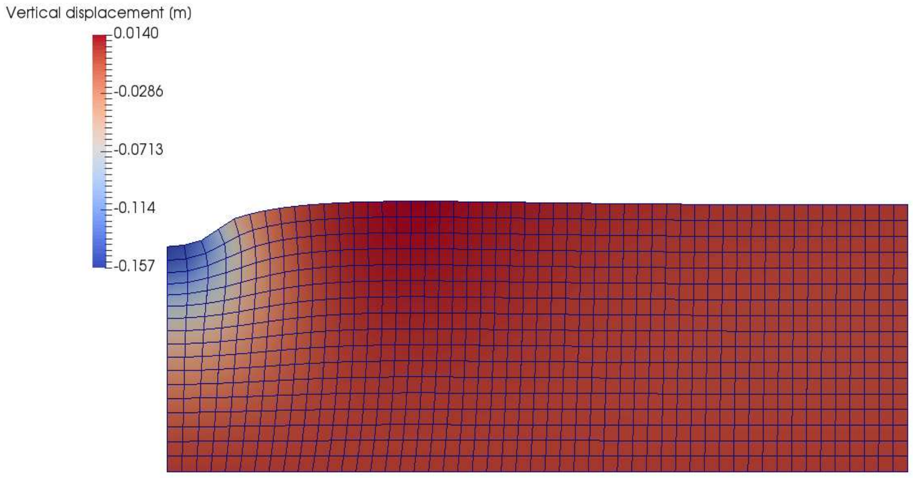
Numerical modeling

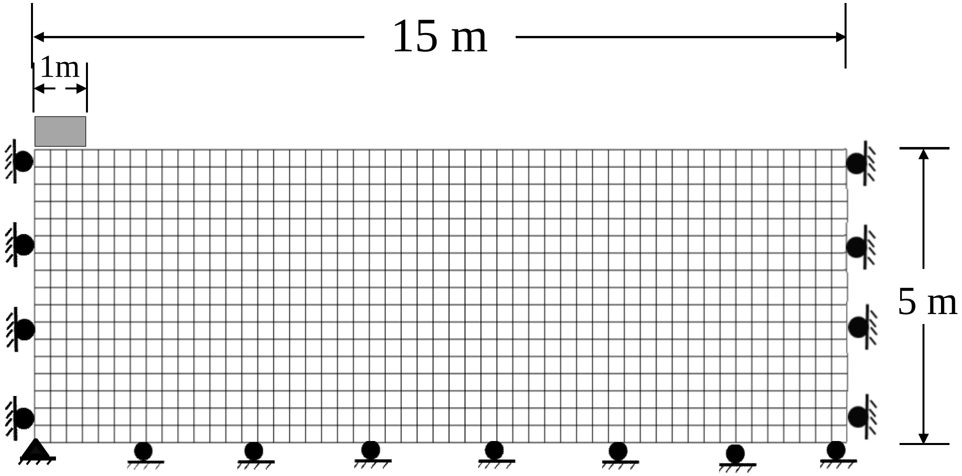
Strip footing simulation (2D)

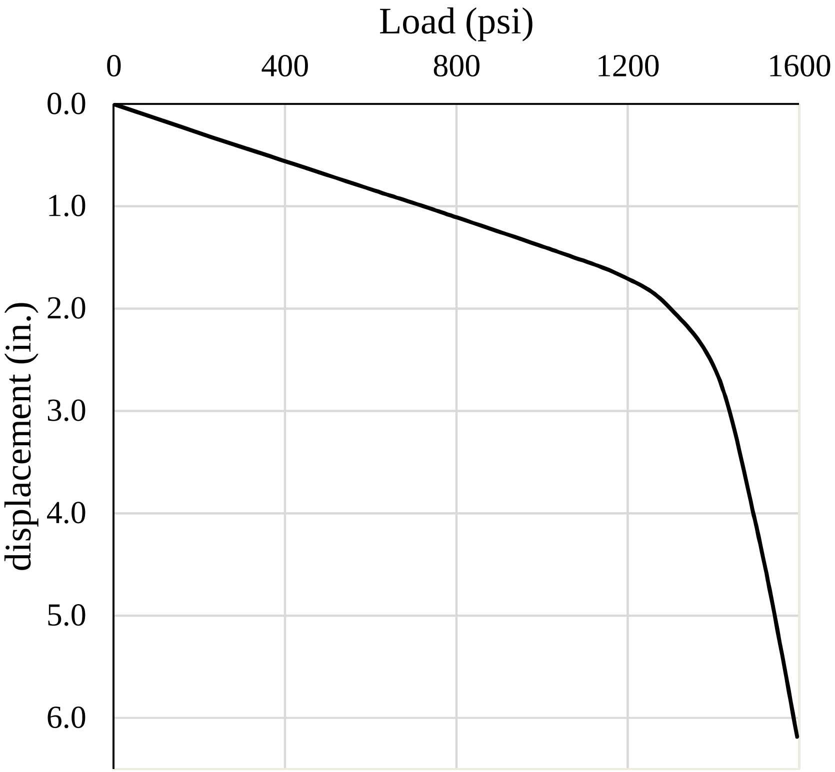
Parameters Table of strip footing (2D)					
geometry size					
length		height		stripfooting length	
15 m		5 m		1 m	
Loading steps		Initial Conditions		Boundary conditions	
Start Time	0	x_displacement	0	fixed_surface	1, 2, 5
End Time	1000	y_displacement	0	displacement	4
Steps	50	pressure	0		
Material parameters					
Dry unit weight	15.71 KN/m^3 (100pcf)	Bulk Modulus	7660kPa (1111psi)		
Porosity	0.4	Poisson	0.2		
Cohesion	383.04 kPa (4 tsf)	Friction Angle	35 dgree		

A strip footing model was simulated by using the boundary conditions which is fixed at the bottom left corner and added roller at both the rest points of bottom and points of two side surface. The strip footing was added at the top left corner. The initial condition like table shown above. The model size and element IDs as shown in following figure.

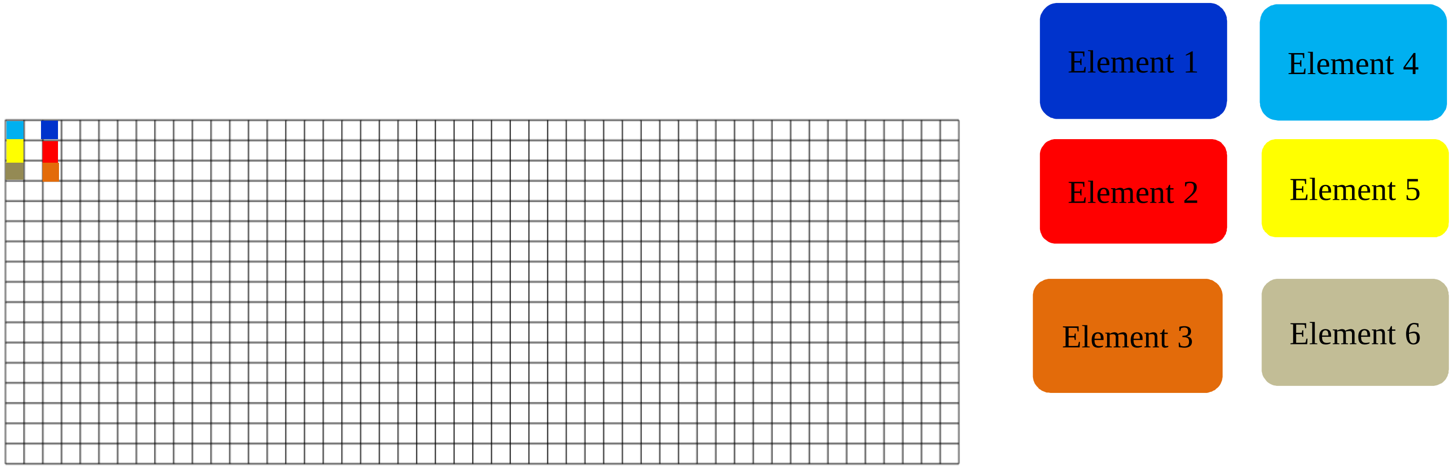
Numerical modeling

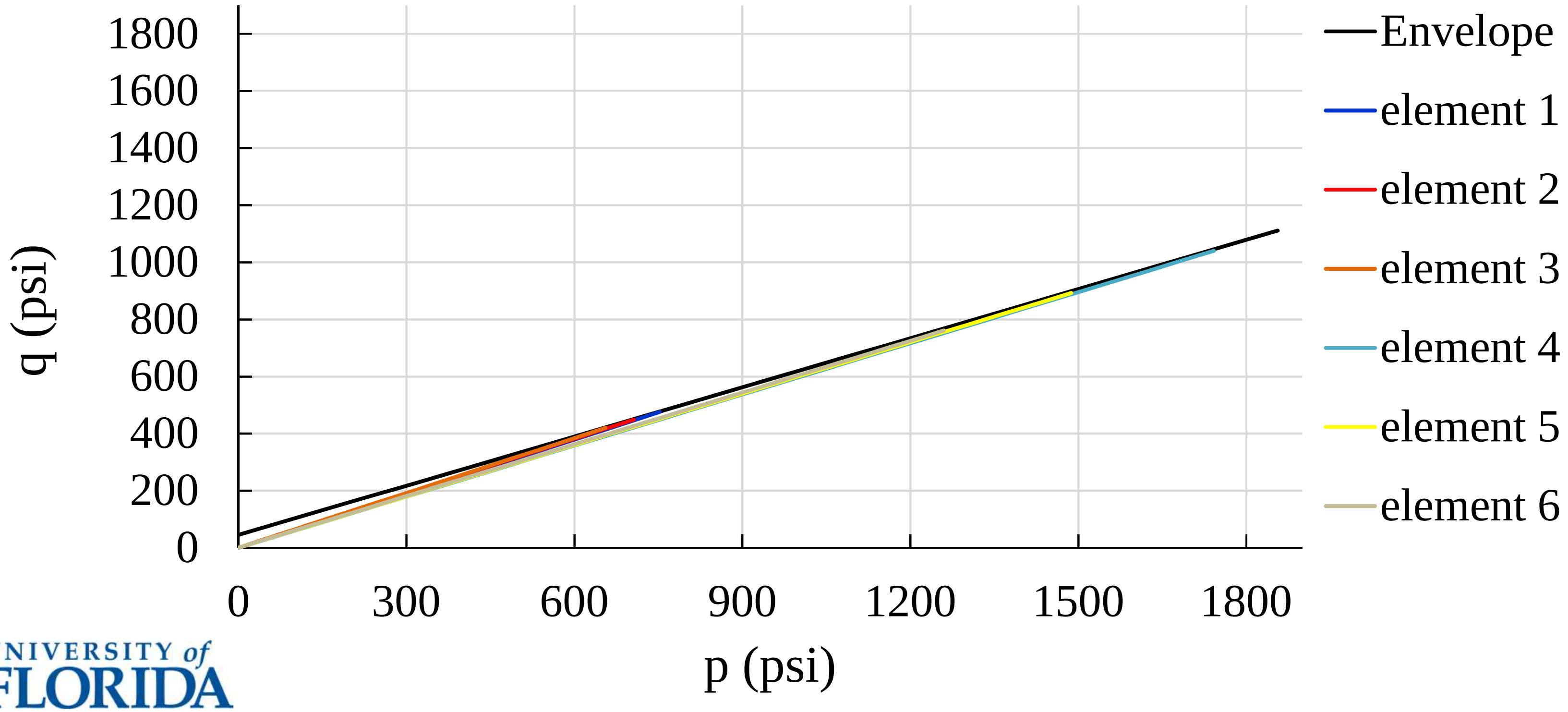




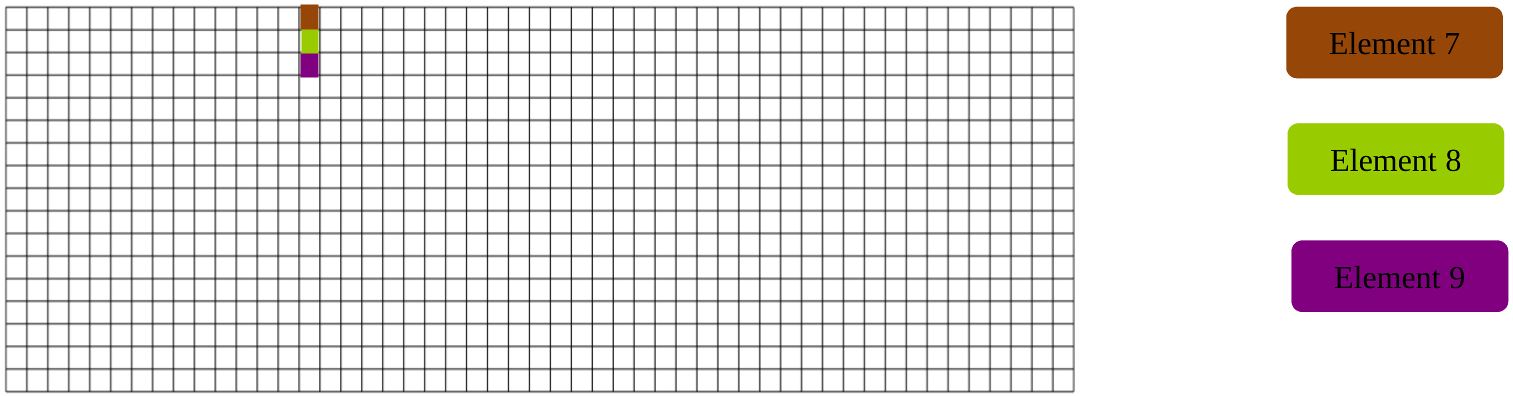


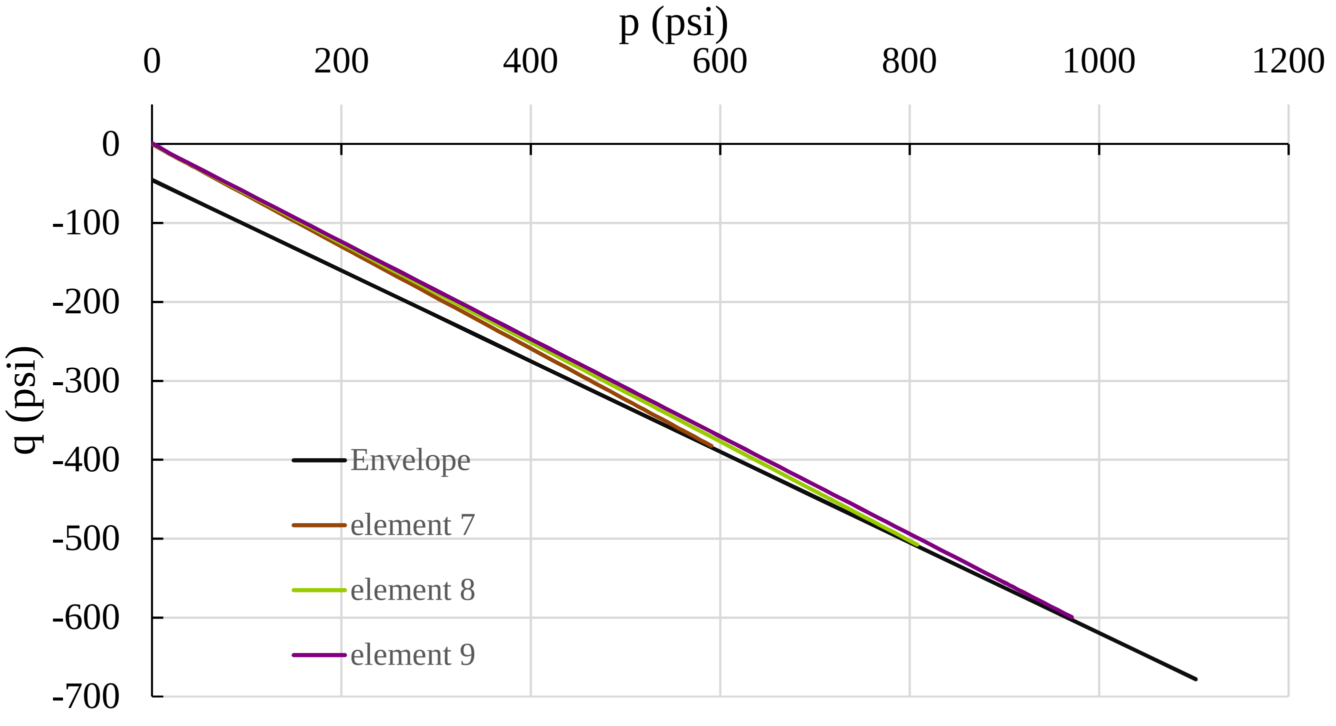
Numerical modeling





Numerical modeling

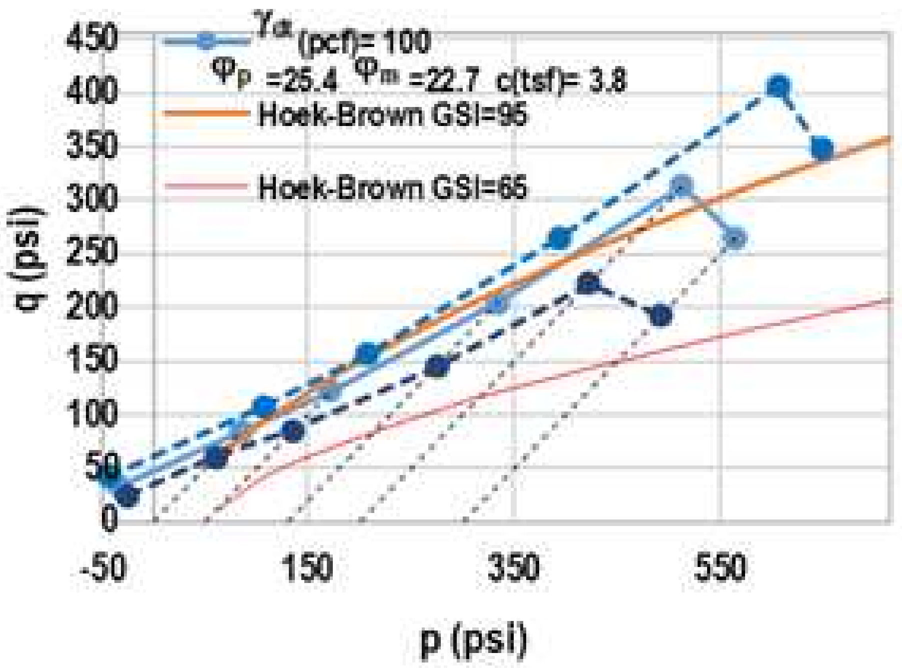




Numerical modeling

Next step tasks

A. The material library will be modified to develop both stress-strain model and strength envelopes for Florida Limestone.



Numerical modeling

Next step tasks

B. The two different boundary value problems will be conducted:

(a) strip footing resting on a deep limestone formation and resting on a finite limestone layer will be simulated.

(b) strip footing resting on two layers (limestone layer overlying sand layer) will be simulated.

The different strength envelope will be considered.

Variable shape of strip footing (L/B=2~10) will be considered in each type simulation.