Sustainable Use of Oil Sands for Geotechnical Construction and Road Building

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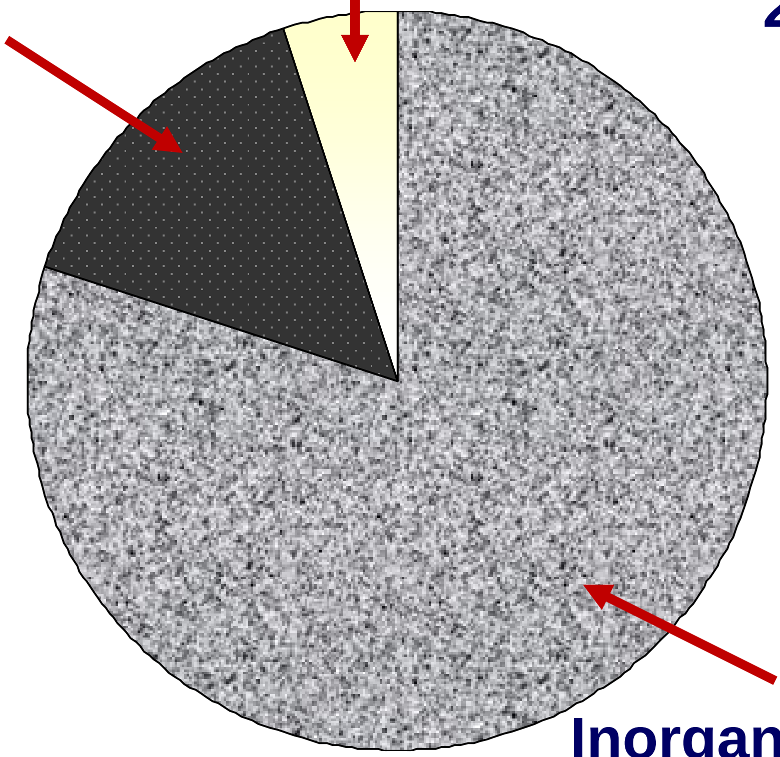
What are Oil Sands..?

- **Oil sand is a generic name given to naturally occurring deposits of bituminous sand materials**
- **Oil sands are rich in bitumen content to the extent that they are mined and processed for crude oil**
- **The largest and most thoroughly studied oil sand deposits are located in Canada, United States and Venezuela. The *Alberta Province in Canada* has the world's largest deposit**

Typical In-situ Properties of Oil Sands



Source: National Energy Board, Canada 2004

Oil Sand Open Pit Mining Activities

Background of Study

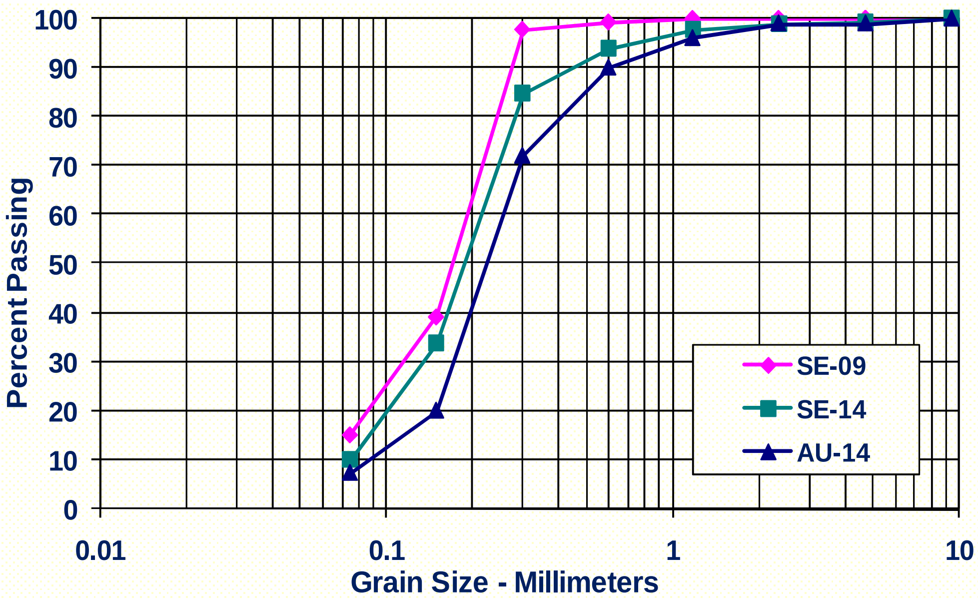
- **Oil sands are natural bituminous materials, which can be sustainable and environmentally friendly in geotechnical construction as they require minimal energy in the preparation for road building**
- **Oil sands can be used as aggregates for road construction to help mitigate aggregate depletion of the environment**
- **Oil sand tailings (by products of bitumen extraction process) can be used for geotechnical applications**
- ***However, to date no standard test procedure/methods exist to characterize behaviour of oil sand materials for geotechnical construction and road building***

Oil Sand Materials Used For This Study

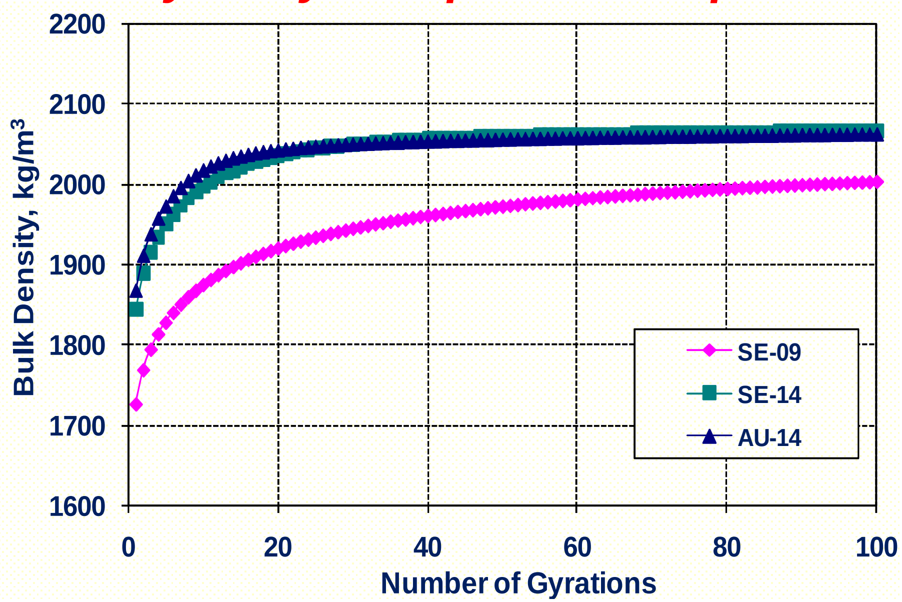
- Oil sand materials were obtained from ***Saskatchewan Province in Canada***
- ***Suncor Energy Inc.*** provided two samples; one low grade and one high grade samples ***(SE-09 & SE-14)***
- ***Syncrude Canada Ltd*** provided one high grade sample from their Aurora mining field ***(AU-14)***
- Samples were shipped to the University of Illinois ***Advanced Transportation Research Laboratory (ATREL)***

Physical Properties of the Three Oil Sand Materials Studied

Particle Size Distribution



Gyratory Compaction Properties



Oil Sand Physical properties (ASTM D 2216, AASHTO T308)

Oil sand ID	Water content, %	Bitumen content, %	Number of gyrations	Bulk density, kg/m^3
SE-09	1.4	8.5	100	2,000
SE-14	3.2	13.3	40	2,050
AU-14	2.2	14.5	25	2,050

Sample Preparation For Laboratory Testing

Oil Sand in Loose State

Gyratory Compacted – Modulus/Deformation Tests

Prismatic specimens cut from gyratory compacted specimens – Direct Shear Test

Standard Proctor Compacted –Shear Test

Proposed Test Procedures for Oil Sands

1. ***Test Procedure for Determining Bulk Modulus of Oil Sand Materials***
2. ***Test Procedure for Determining Shear Strength Parameters of Oil Sand Materials***
3. ***Repeated Load Testing for Determining Resilient Modulus and Permanent Deformation of Oil Sand Materials***
4. ***Pure Shear Test Procedure for Determining Shear Modulus of Oil Sand Materials***
5. ***Test Procedure for Determining Dynamic (Complex) Modulus of Oil Sand Materials***

Field Loading Conditions on Oil Sand Materials

- **Trucks and Shovels loading conditions**

Equipment	Vertical Pressure	Confining Pressure	Speed Range
CAT 797 Truck	800 kPa	250 – 300 kPa	13 – 42 mph
P&H 4100 Shovel	220 kPa	70 kPa	0.52 – 2.8 mph

- **Field loading temperatures**
  - Max summer and winter temperatures = +40^{o}C and -40^{o}C
  - Actual temperature used for field studies = 28^{o}C (Oil sands become softer/problematic)

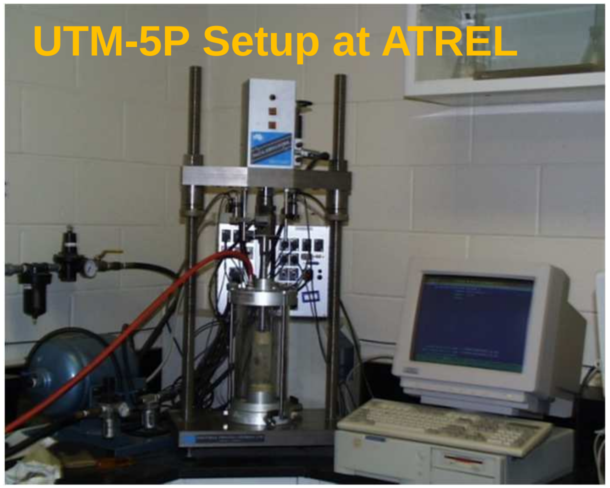
Test Equipment

UI-FastCell Setup at ATREL

- Both UI-FastCell & RaTT Cell are used for **Test Procedures 1, 3, 4 & 5 (Modulus & Deformation Tests)**
- RaTT Cell Commercially available
- UI-FastCell mainly for research at the moment

RaTT Cell Setup at ATREL

- UTM-5P use for Triaxial Shear Test **(Procedure 2)**
- Direct Shear Device use for **Test Procedure 2**
- Both UTM-5P & Direct Shear equipment Commercially available



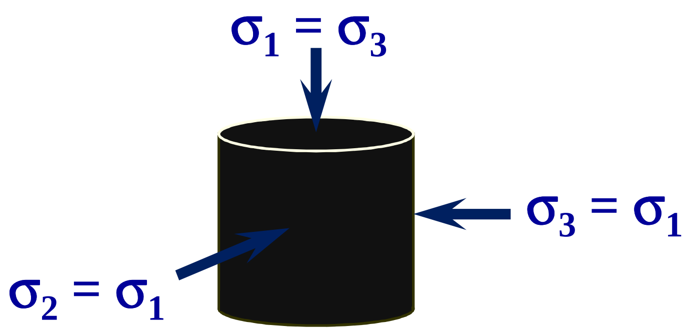
Hydrostatic Compression Test Procedure

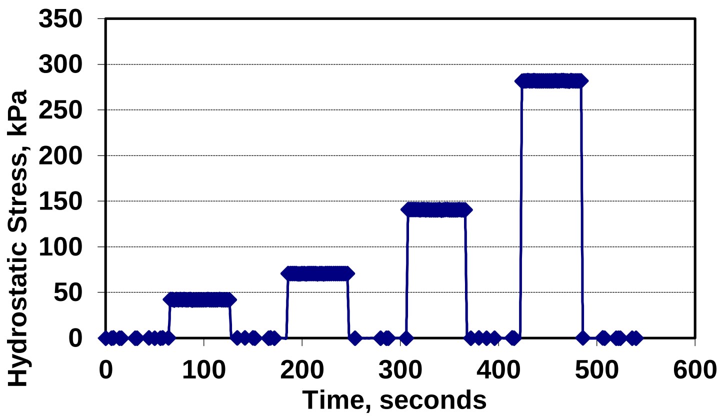
Material Property: ***Bulk modulus K***

- **Pulsed wave shape with 60-second loading and 60-second unloading was applied on the test specimens**
- **Replicate samples were tested at test temperatures of 20ºC and 30ºC**

Loading Conditions

($\sigma_1 = \sigma_3 = 0 \rightarrow 41.4$ kPa $\rightarrow 0 \rightarrow 69$ kPa $\rightarrow 0 \rightarrow 138$ kPa $\rightarrow 0 \rightarrow 276$ kPa $\rightarrow 0$)





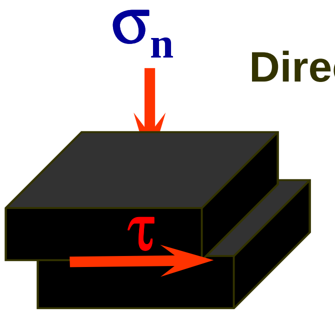
Direct Shear Test Procedure*

Material Properties: ***Friction angle ϕ and Cohesion c***

- **Square prismatic specimens (100 mm x 30 mm thick)**
- **Shearing rate of 1% strain/min or 1 mm/min**
- **Replicate specimens tested for each oil sand sample at test temperatures of 20°C and 30°C**

Applied Normal Stress Levels (KPa)					
Test #1	Test #2	Test #3	Test #4	Test #5	Test # 6
20.7	41.4	69.0	138.0	276.0	552.0

Humboldt Direct Shear Device at ATREL



Direct Shear testing

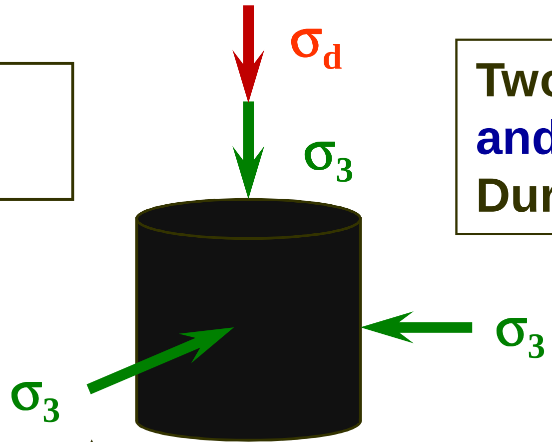
**** Direct Shear Preferred to Triaxial shear Test for Oil Sand Materials***

Repeated Load Test Procedure

Material Properties: ***Resilient Modulus M_R and Permanent Deformation ε_p***

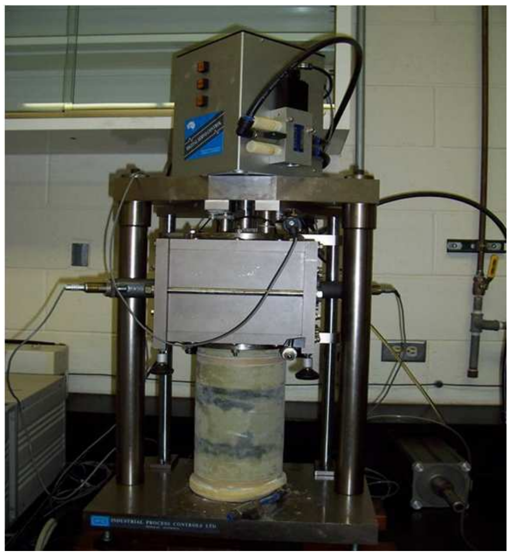
Loading Conditions

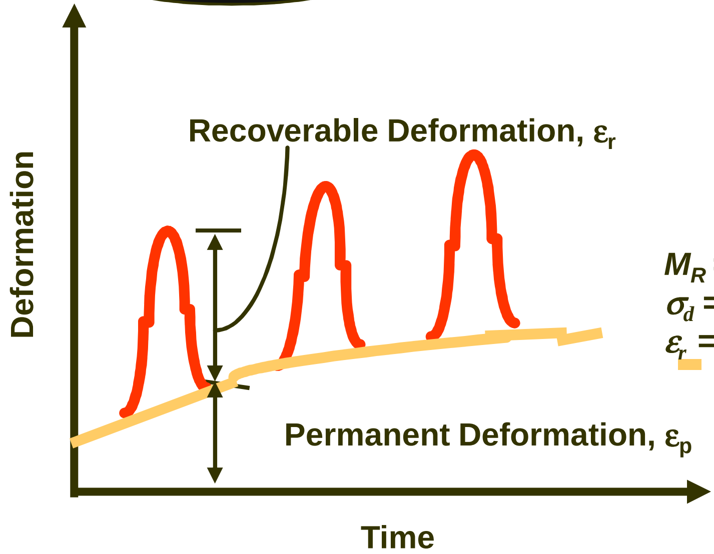
σ_3 = 41.4, 138 and 276 kPa
σ_d = 41.4, 138 and 276 kPa



Two Test Temperatures (20°C and 30°C) and Two Load Pulse Durations (0.1-sec, 0.5-sec)

UI-FastCell Setup





$M_R = \sigma_d / \varepsilon_r$
σ_d = Deviator Stress
ε_r = Recoverable axial strain

Pure Shear Test Procedure

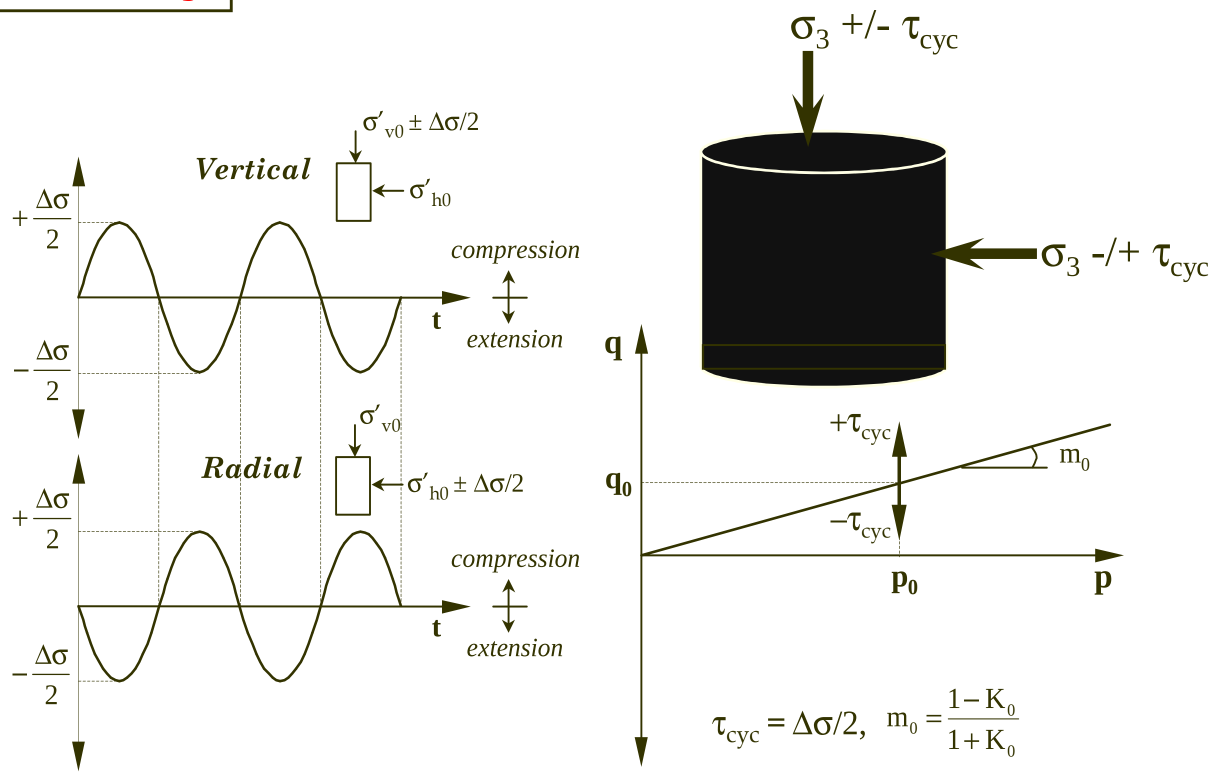
Material Property: *Shear Modulus G*

Loading Conditions

σ_3 = 41.4, 69, 138 kPa
τ_{cyc} = 20.7, 41.4, 69, 138 kPa to max σ_3

Two Test Temperatures (20ºc & 30ºc) and Loading Frequencies (2 and 10 Hz)

RaTT Cell setup



$$\tau_{cyc} = \Delta\sigma/2, \quad m_0 = \frac{1-K_0}{1+K_0}$$

(a) Applied cyclic stresses

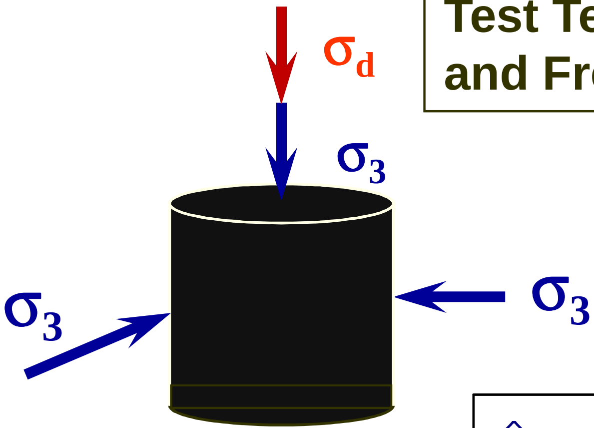
(b) Corresponding stress path

Dynamic (Complex) Modulus Test Procedure

Material Properties: ***Dynamic modulus and Phase Angle (|E*| and δ)***

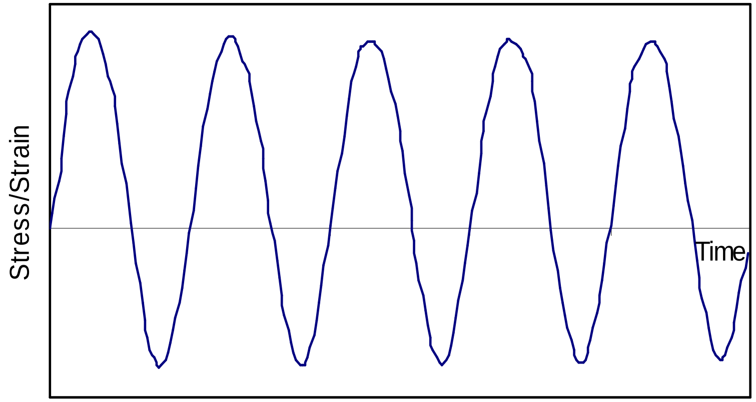
Loading conditions

σ_3 = 41.4, 69 and 207 kPa
σ_d = 41.4 kPa



Test Temperatures (20°C, 30°C) and Frequencies (2, 5 ,10 Hz)

RaTT Cell setup



Material Characterization Models Developed for the Oil Sands

- **Stiffness/Modulus models**

Material Property	Model	R^2	RMSE
Bulk Modulus K	$K = 17.8 \times \sigma^{0.441} w_b^{-0.585} T^{-0.607}$	0.93	0.049
Shear modulus G	$G = 57.8 \times \theta^{2.029} \tau^{-1.614} w_b^{-1.059} T^{-1.183}$	0.87	0.147
Dynamic modulus |E*|	$\lvert E^* \rvert = 204.2 \times \theta^{1.712} w_b^{-1.882} T^{-1.930}$	0.90	0.161
Resilient modulus M_R	$M_R = 33.1 \times \theta^{0.690} w_b^{-0.464} T^{-0.533}$	0.88	0.074

- **Sinkage / Permanent deformation model**

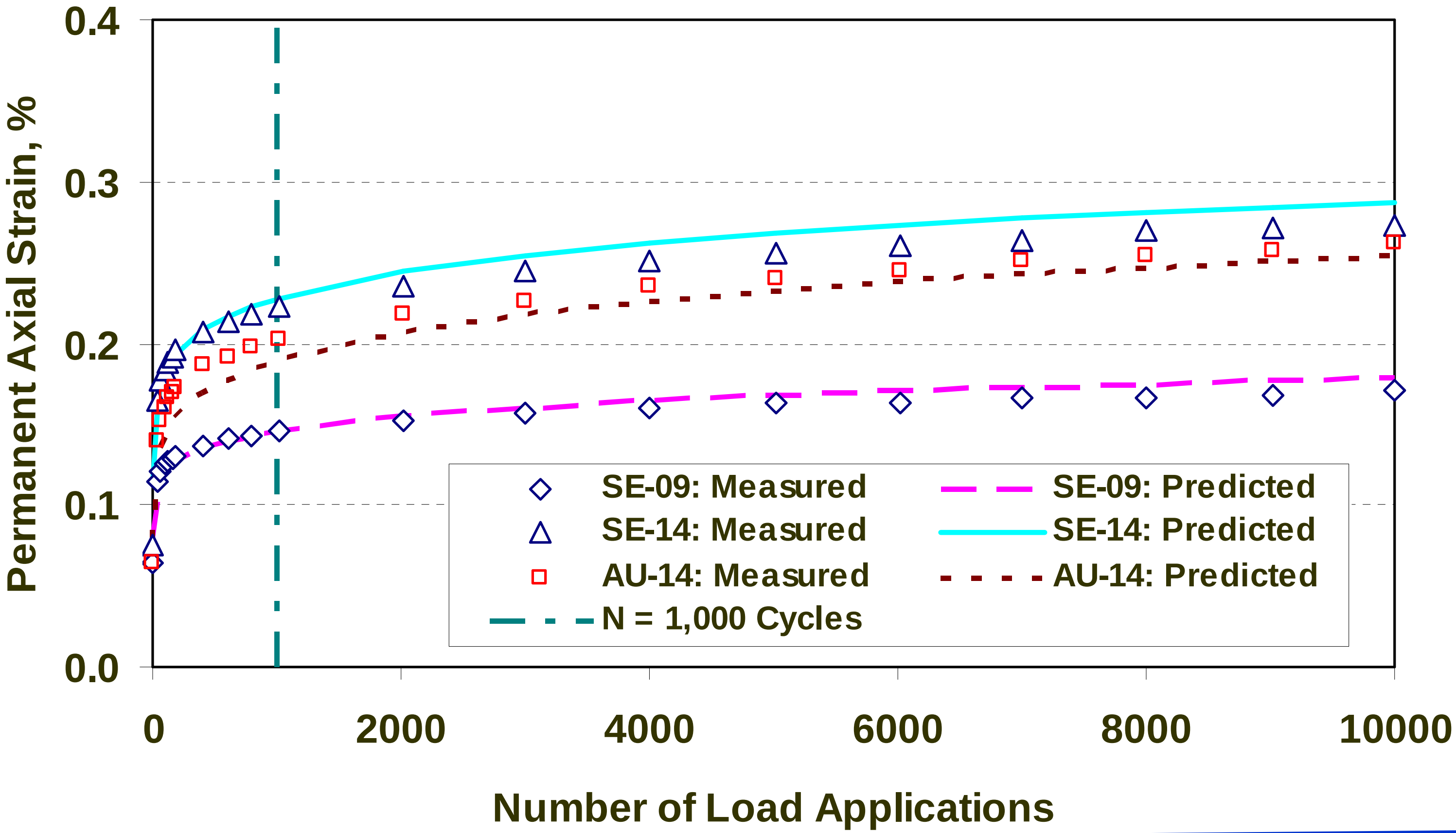
$$\varepsilon_p = 1.389 \times 10^{-3} N^{0.186} \left(\sigma_1 / \sigma_3 \right)^{1.875} \sigma_d^{0.386} w_b^{0.650} T^{0.661} \qquad R^2 = 0.93 \quad RMSE = 0.185$$

Material Characterization Models Developed for the Oil Sands

- **Shear Strength Models at Two Temperatures**

Temperature = 20°C	Temperature = 30°C
$\text{SE-09}: \tau_{max} = 0.82\sigma_n + 6.2$	$\text{SE-09}: \tau_{max} = 0.65\sigma_n + 17.6$
$\text{SE-14}: \tau_{max} = 0.72\sigma_n + 15.2$	$\text{SE-14}: \tau_{max} = 0.59\sigma_n + 29.5$
$\text{AU-14}: \tau_{max} = 0.63\sigma_n + 22.9$	$\text{AU-14}: \tau_{max} = 0.55\sigma_n + 31.3$

Permanent Deformation Model Validation



Loading Conditions:

- **Stress states: $\sigma_d = \sigma_3$ = 138 kPa (20 psi)**
- **Load pulse duration = 0.1 sec.**
- **Number of load applications = 10,000**
- **Test temperature = 20°C**

Two replicate specimens of each oil sand material were used for Lab validation

Conclusions

- **There is a need to establish test procedures/methods and material characterization models for oil sand materials**
- **This study has provide a platform and opportunity to establish standard ASTM laboratory test protocols for the sustainable use of oil sand deposits as temporary and permanent roads materials in mine fields**
- **Reasonable material characterization and performance models have been developed to properly characterize field behavior of oil sand materials under both static and dynamic loading conditions**

Acknowledgements

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End of Presentation – Questions..?

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