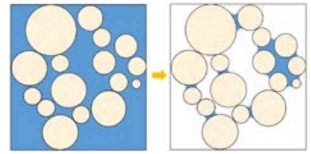


Principles of Unsaturated Soil Mechanics and Its Application in Geotechnical and Pavement Engineering

Prof. William J. Likos Ph.D. *UW- Madison*
Prof. Bora Cetin Ph.D. - *MSU*
Raul Velasquez P.E. Ph.D.- *MnDOT*
John Siekmeier P.E. - *MnDOT*
Terry Beaudry P.E. - *MnDOT*

NRRA Webinar
May 19, 2020

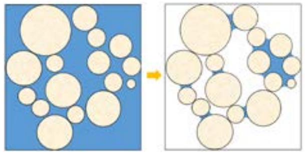
MN DEPARTMENT OF TRANSPORTATION
MICHIGAN STATE UNIVERSITY
Department of Civil and Environmental Engineering
UNIVERSITY OF WISCONSIN–MADISON
NRRA National Road Research Alliance

Housekeeping

- Webinar will be recorded and available at a later time @ NRRA Website
- Due to large participation, please type any question or comment on chat box. Moderator will ask questions to Panelists during QA sessions
- Webinar organizers are not planning to provide a certificate of participation. However, to best of our knowledge, this course/activity meets continuing education requirements for PDHs as outlined in Minnesota Statute 326.107. (Please check your state statute)

Agenda

- Welcome – Introduction – *T. Beaudry*
- Fundamental Concepts in Unsaturated Soil – *W. Likos*
- Measurement of Unsaturated Properties – *R. Velasquez*
- Q&A – Fundamentals – *All*
- Break (10 min)
- Impact of Moisture on Pavement Foundation Materials – *B. Cetin*
- Importance of Unsaturated Soil Mechanics in ME Design – *B. Cetin*
- Correlations between Unsat Soil Parameters and ME Design Input – *B. Cetin*
- Use of Unsaturated Soil Mechanics by MnDOT– *J. Siekmeier*
- Q&A –Applications – *All*
- Closing Remarks – *T. Beaudry*



Introduction

Terry Beaudry P.E.

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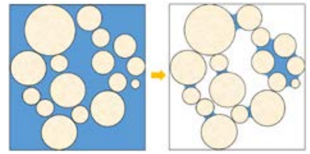
Why Should I Care?

- Recent developments in soil mechanics warrant a change in classic conservative approach
- Saturated conditions is not appropriate design assumption in explaining heave of road foundations, through swelling of expansive subgrades soils
- Technology has improved our ability to measure and characterize unsaturated soil
- Designing based upon saturated conditions is too conservative and more costly



Principles of Unsaturated Soil Mechanics

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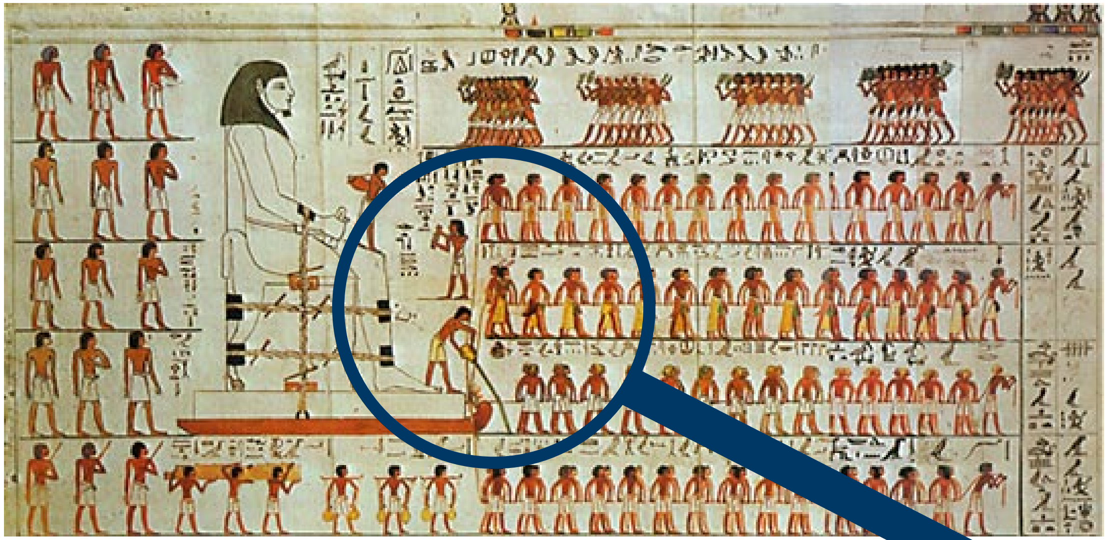
Unsaturated Soil Mechanics and the Great Pyramids?

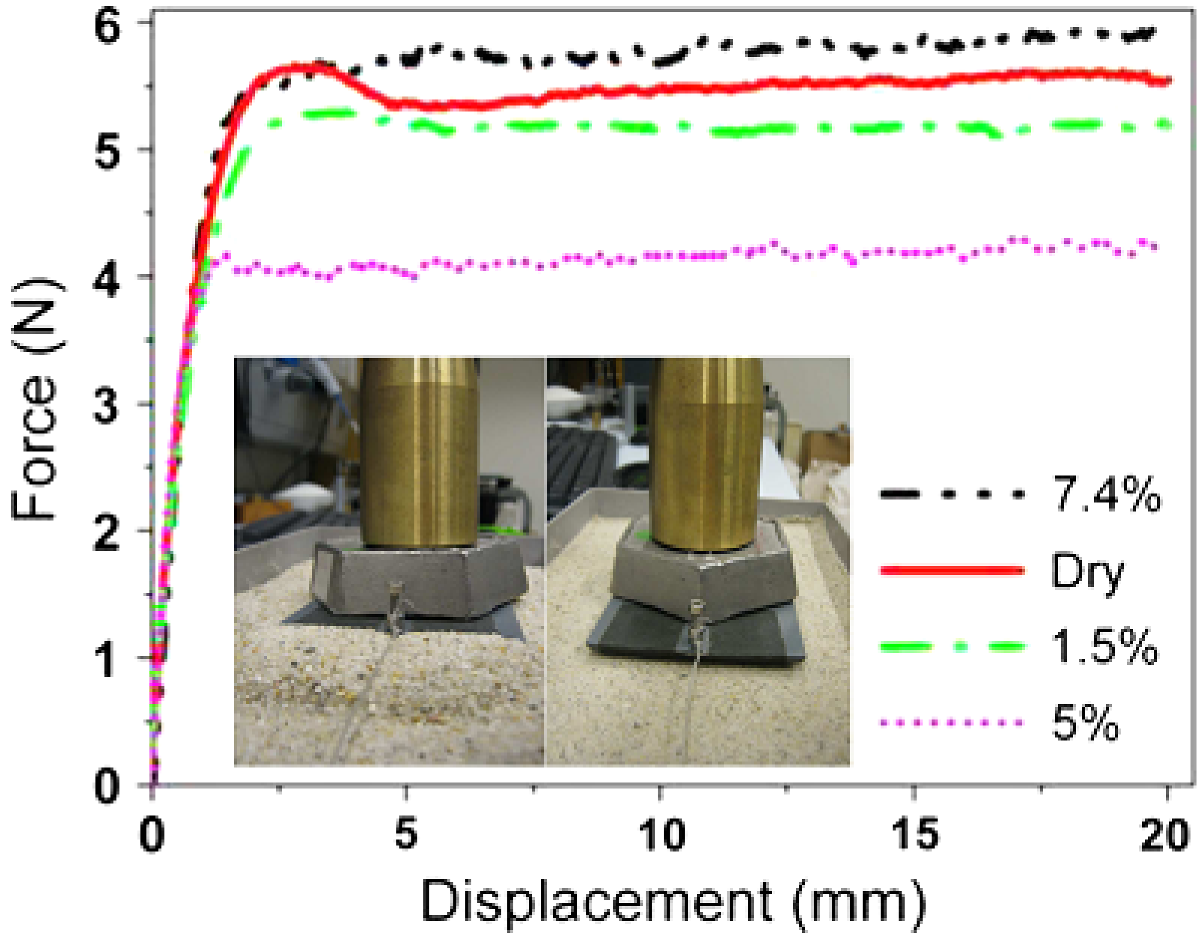
Wall painting from 1880 B.C. on the tomb of Djehutihotep in southeastern Egypt (Newberry, 1895).



Colossal statue of Djehutihotep (7 m high) transported by 172 workers using ropes and a slide.

Water being poured in the path of the sled.

Ritual or Unsaturated Soil Mechanics?



(from Fall *et al.*, 2014, *Phys. Rev. Letters*, 112, 175502)

Topics for Discussion

- What is unsaturated soil?
  - Soil as a multiphase system
  - Properties depend on degree saturation
- What are differences between saturated and unsat. soils?
  - Concepts from interfacial physics
- What is soil suction?
  - Concept of pore water potential
- Why is unsaturated soil mechanics important?
  - Examples of engineering problems with unsat. soils.

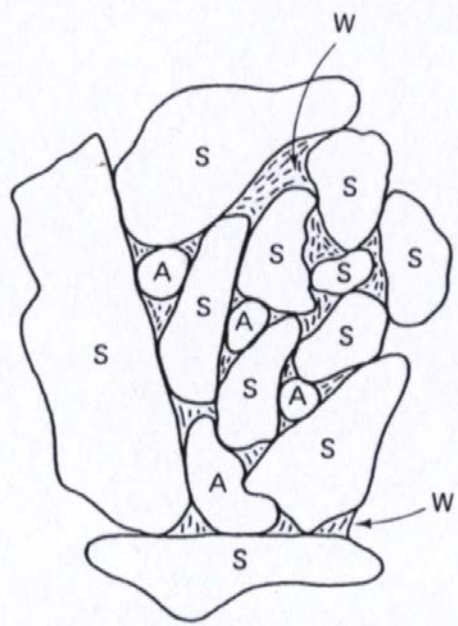
Soil is a multiphase system

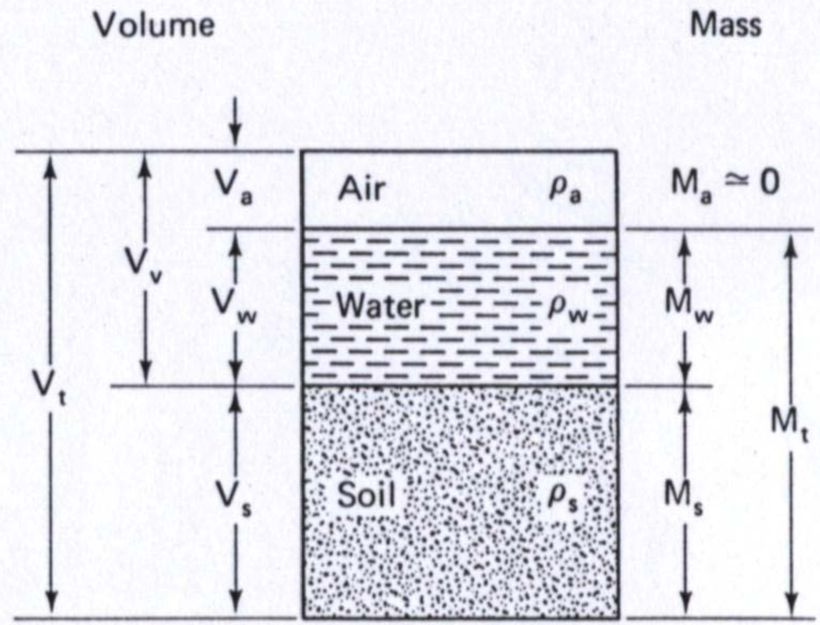
S = Solids

W = Water

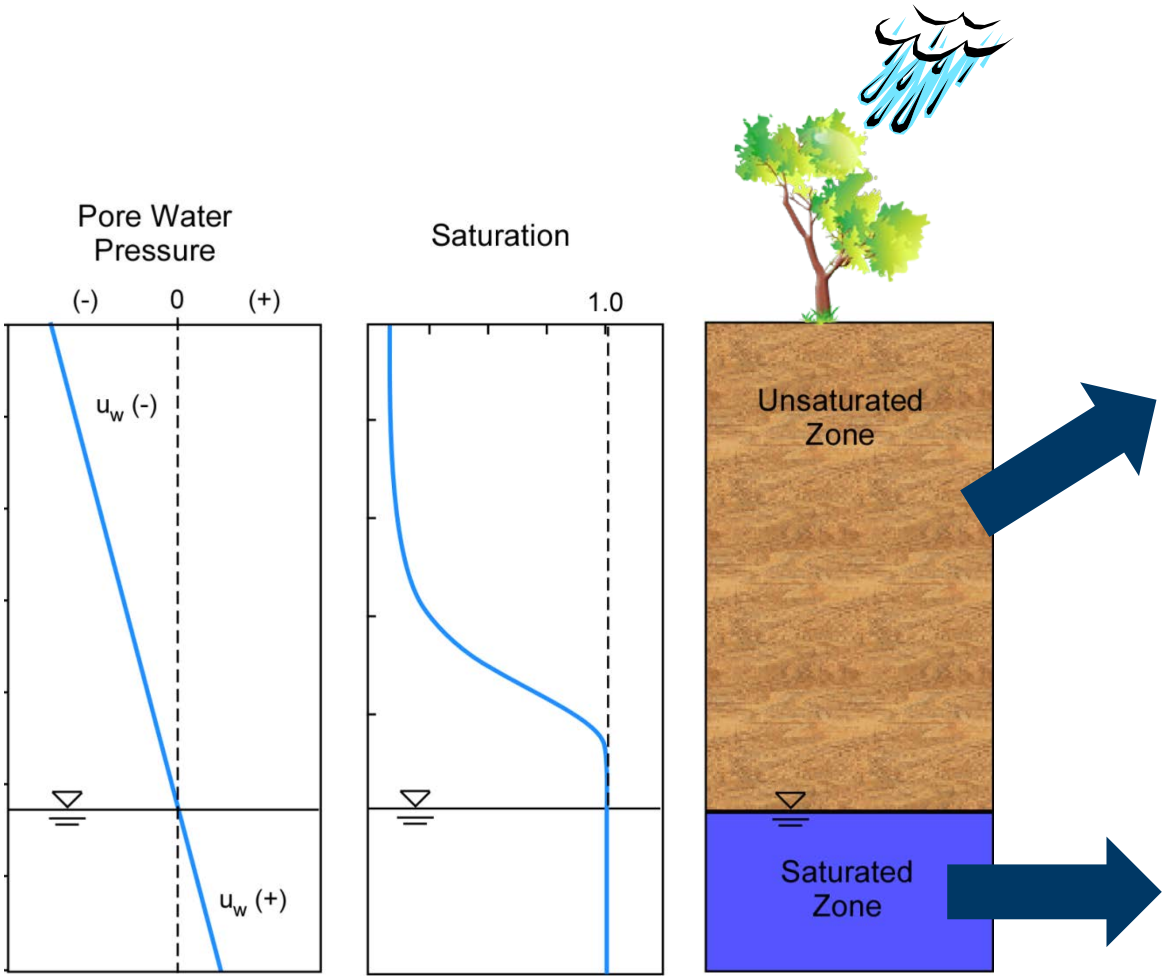
A = Air

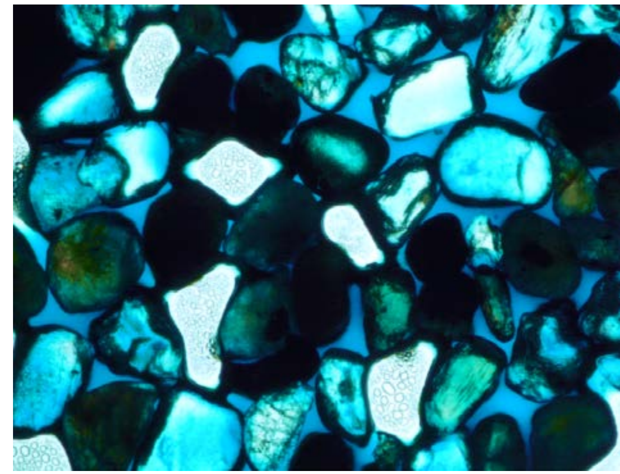
Relative amount of each phase will affect behavior

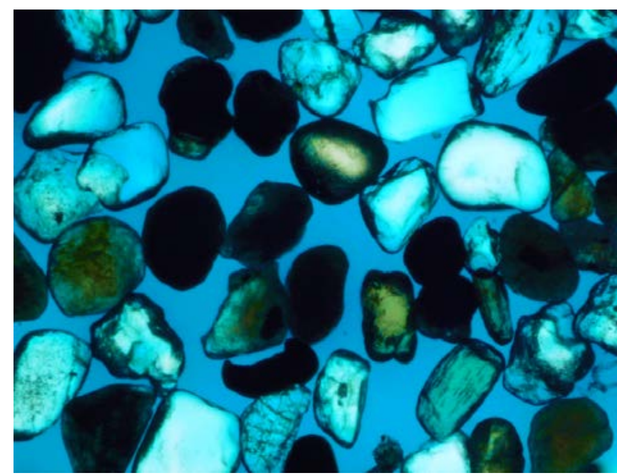




"block diagram"







Aeolian Sand – Alamosa, CO
Average Grain Diameter = 150 µm.

Saturated Soil

- *2-Phase System*

- *Pore Fluid Pressure,* u_w

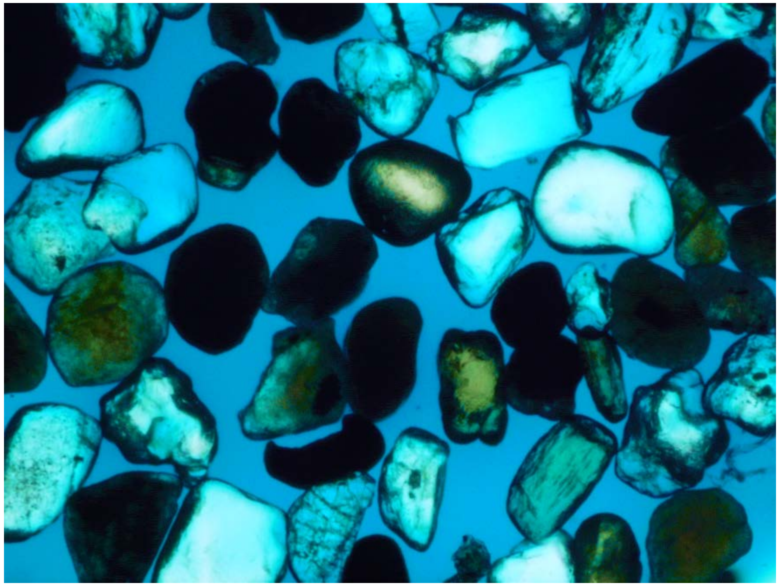
  u_w *(+)*

- *Volumetric Water Content,* θ

  $\theta = V_w/V_t = V_v/V_t = n$

- *Degree of Saturation, S*

  $S = V_w/V_v = 1.0$ *(100%)*



- *Conductivity (hydraulic, thermal) is constant at constant state (volume, temp.)*

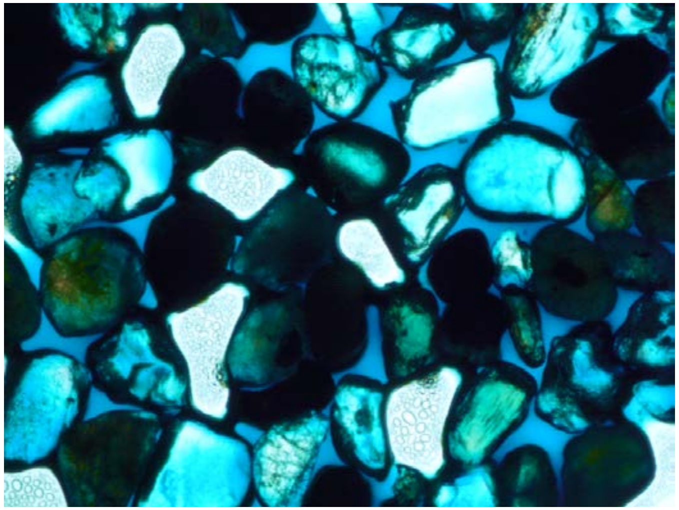
Unsaturated Soil

- *3-Phase System*
- *Pore Fluid Pressure, u_w and u_a*

$$u_a = 0 \text{ (atmospheric)}$$

$$u_w < u_a$$

$$\psi = u_a - u_w \text{ (matric suction)}$$



- *Volumetric Water Content, θ*

$$\theta = f(\psi), \quad 0 < \theta < n$$

- *Degree of Saturation, S*

$$S = f(\psi), \; 0 < S < 1.0$$

Soil-water characteristic curve (SWCC)

- *Hydraulic Conductivity, k*

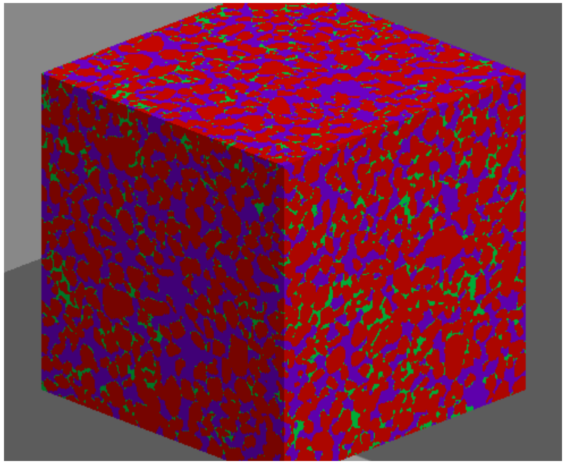
$$k = f(\theta)$$

or

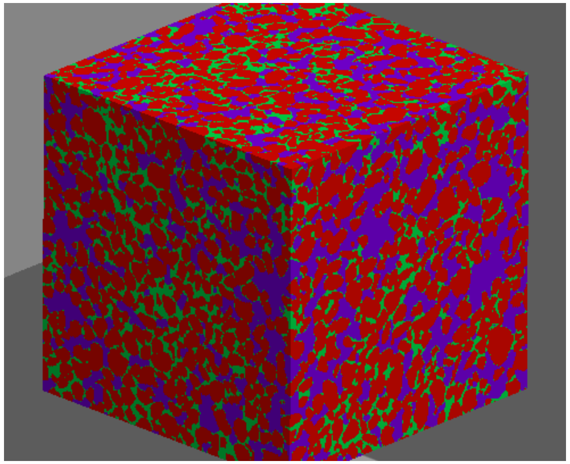
$$k = f(\psi)$$

Hydraulic conductivity function (HCF)

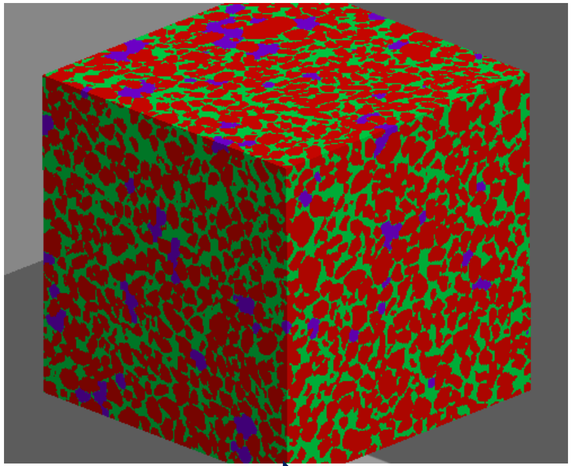
S ~ 20%



S ~ 40%



S ~ 80%



Hydraulic Conductivity

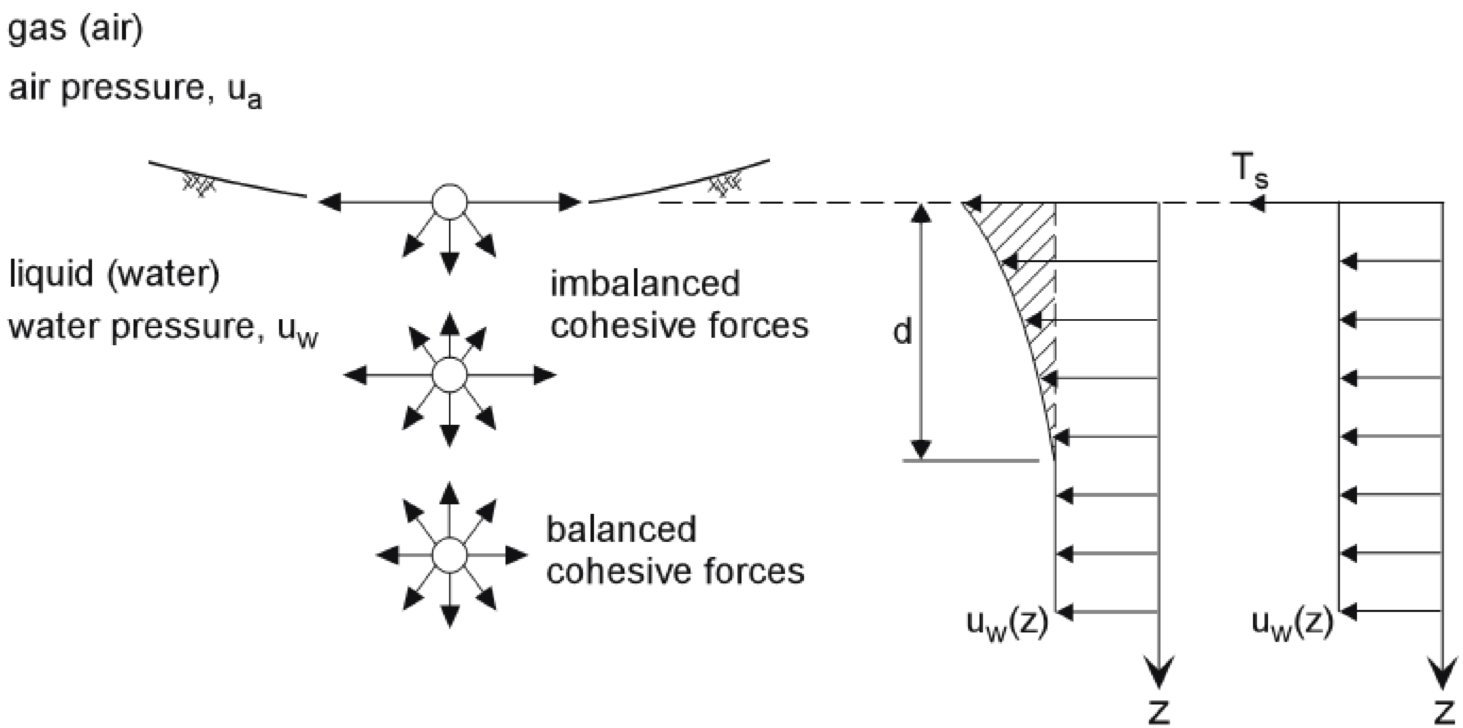
Thermal Conductivity

? Strength and Compressibility ? ?

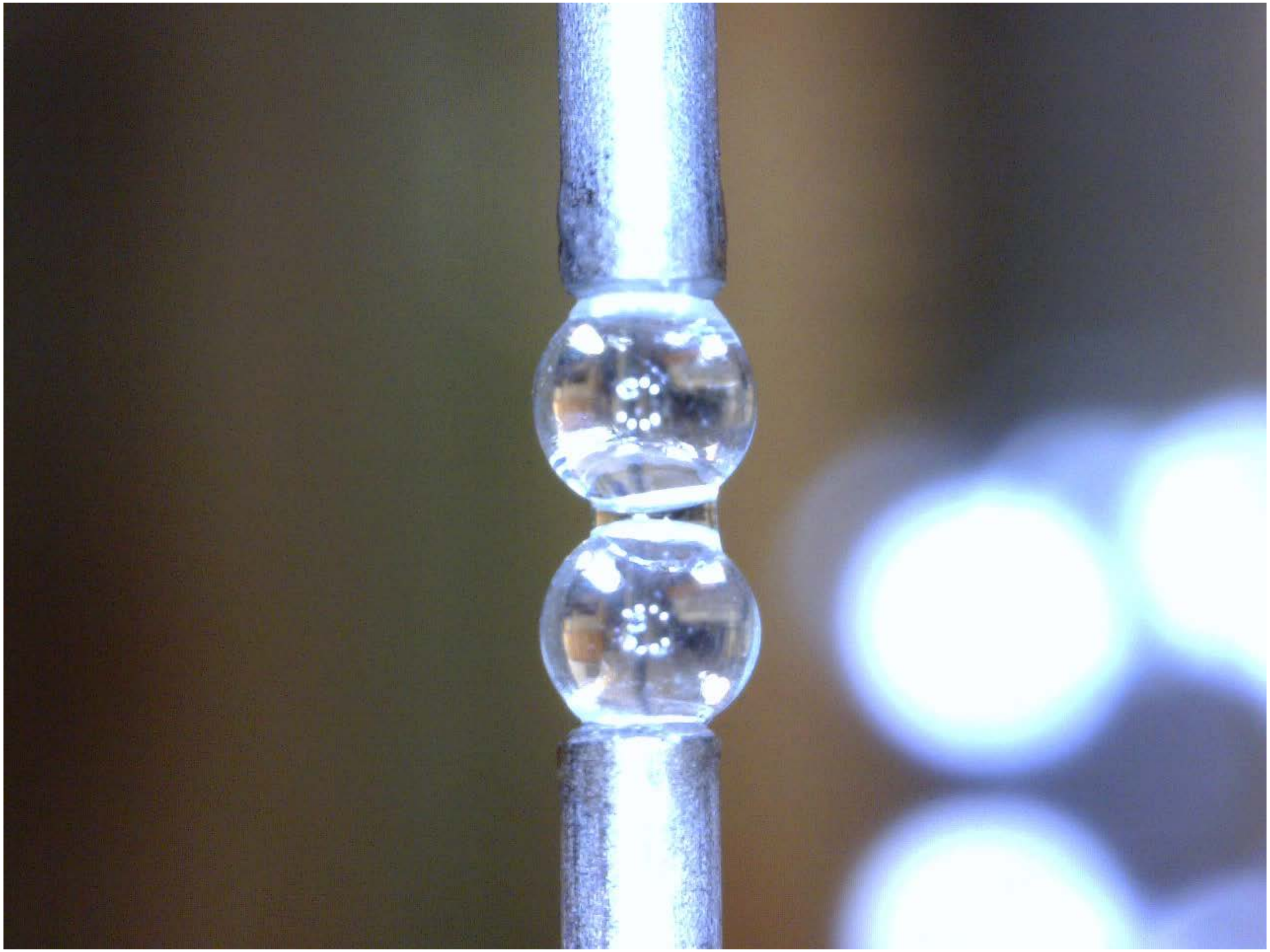
Concepts from Interfacial Physics

- *surface tension*
- *capillarity*
- *soil-water characteristic curve (SWCC)*
- *components and units of soil suction*

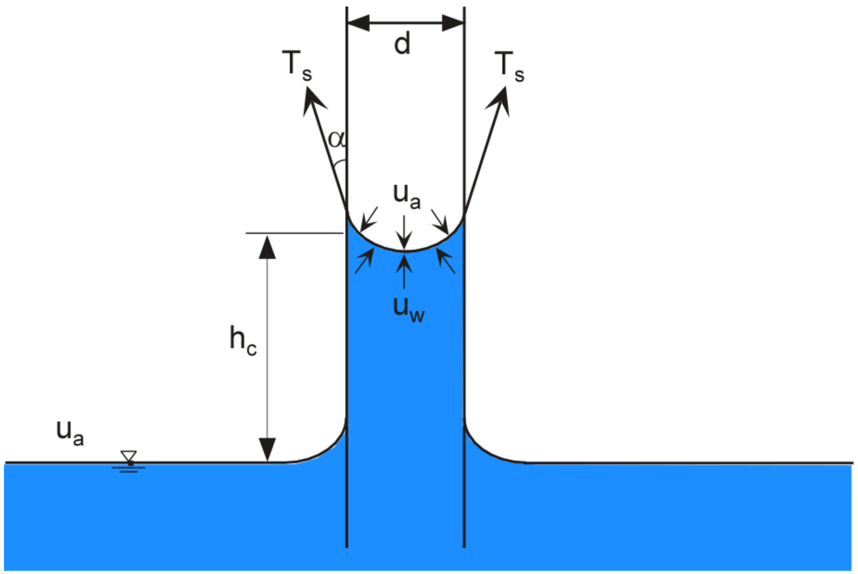
Surface Tension, Ts



(Lu and Likos, 2004)



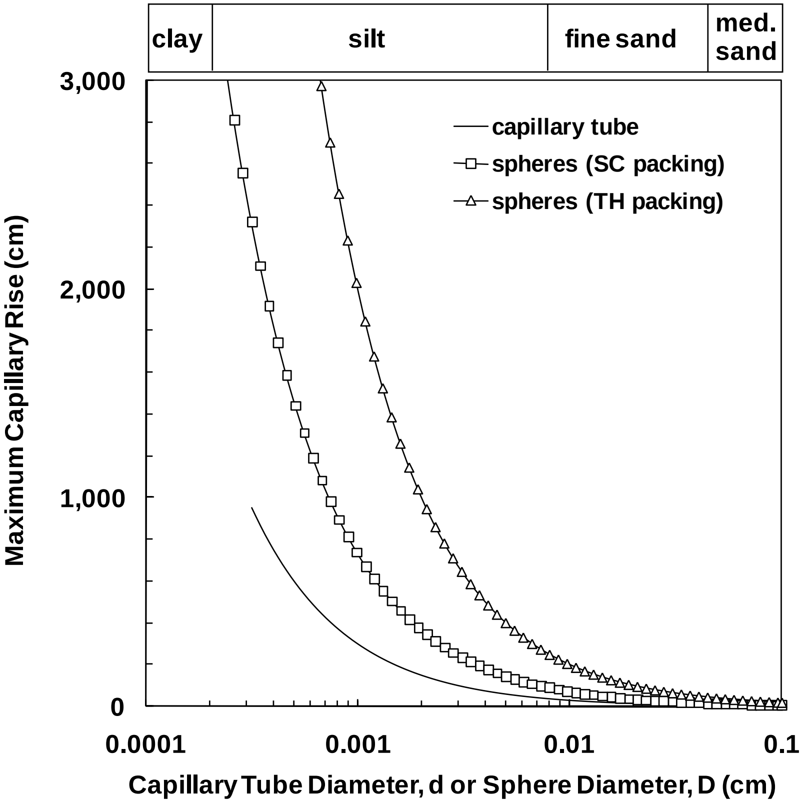
Height of Capillary Rise, hc



$$h_c \frac{\pi}{4} d^2 (\rho_w g) = T_s \pi d \cos\alpha$$

$$h_c = \frac{4T_s \cos\alpha}{d\rho_w g}$$

$$\longrightarrow h_c(cm) \approx \frac{0.3}{d(cm)}$$



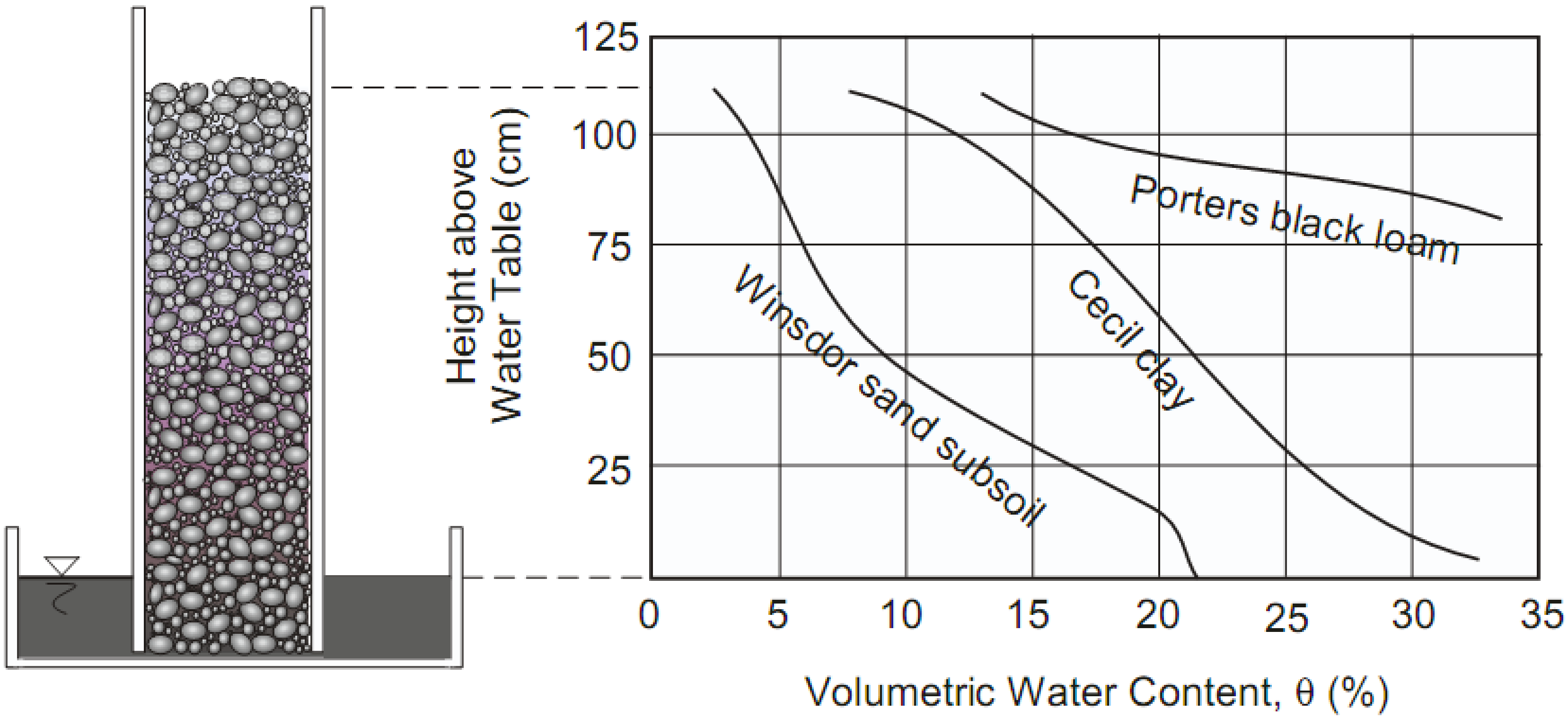
Soil-Water Characteristic Curve (SWCC)

a.k.a. ***Water Retention Curve (WRC)***

Capillary Pressure – Saturation Curves (P_c-S)

etc…

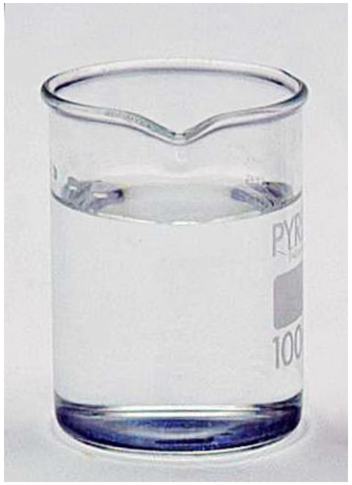
(Buckingham, 1907)



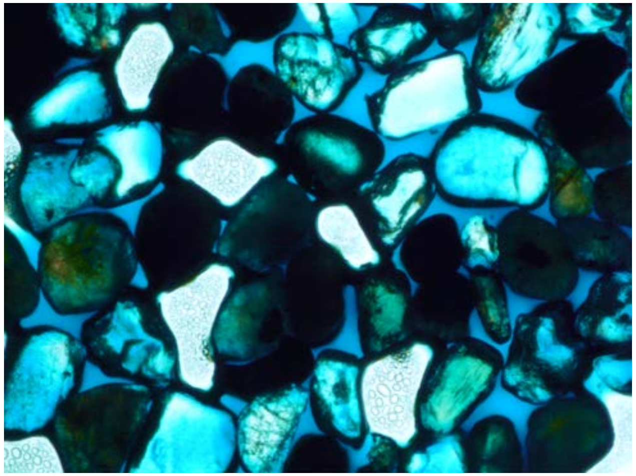
(Lu and Likos, 2004)

Components of Soil Suction

Pore Water Potential, μ (energy per unit mass of water)



Flow

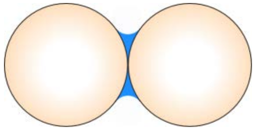


Free Water, μ_i

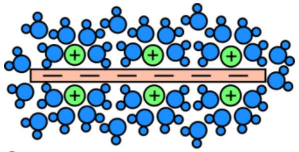
Soil Water, $\mu < \mu_i$

Total change in potential: $\Delta\mu_t = \Delta\mu_c + \Delta\mu_a + \Delta\mu_o$

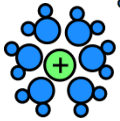
$\Delta\mu_c$: Reduction from capillary effects



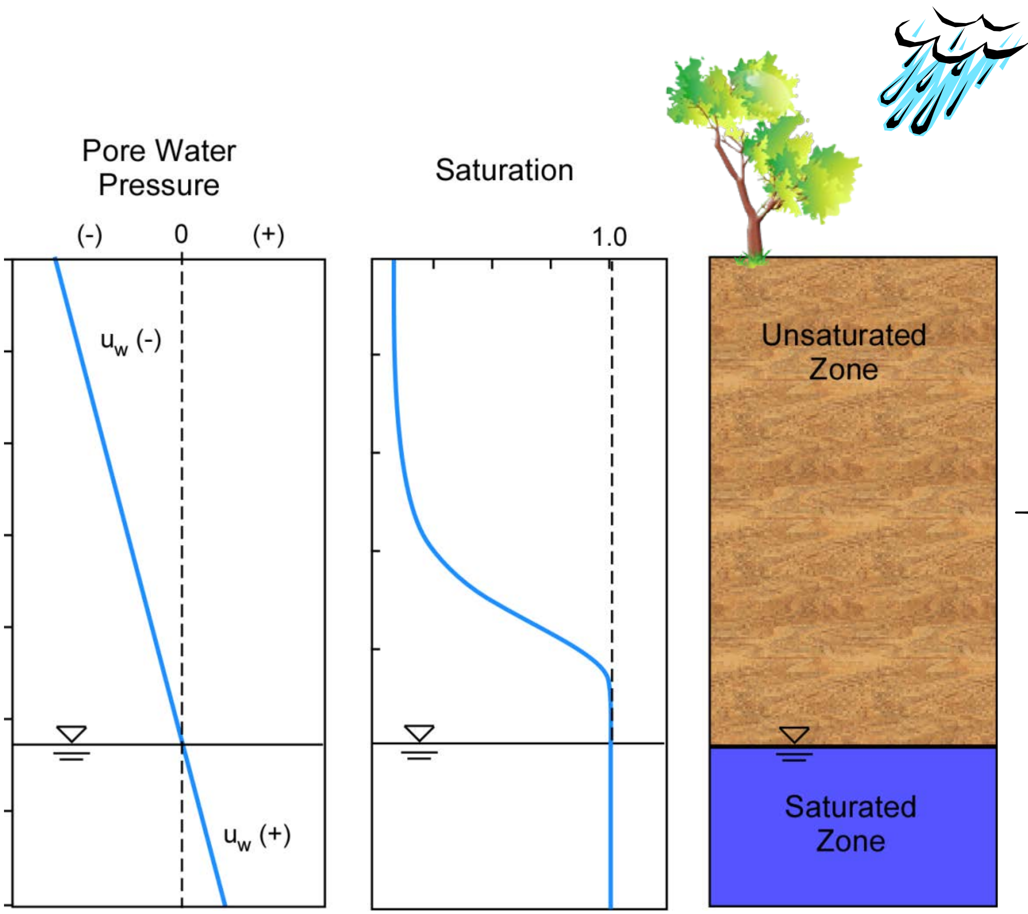
$\Delta\mu_a$: Reduction from adsorptive effects



$\Delta\mu_o$: Reduction from osmotic effects



Unsaturated soils in geotechnical engineering

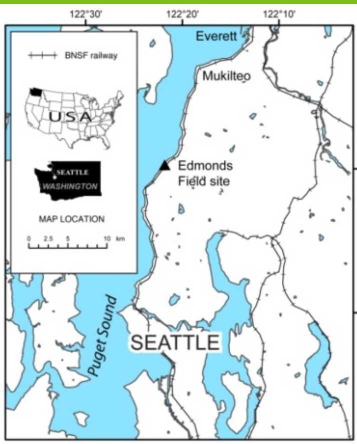


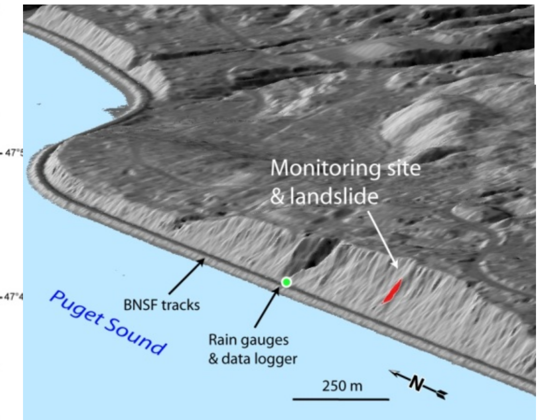
- ***slopes***
- ***compacted soils***
- ***retaining walls***
- ***excavations***
- ***expansive soils***
- ***shallow foundations***
- ***pavement subgrades***
- ***waste covers***
- ***thermal backfills***

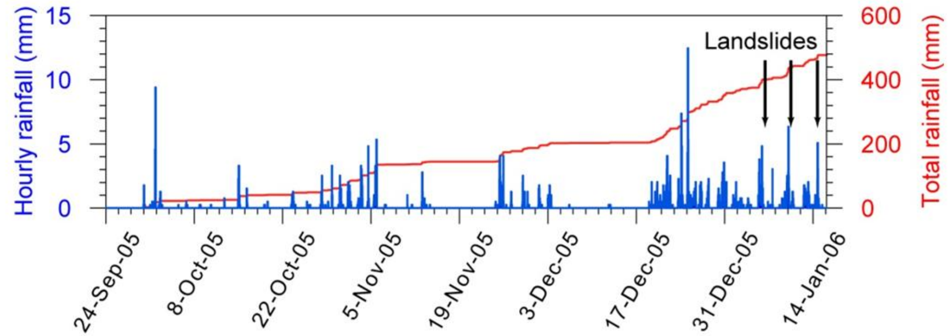
Precipitation-induced landslides

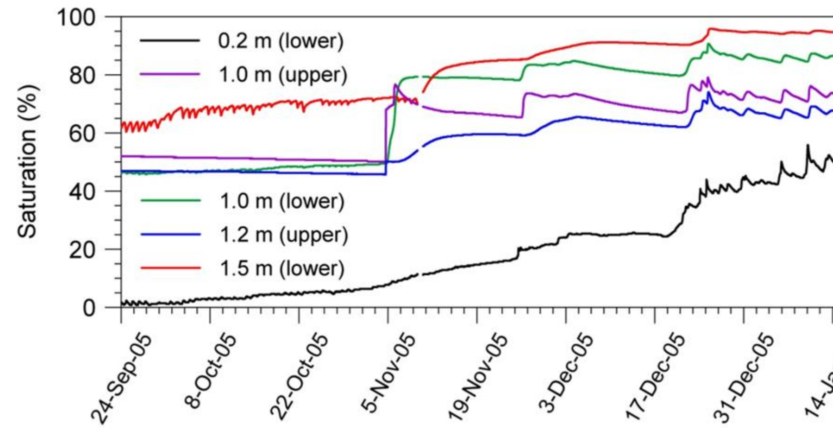
Photograph showing abundant shallow landslides near Valencia, California. The un-vegetated scars are shallow failures caused by heavy rainfall in the winter of 2005. The internal stress-suction stress changes only a few kPa!

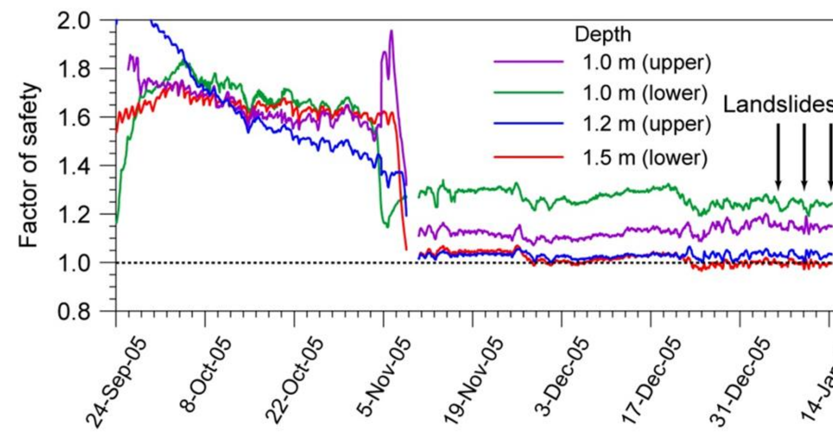
Landslide Case History: Edmonds WA (2006)



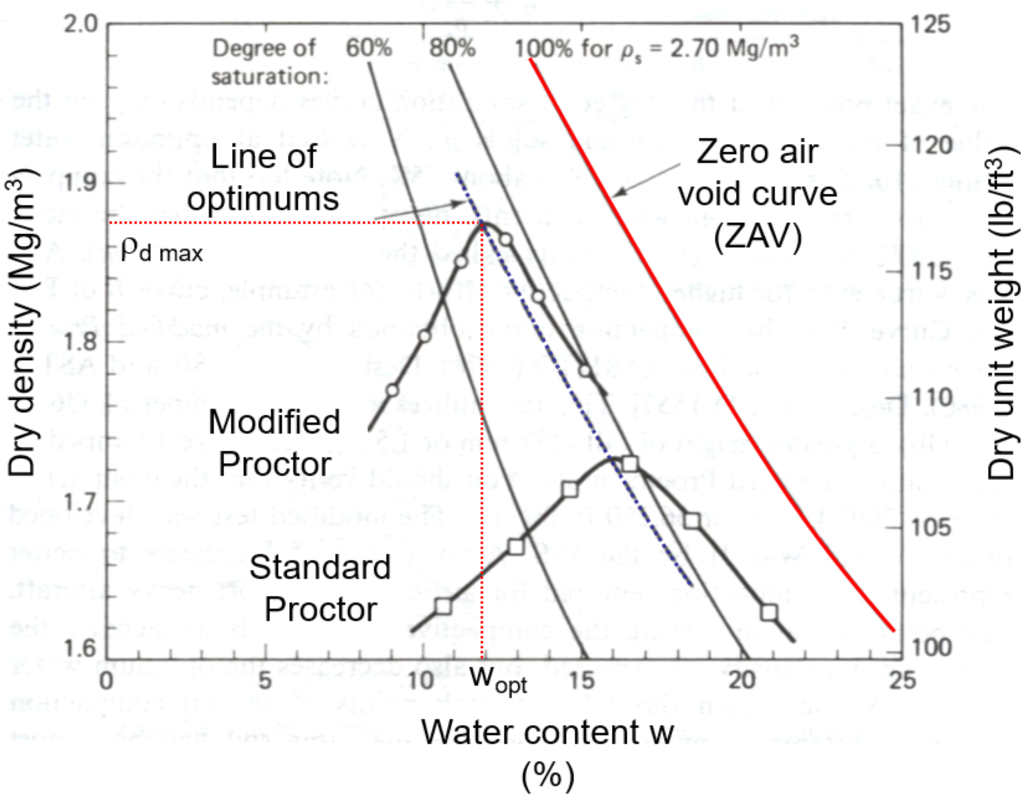




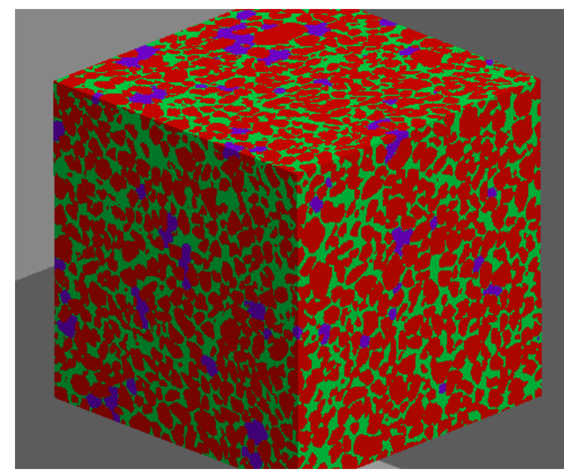




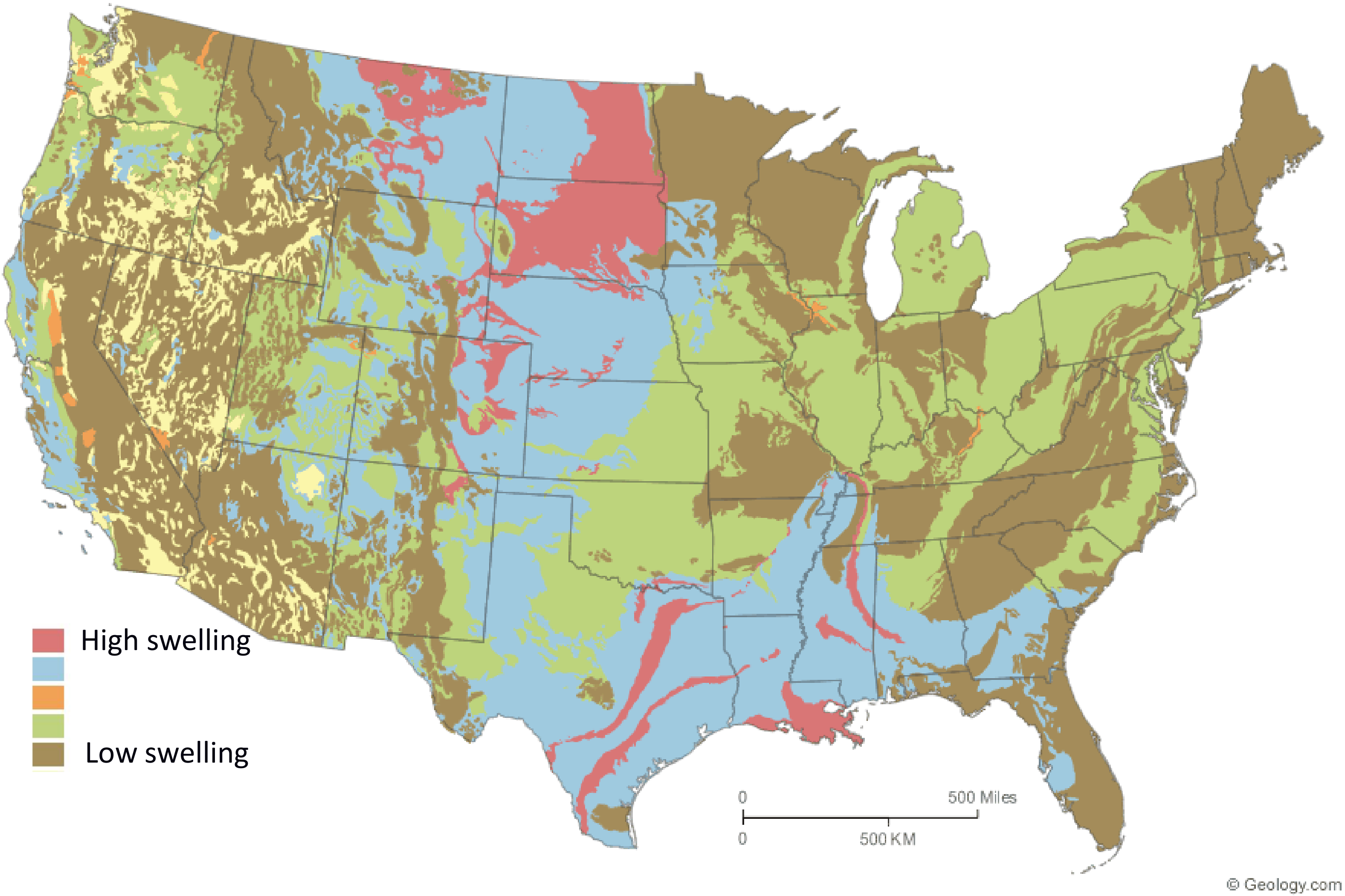
Soil Compaction



S ~ 80%

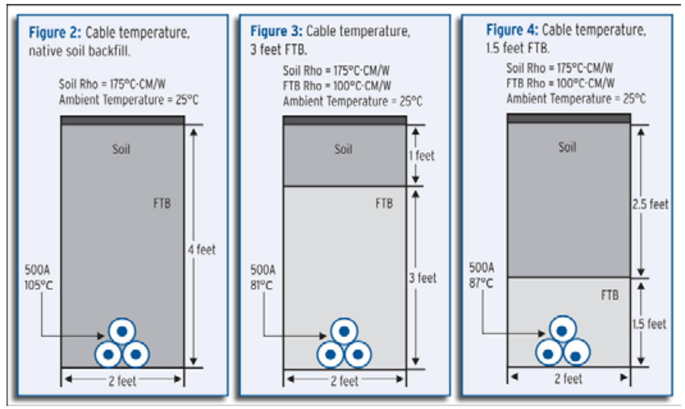


Expansive Clays

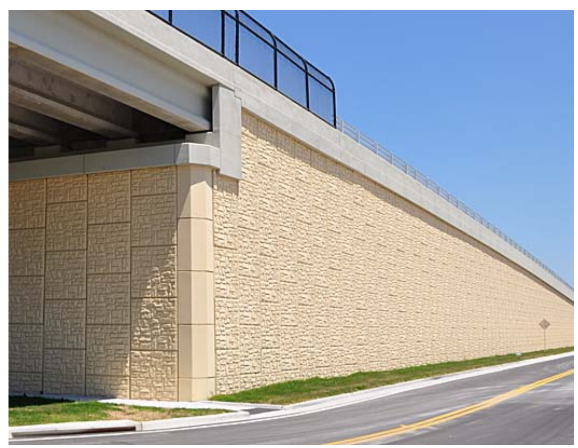


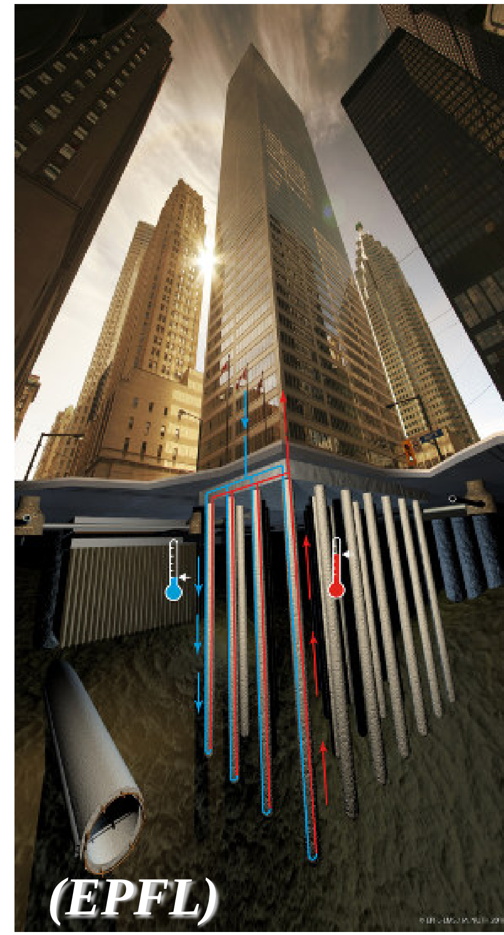
Source: Geology.com – "Swelling Clays Map of the Conterminous United States" (Olive et al.)

Thermal Geotechnics



Buried high-voltage power cables

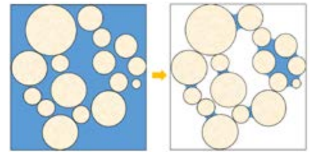




Shallow geothermal systems

Geosynthetic heat exchangers

"energy" piles



Measurement of Unsaturated Properties Pavement Applications

Raul Velasquez P.E. Ph.D.
MnDOT

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Measurement of Unsaturated Properties
Pavement Applications

1. Soil Water Characteristic Curve (***SWCC***)

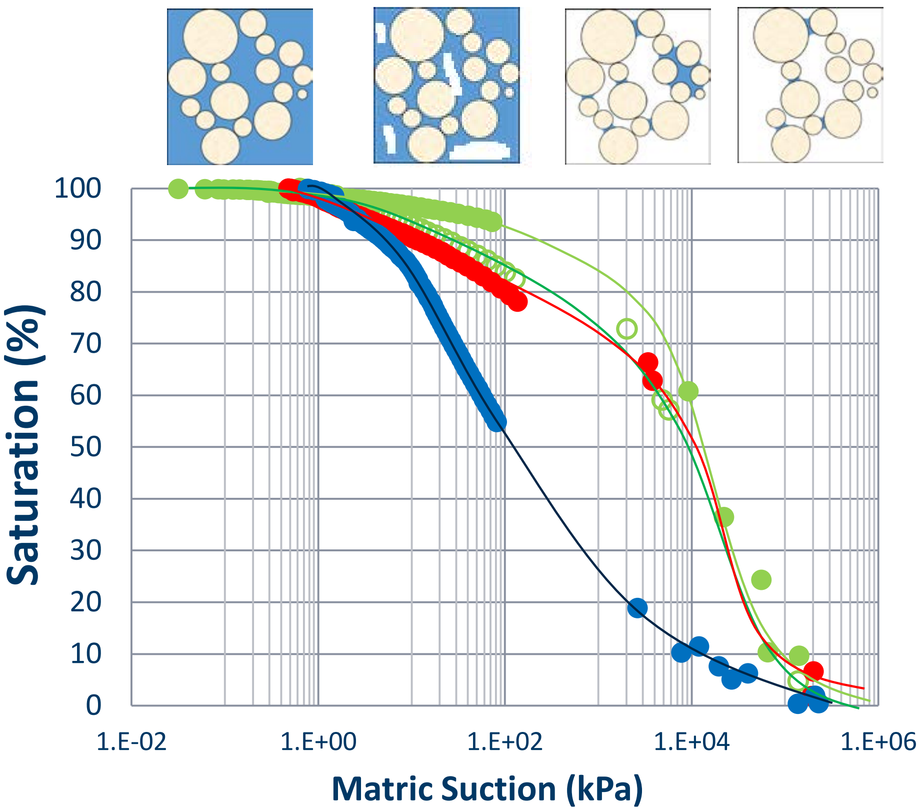
- Tensiometers
- Axis Translation Techniques (Pressure Plates)
- Humidity Measurement Techniques
- Filter Paper Techniques

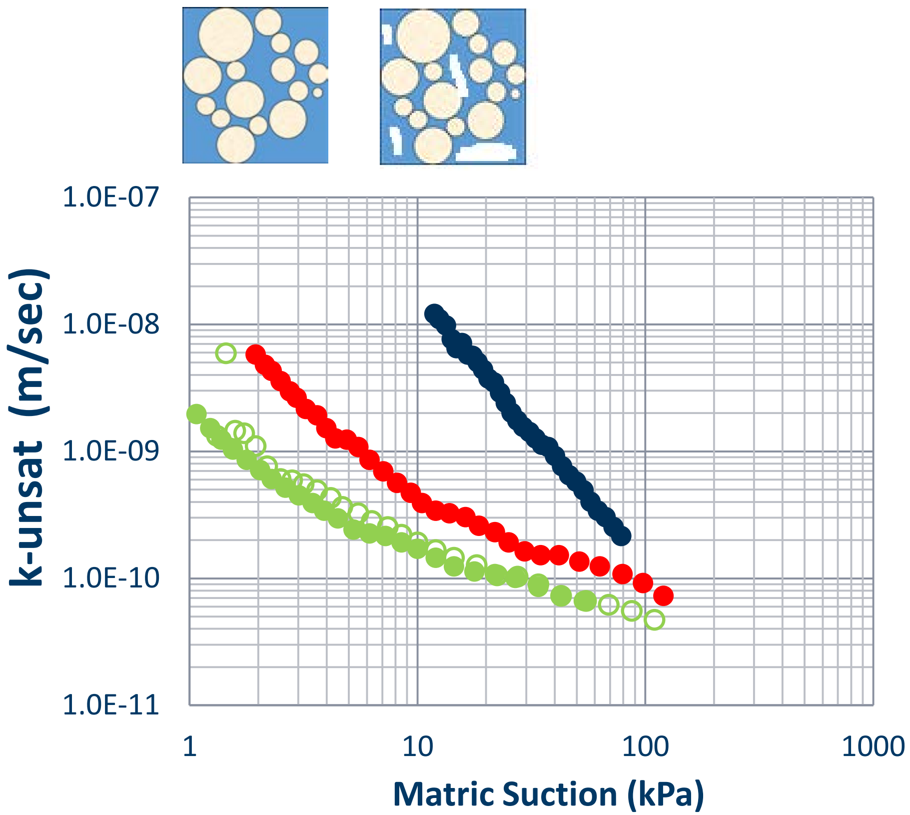
2. Unsaturated Hydraulic Conductivity (***k-unsat or HCF***)

3. Models for *SWCC* and *k-unsat*

- *SWCC*
  - Brooks and Corey (BC) Model
  - van Genuchten (VG) Model
  - Fredlund and Xing (FX) Model
- *k-unsat*
  - Empirical and Macroscopic Models
  - Statistical Models

Measurement of Unsaturated Properties
Pavement Applications

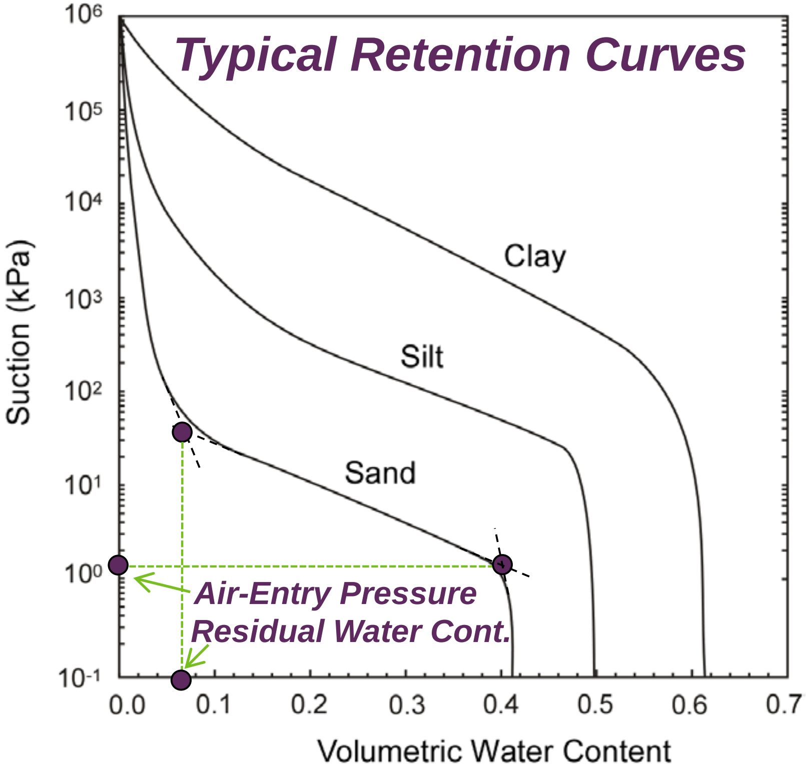


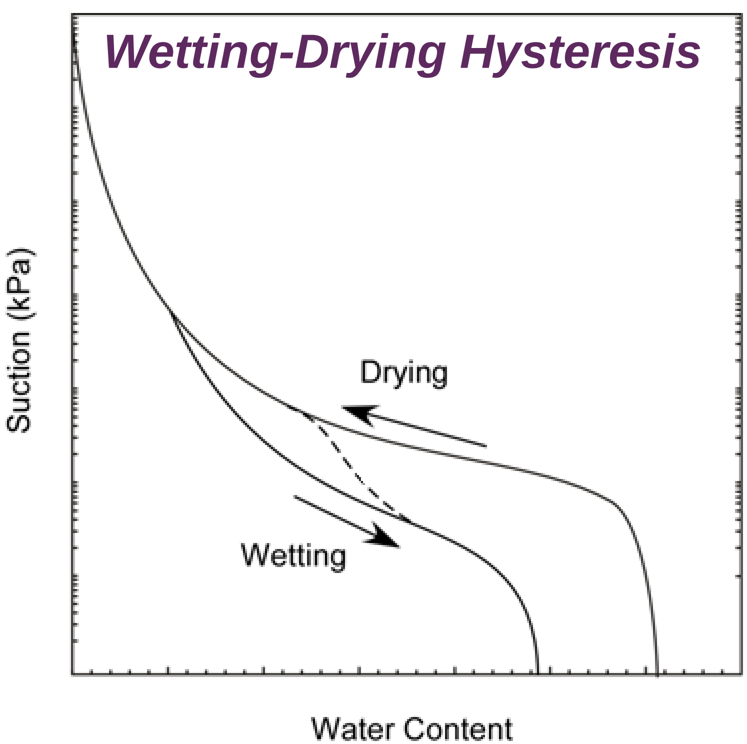


Soil Water Characteristic Curve (SWCC)

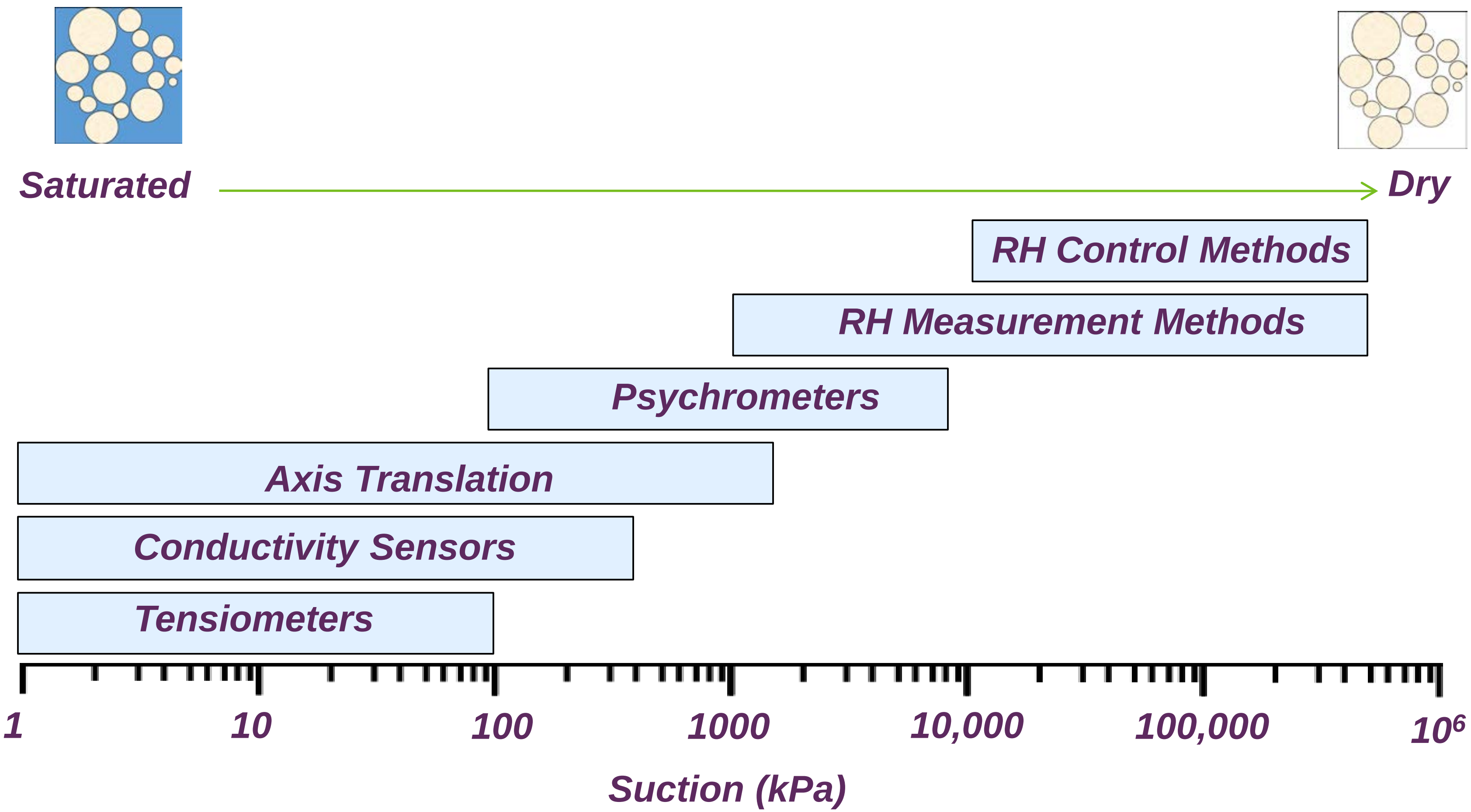
- Common to express as a pressure potential (suction)
- Energy per unit volume, ψ ($J/m^3 = N/m^2 = Pa$)
- Lump total suction into matric and osmotic components

$$\underbrace{\Delta\mu_t = \Delta\mu_o}_{\text{osmotic suction}} + \underbrace{\Delta\mu_a + \Delta\mu_c}_{\text{matric suction}} \longrightarrow \psi_t = \psi_o + \psi_m$$





Soil Water Characteristic Curve (SWCC)

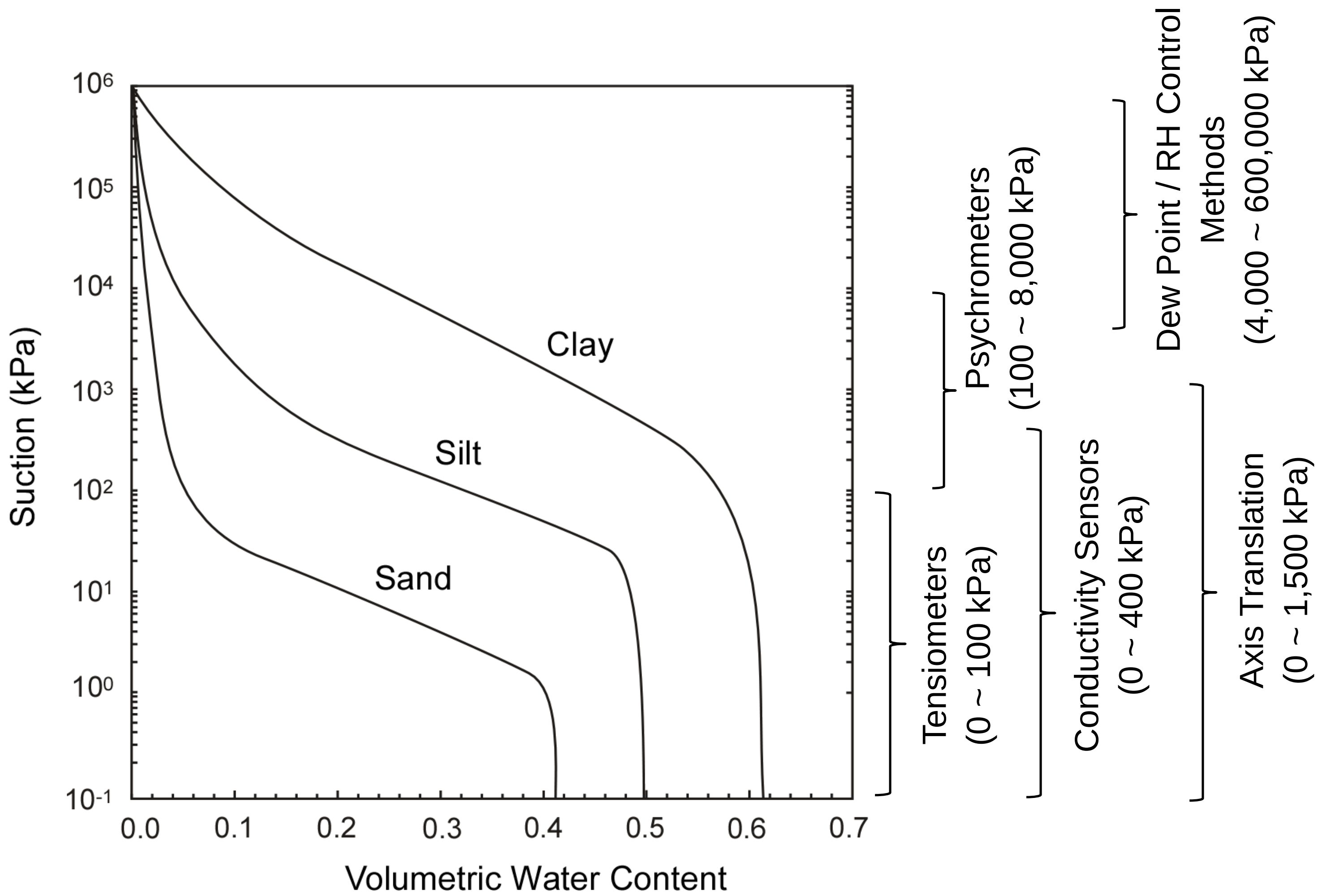


Soil Water Characteristic Curve (SWCC)

Component	Technique/Sensor	Range (kPa)	Principle	Applications
Matric Suction (ψ_m)	Tensiometers	0 - 100	Measurement of negative pressure	Lab/Field
	Axis Translation	0 - 1500	Elevated air pressure	Lab
	Conductivity Sensors	0 - 400	Therm. cond. material in contact	Lab/Field
	Contact Filter Papers	50 - 100,000	Sorption of filter paper in contact	Lab/Field
Total Suction (ψ_t)	Psychrometers	100 - 8,000	RH meas. by dew point method	Lab/Field
	Chilled-Mirror Hygrometers	1,000 - 500,000	RH meas. by dew point method	Lab
	Capactitance Sensors	1,000 - 500,000	RH meas. by polymer sensor	Lab/Field
	Non-contact Filter Papers	1,000 - 500,000	RH meas. by filter paper not in contact	Lab/Field
	Osmotic Humidity Control	10 - 50,000	RH control using salt solutions	Lab
	Flow-Through RH Control	10,000 - 500,000	RH control using controlled gas flow	Lab
	Dynamic Dew Point Method	10,000 - 500,000	Hybrid RH control/meas. method	Lab

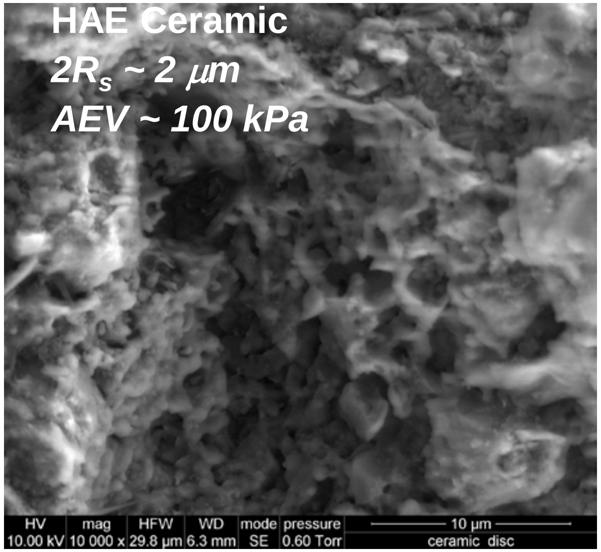
Selecting Proper Technique

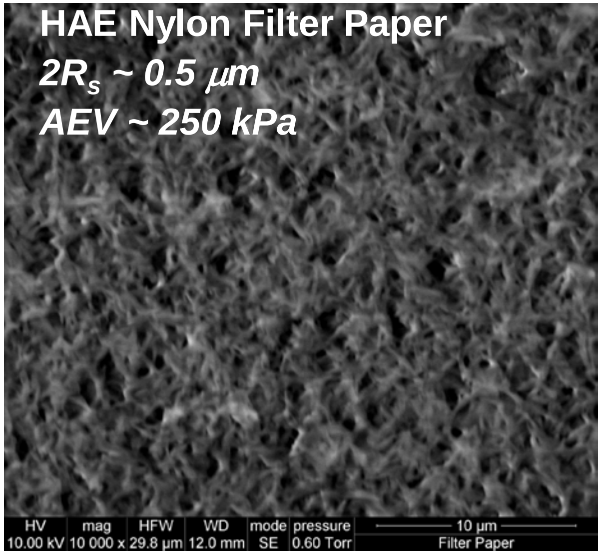
- Need to consider soil type & anticipated range
- Often need to combine multiple techniques
- Often need to consider wetting-drying path

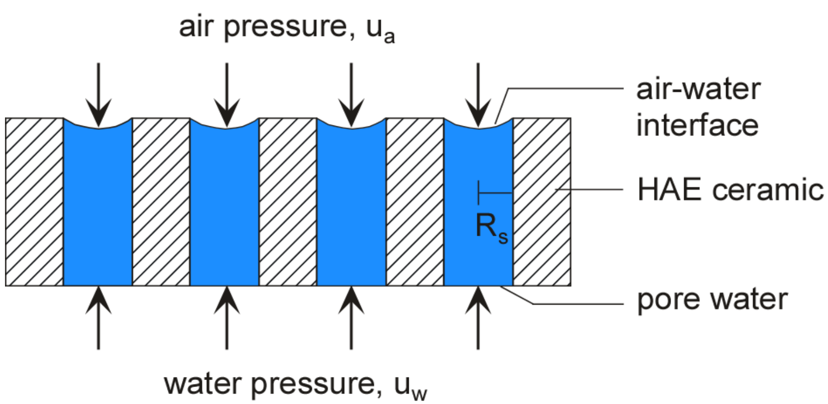


High-Air-Entry (HAE) Materials

(Image: Envco)







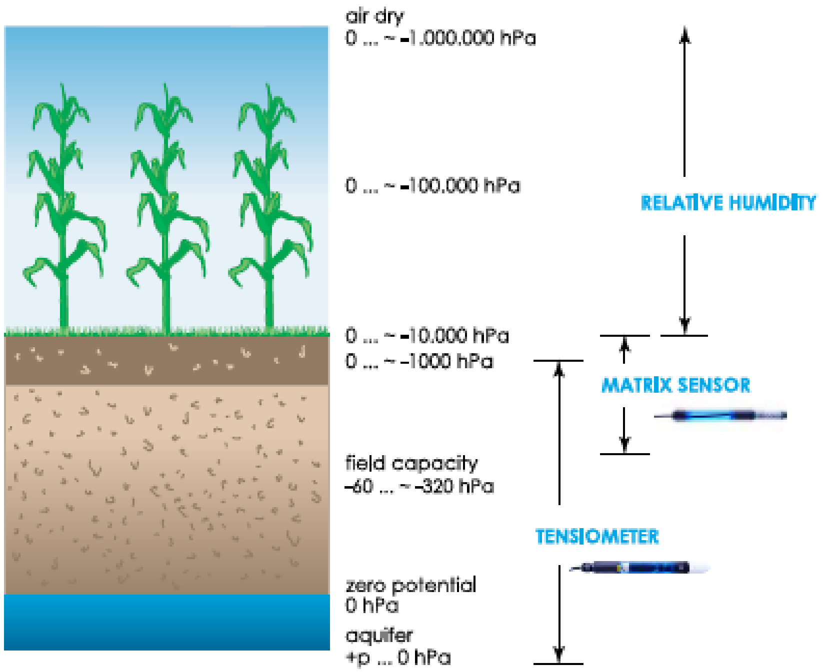
$$(u_a - u_a)_b = \frac{2T_s}{R_s}$$

Type of HAE Ceramic	Approx. Pore Diameter ($\times 10^{-3}$ mm)	Saturated Hydraulic Cond. (m/s)	Air-Entry Value (kPa)
1/2 bar high flow	6.00	3.11×10^{-7}	48–62
1 bar	1.70	7.56×10^{-9}	138–207
1 bar high flow	2.50	8.60×10^{-8}	131–193
2 bar	1.10	6.30×10^{-9}	262–310
3 bar	0.70	2.50×10^{-9}	317–483
5 bar	0.50	1.21×10^{-9}	550
15 bar	0.16	2.59×10^{-11}	1520

Source: Soilmoisture Equipment Corp. (2003).

SWCC - *Tensiometers*

- Direct measurement of negative u_w
- Requires exchange of water
- Response time ~ 1-10 min
- Sensors require servicing
- Limited to ψ_m ~ 100 kPa



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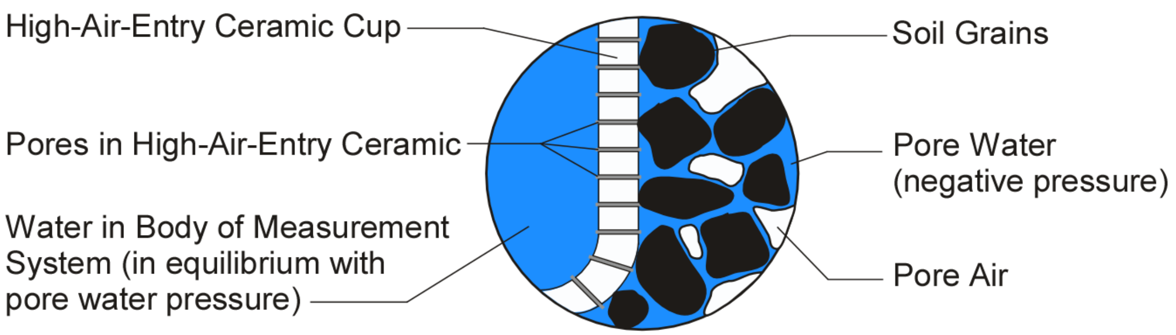
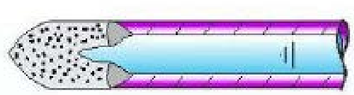
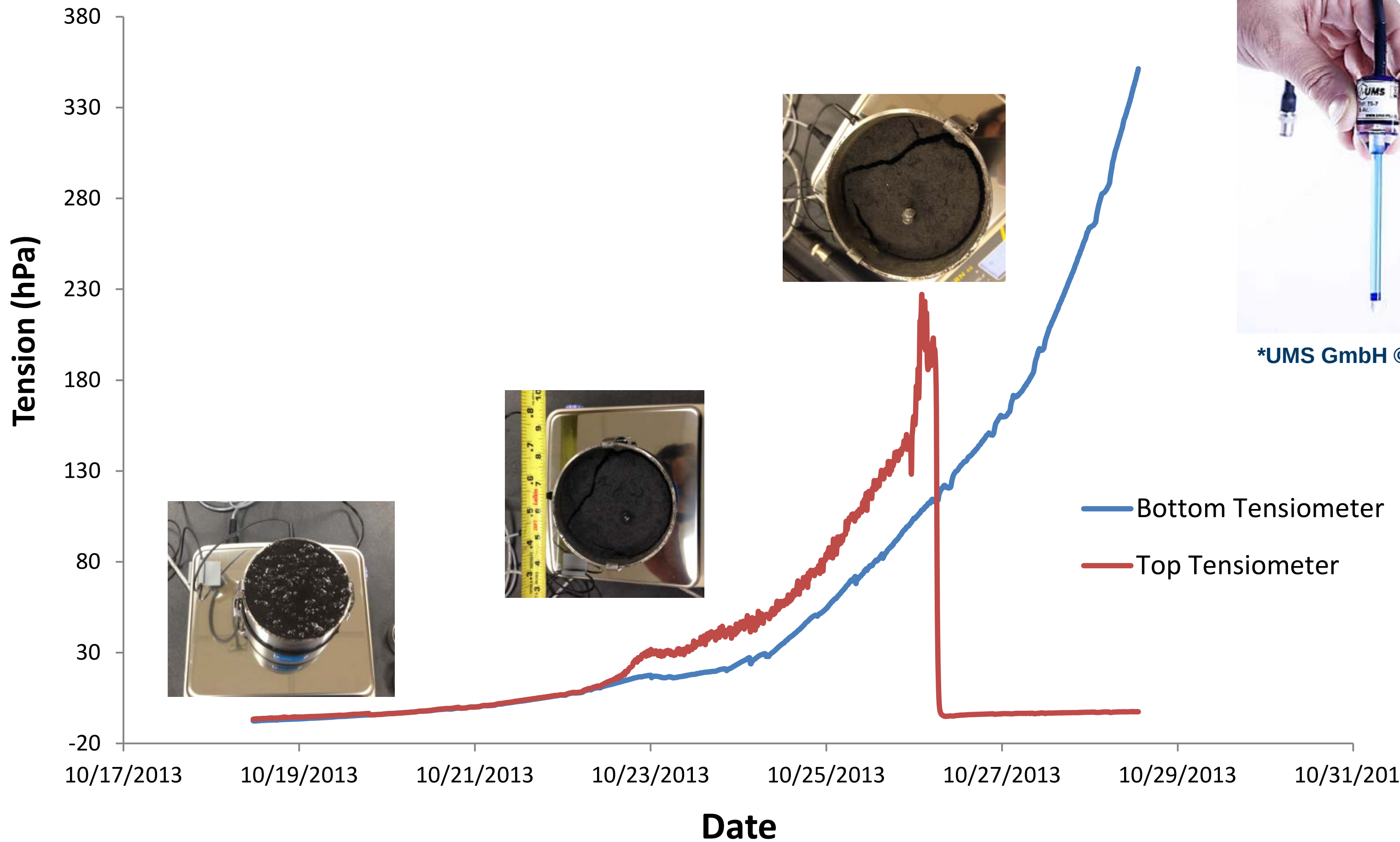




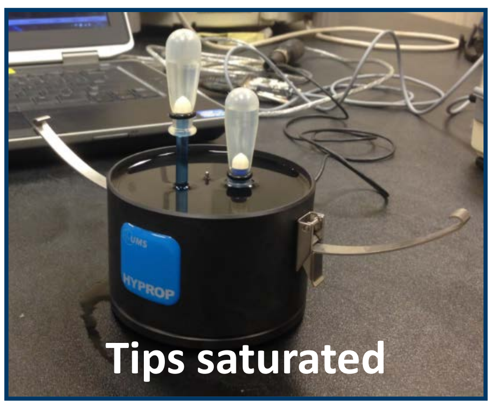
SWCC - ***Tensiometers***

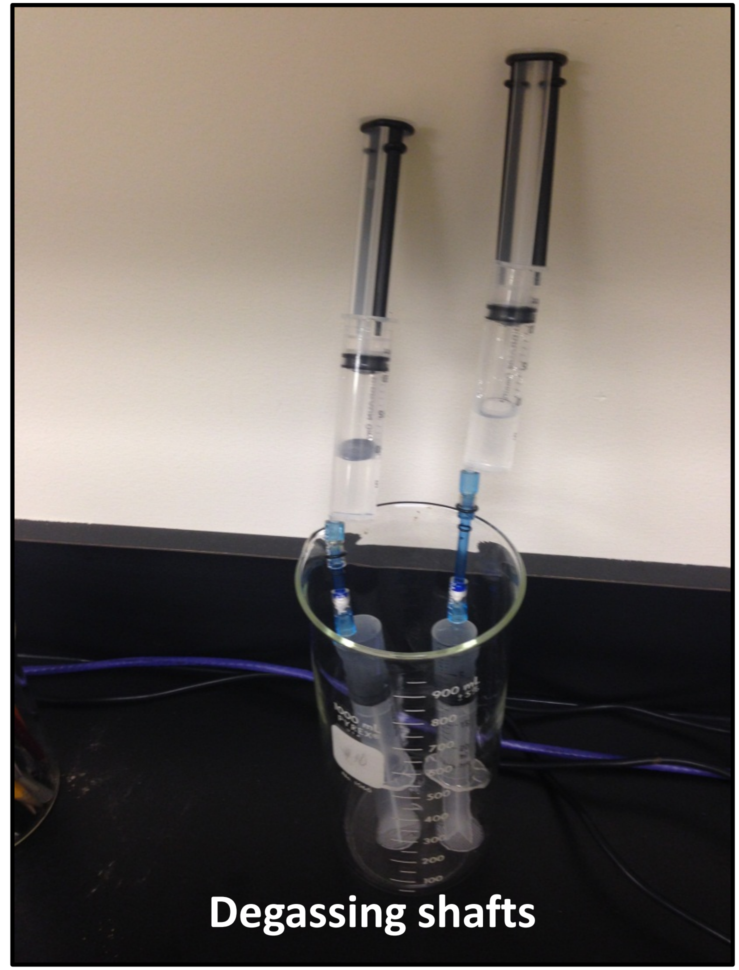
Raw Data



*UMS GmbH © 2012

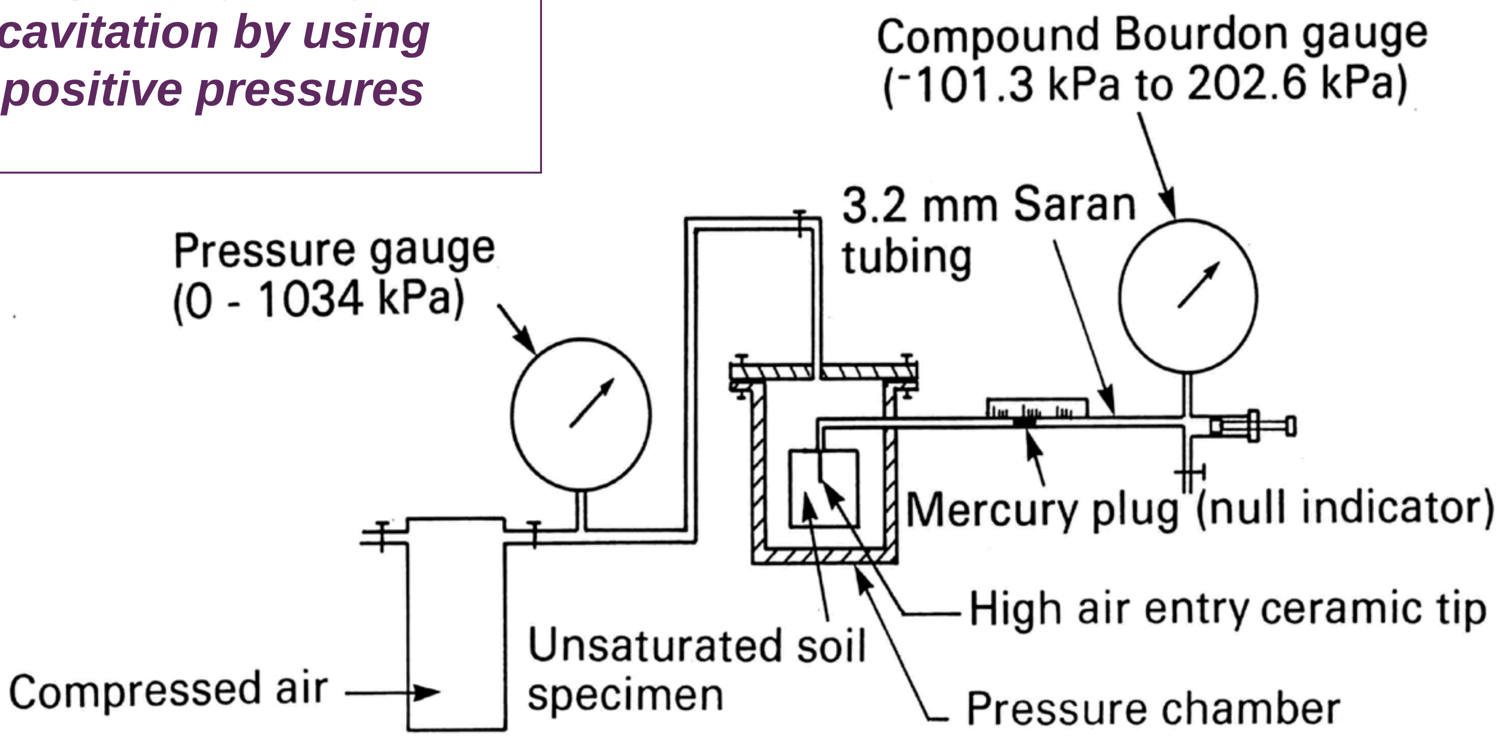
SWCC – ***Tensiometers Issues***





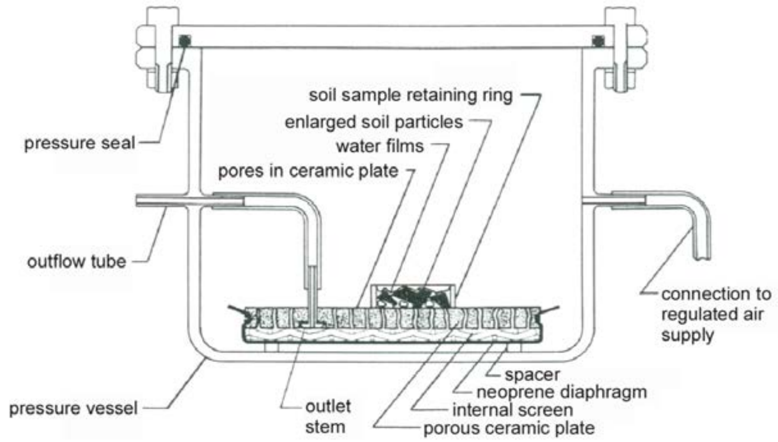
SWCC – ***Axis Translation Techniques***

Concept: Stay away from cavitation by using positive pressures

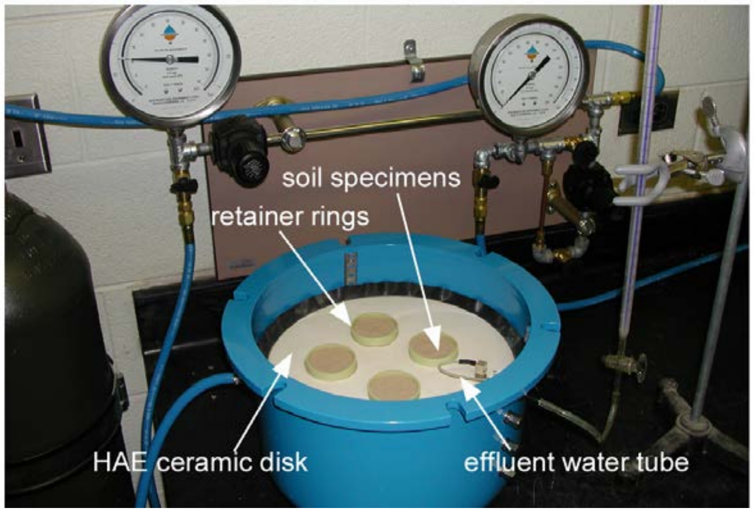


Original set up for the null type, axis-translation device for measuring negative pore-water pressure (from Hilf, 1956)

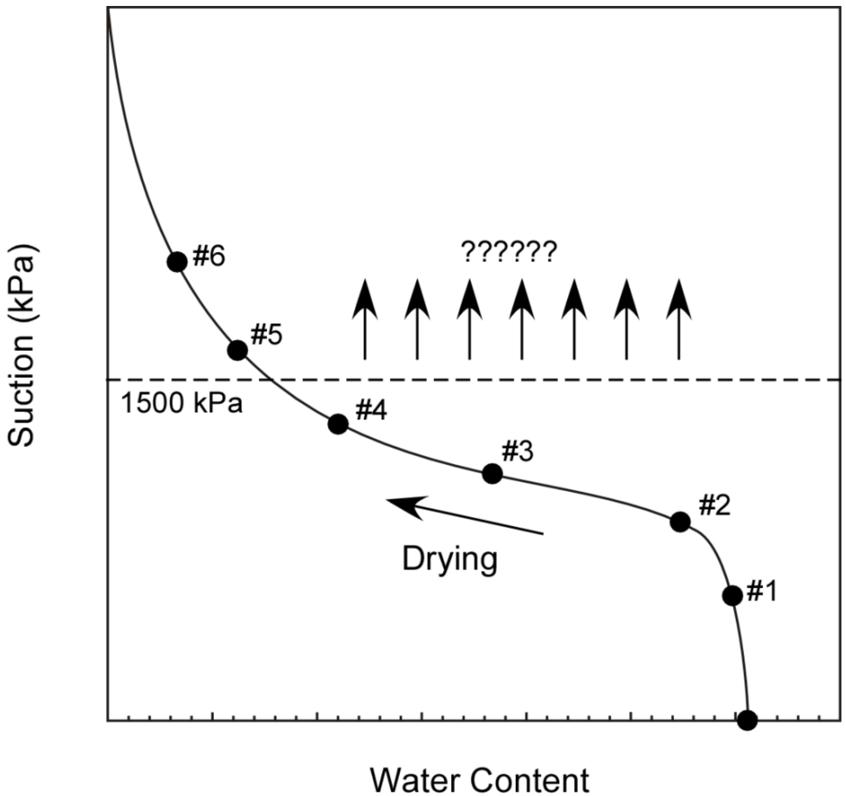
SWCC – ***Axis Translation Techniques Pressure Plate***



***Soilmoisture Equipment Corp**



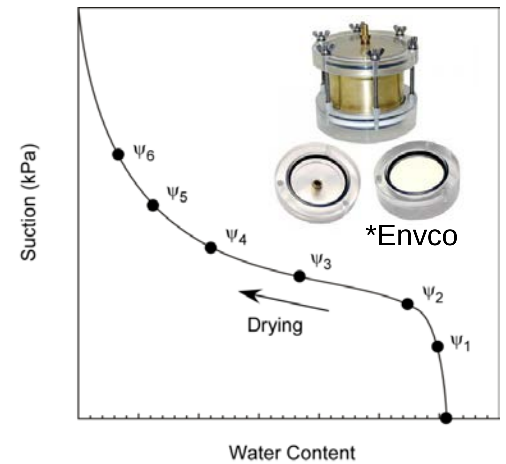
- Multiple "identical" specimens
- *Combine to construct SWCC*
- ψ_{max} *~ 1500 kPa*
- *Caution beyond residual suction!*

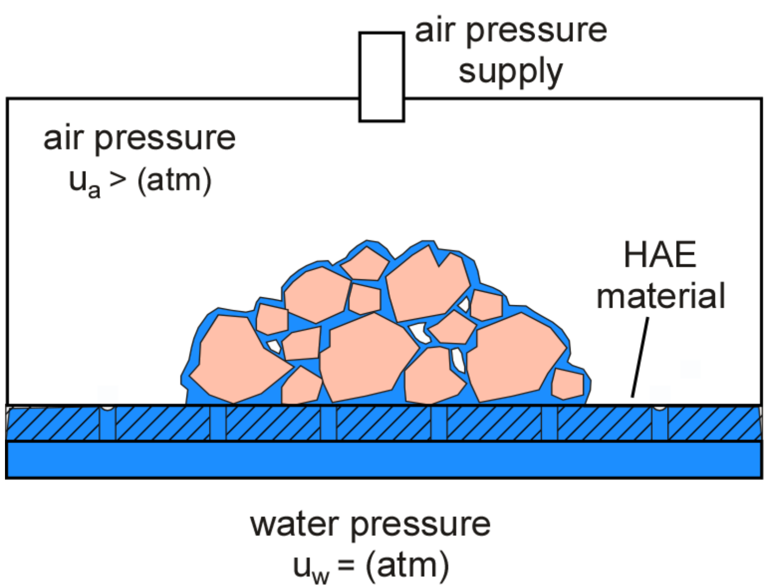


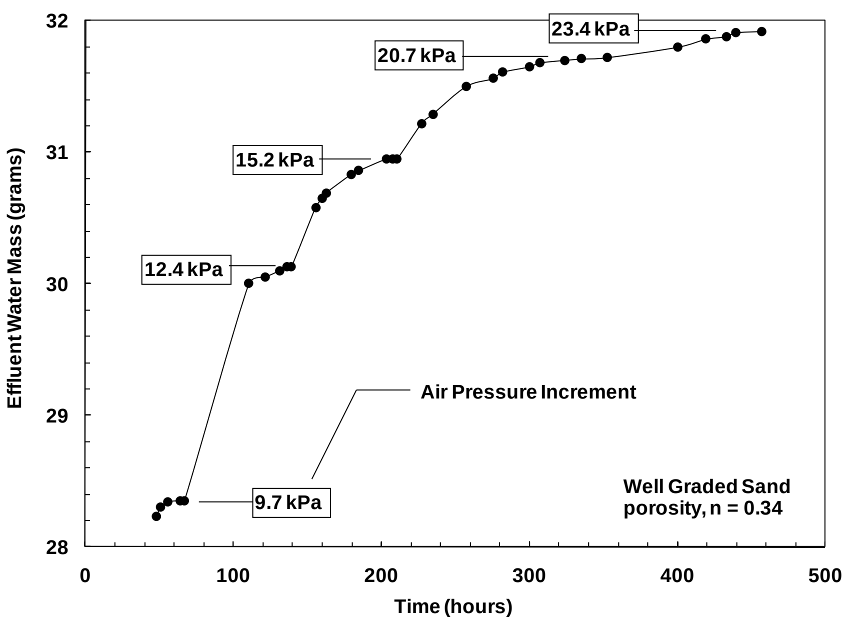
SWCC – ***Axis Translation Techniques***

Tempe Cell System

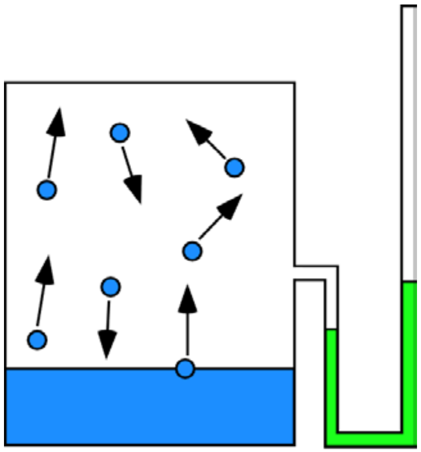
- Elevated air pressure and HAE material
- Matric suction, $\psi_m = (u_a - u_w)$
- Single specimen, primarily drainage path
- Typically back-calculate S from effluent
- Range: ~ 100 kPa (sands)





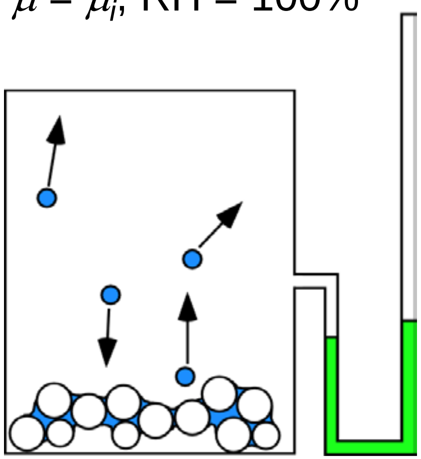


SWCC- *Humidity Measurement Techniques*



Free Water

$\mu = \mu_i$, RH = 100%

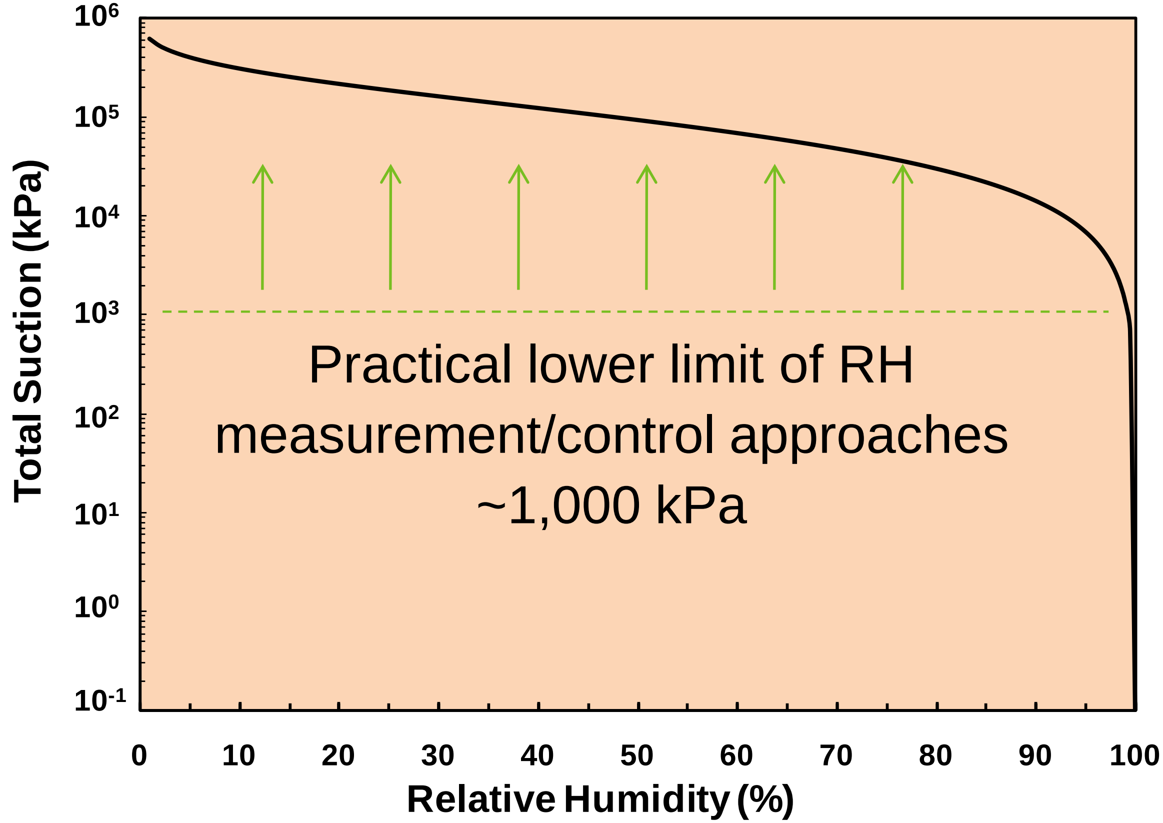


Soil Water

$\mu < \mu_i$, RH < 100%

Kelvin's Equation

$$\psi_t = -\frac{RT}{v_w}\ln\left(\frac{u_v}{u_{v\,sat}}\right) = -\frac{RT}{v_w}\ln(RH)$$

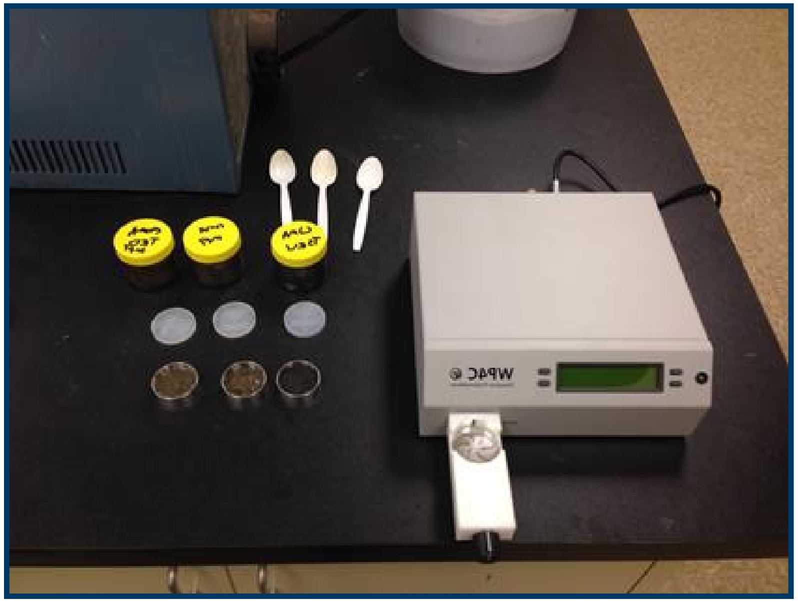


SWCC- *Humidity Measurement Techniques*
Dew Point Methods

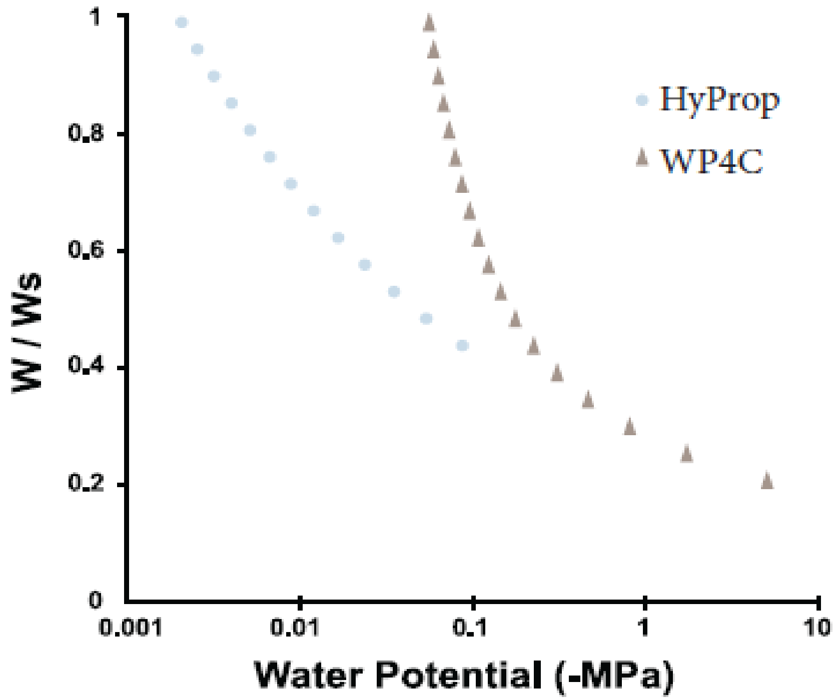
Water potential=> measurement of energy status of water in a soil. It indicates how tightly water is bound structurally or chemically

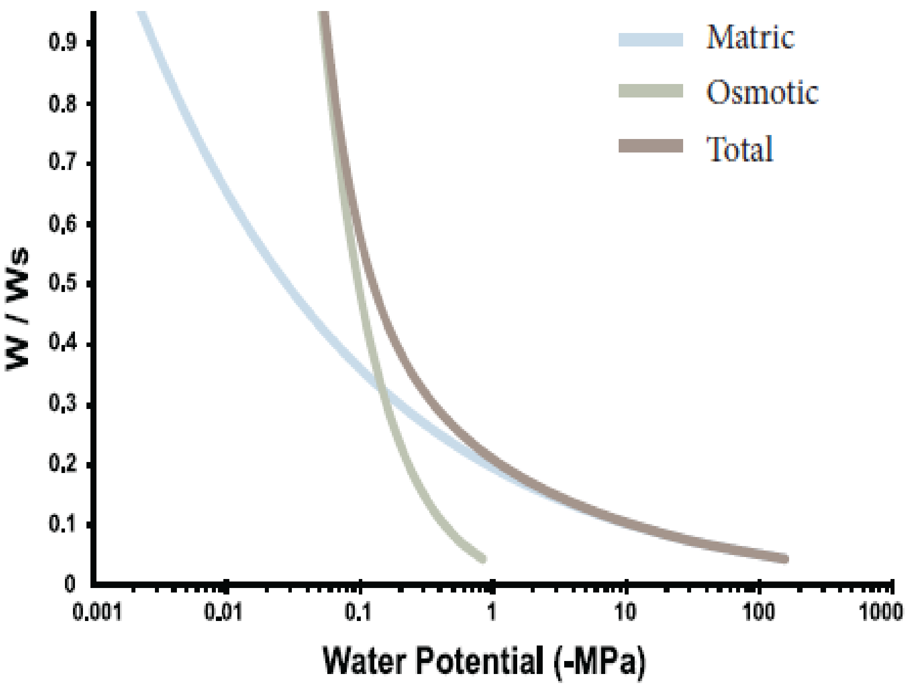
WP4c=> uses the chilled mirror dew point technique (ASTM 6836 Method D)

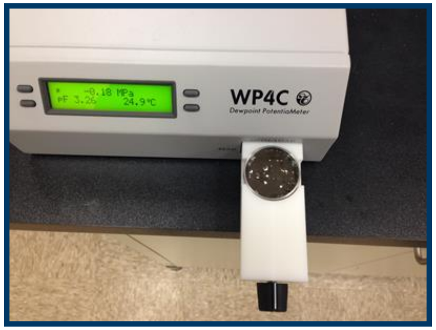
Water potential can be computed from vapor pressure of air in *equilibrium* with soil sample in a sealed chamber



WP4C Measure Osmotic and Matric Components of Water Potential

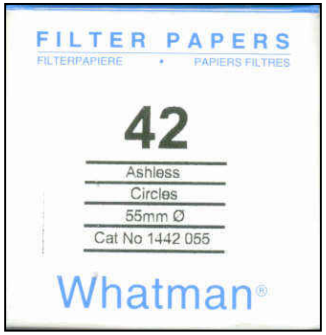


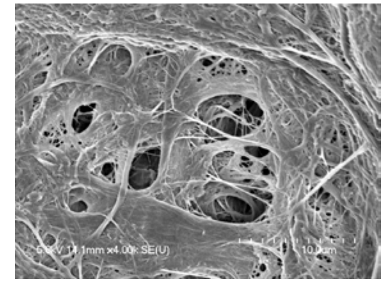


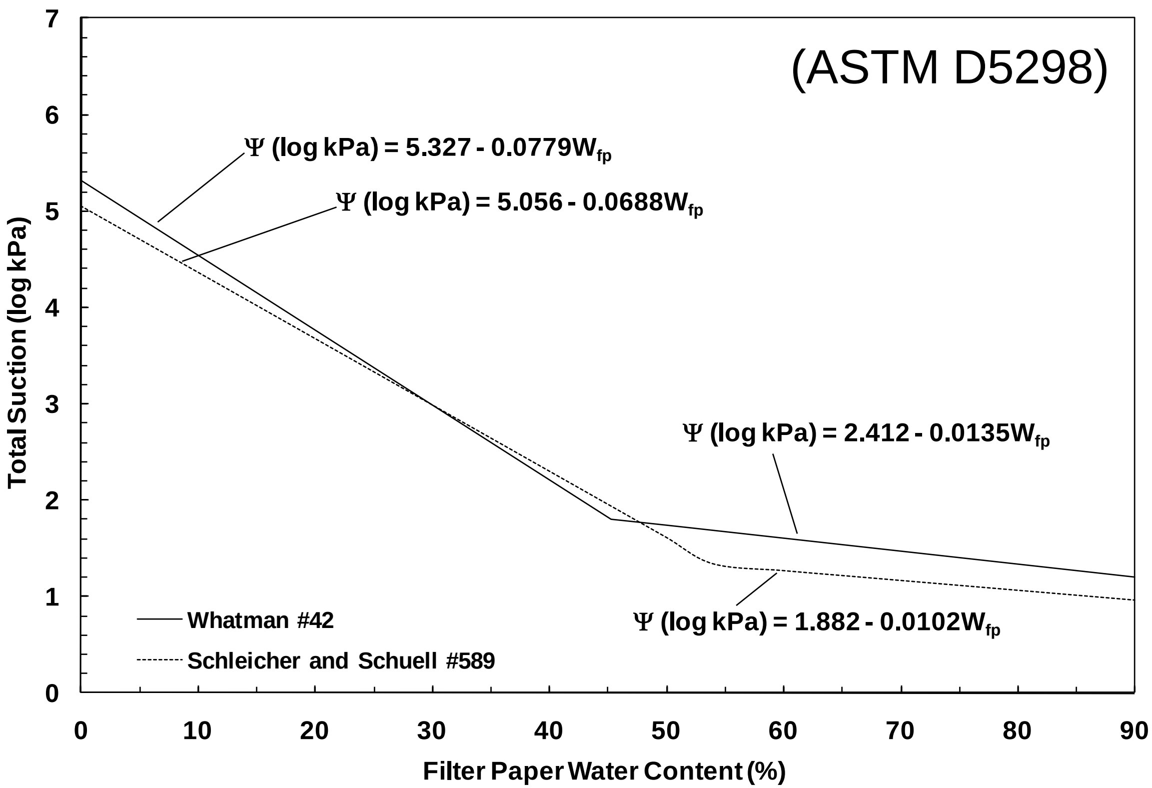


*Decagon (2013), How to Create a Full Moisture Release Curve Using the WP4C and HyProp, Inc, Pullman, WA.

SWCC- *Filter Paper Techniques*

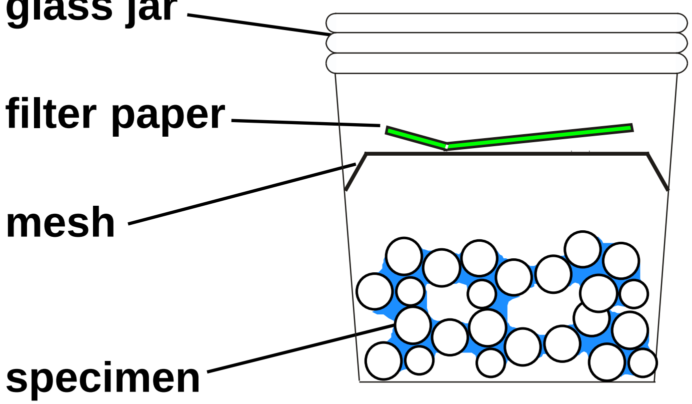




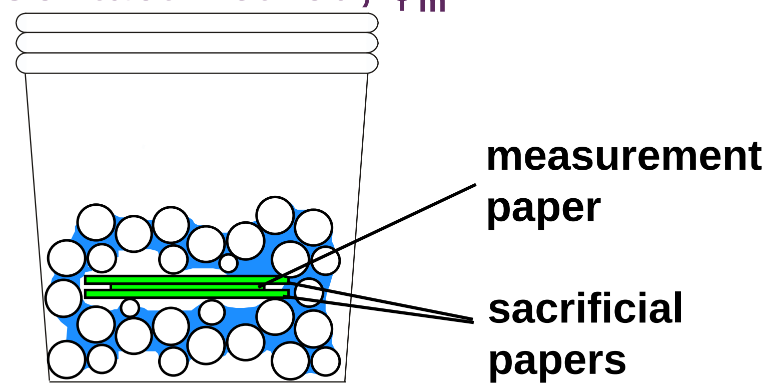


SWCC- ***Filter Paper Techniques***

Noncontact Method, ψ_t

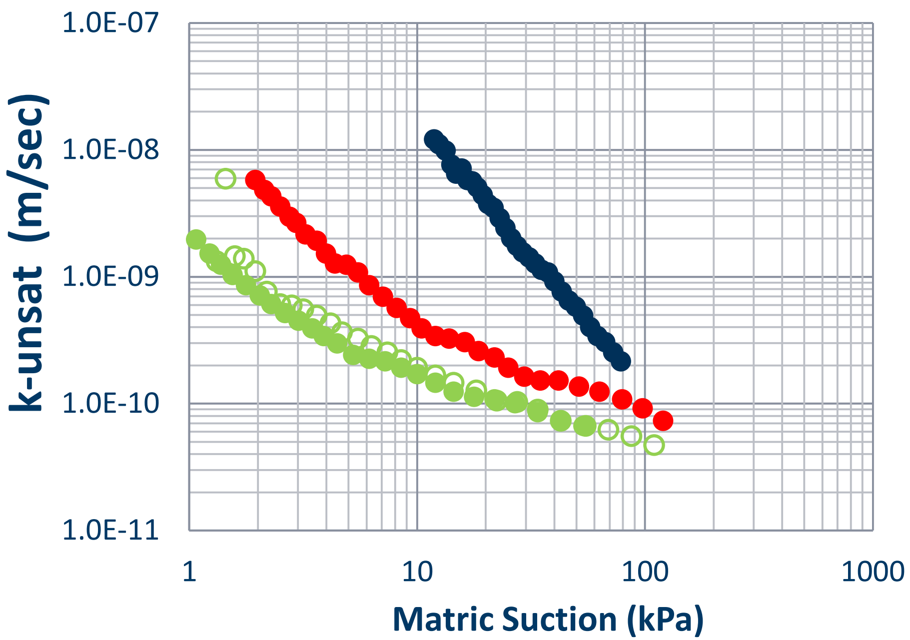


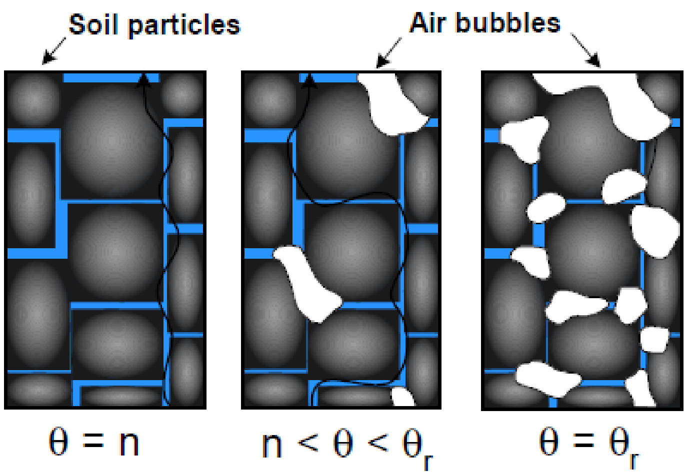
Contact Method, ψ_m



*Lytton and Bulut, 2003

Unsaturated Hydraulic Conductivity (*k-unsat or HCF*)





*Seepage Modeling with SEEP/W, (2012),GEO-SLOPE International, Ltd.

Unsaturated Hydraulic Conductivity (***k-unsat***)

- *<u>Mostly estimated/calculated</u>* from k-sat and SWCC

- Alternatively =>evaporation method with two tensiometers:

$$q^i = \frac{1}{\beta}\left(\frac{\Delta V^i}{\Delta t^i} A\right)$$

q^i = water flow at evaluation point i

ΔV^i = water loss determined by weight changes at evaluation point i

Δt^i = time interval between two measurement points

A = cross sectional area

β = geometry coefficient (standard β=2)

Unsaturated Hydraulic Conductivity (***k-unsat***)

Darcy's law:

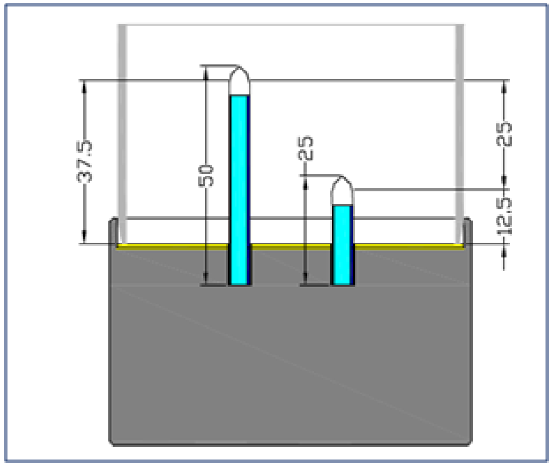
$$K_{unsat}^{i}(\Psi) = -\frac{q^{i}}{\Delta h^{i}/_{\Delta z} + 1}$$

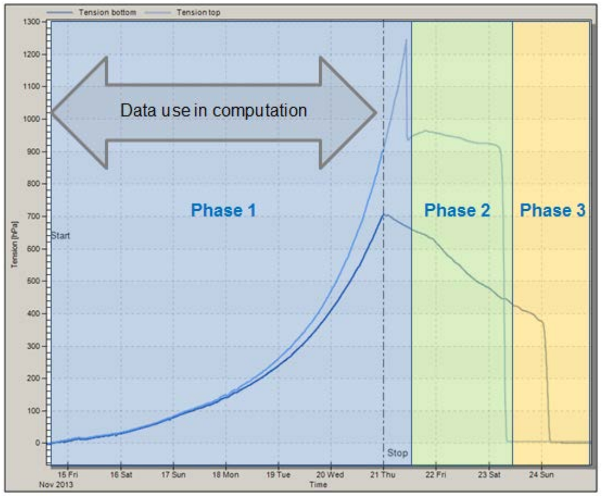
$K_{unsat}{}^{i}$ = unsaturated hydraulic conductivity at evaluation point i

Ψ = average suction between two measurement points in time

Δh^{i} = difference in water tension between tensiometers at evaluation point i

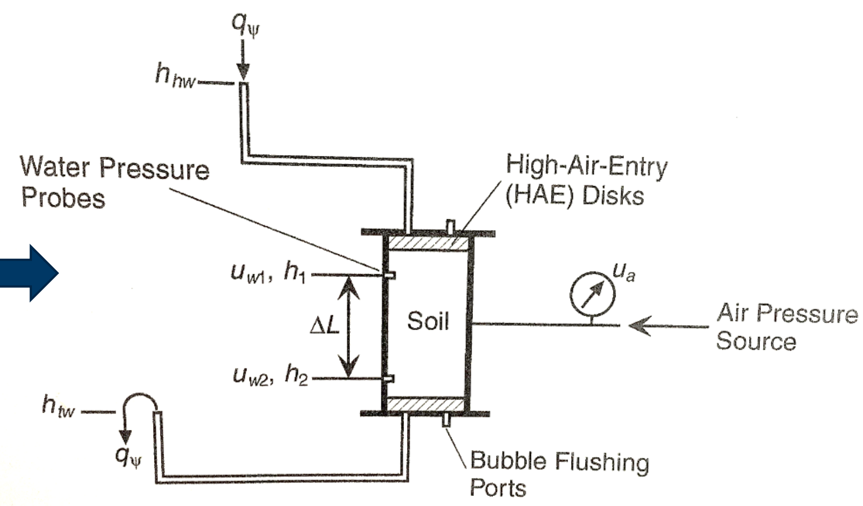
Δz = distance between tensiometers tips





Unsaturated Hydraulic Conductivity (***k-unsat***)

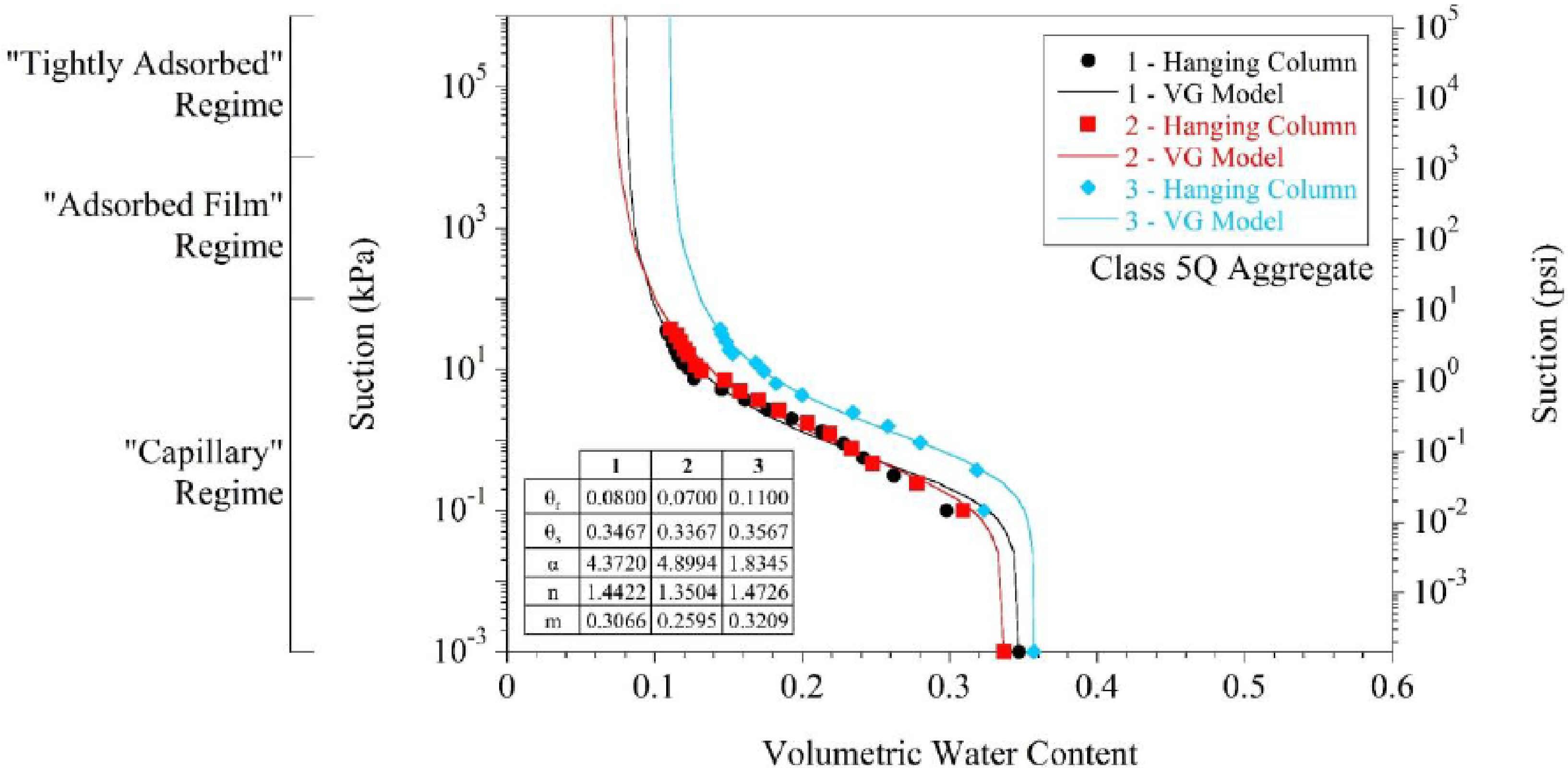
- Steady-state techniques:
  - *Constant-head method*
  - Constant-flow method



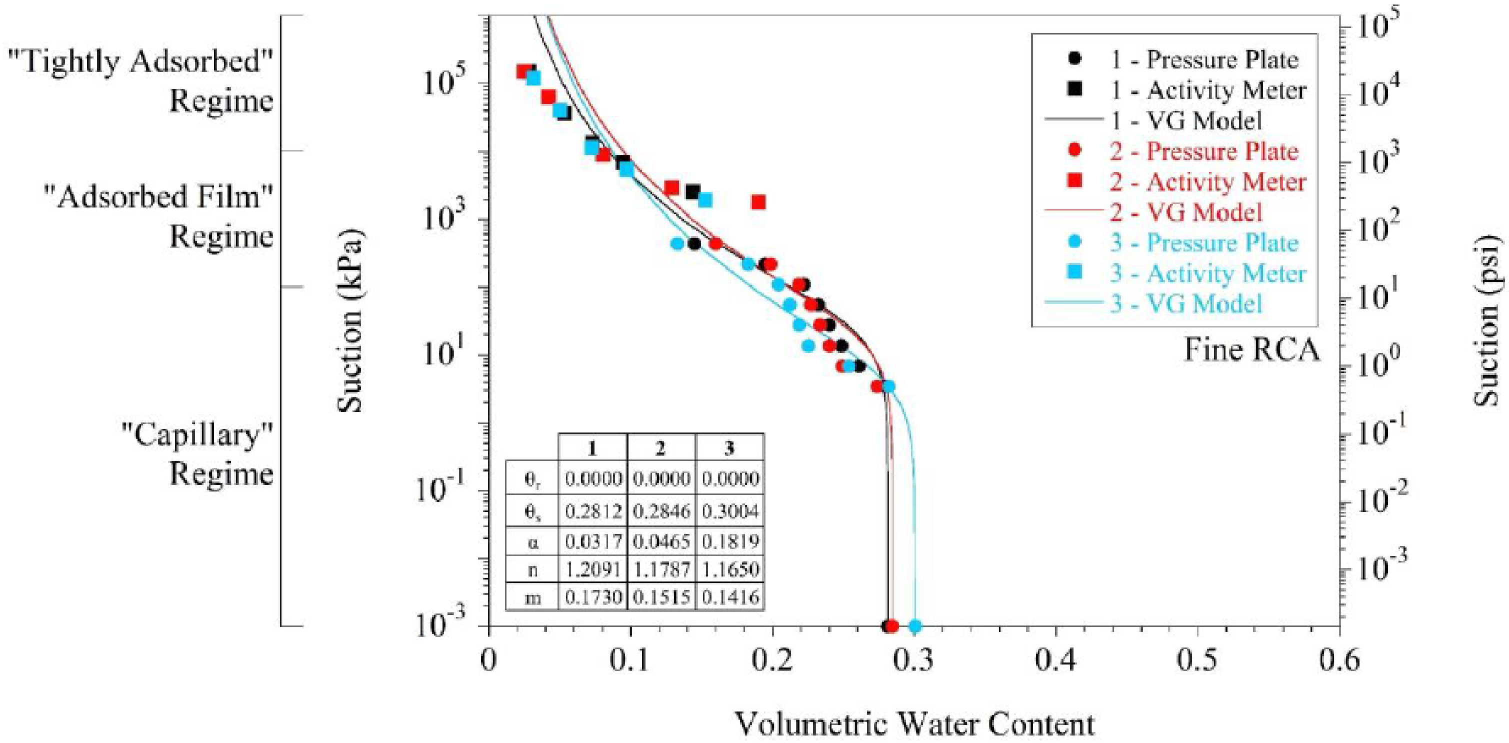
- Transient techniques (*hydraulic diffusivity*):
  - Horizontal infiltration method
  - Outflow methods
  - Instantaneous profile methods
    - Lab
    - Field

Common Models for ***SWCC***

- Brooks and Corey (BC) Model
- **van Genuchten (VG) Model**
- Fredlund and Xing (FX) Model



Common Models for ***SWCC***
van Genuchten (VG)



$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = [1 + (\propto \psi)^n]^{-m}$$

S_e = effective saturation

ψ = matric suction

θ_s= sat vol. water content

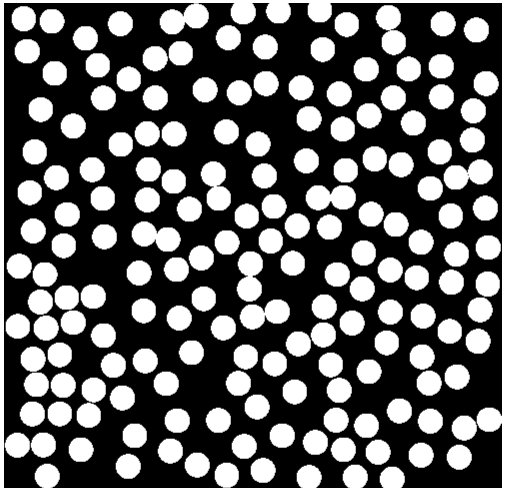
θ_r= residual vol. water content

$\propto, n, m$ = empirical fitting parameters

Common Models for *k-unsat (HCF)*

- Empirical and Macroscopic Models
- Statistical Models
  - van Genuchten (VG) Model
  - Fredlund Model

Basis of Statistical Modeling



Randomly sized and randomly distributed pores

Common Models for ***k-unsat (HCF)***
van Genuchten (VG)

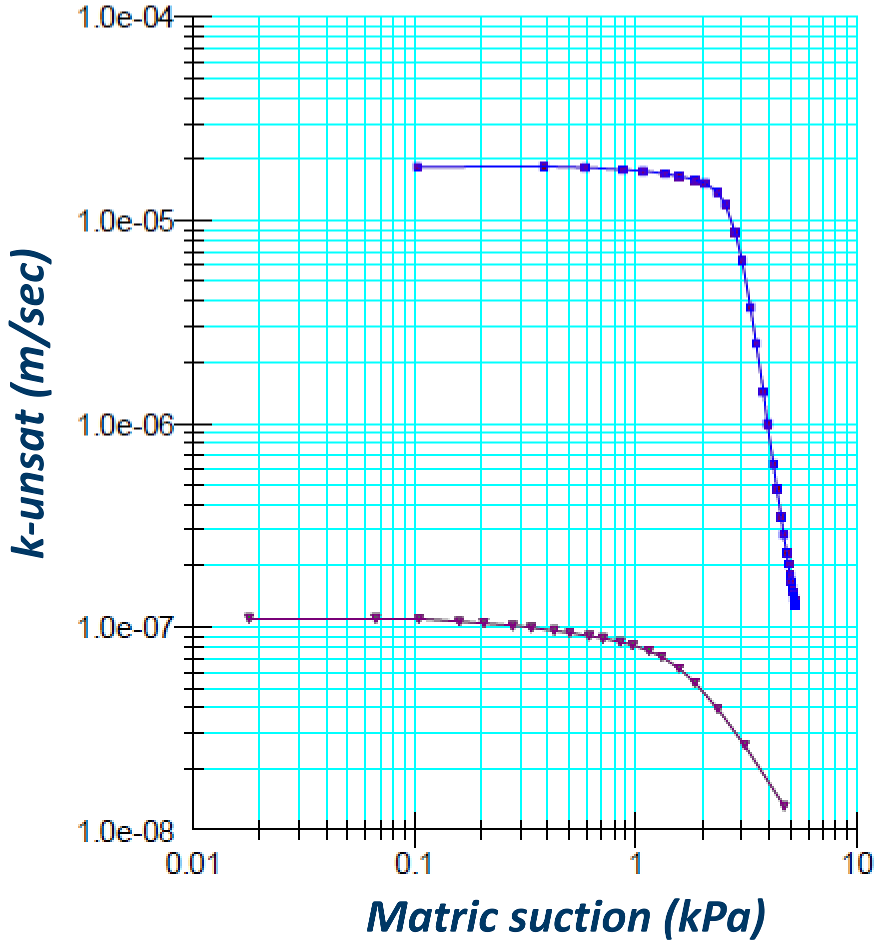
$$k_w = k_s \frac{\left[1-\left(a\Psi^{(n-1)}\right)\left(1+\left(a\Psi^{n}\right)^{-m}\right)\right]^2}{\left(\left(\left(1+a\Psi\right)^{n}\right)^{\frac{m}{2}}\right)}$$

k_s = saturated hydraulic conductivity

ψ = matric suction

a, n, m = empirical fitting parameters

$$n = \frac{1}{1-m}$$



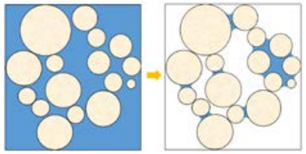
***Seepage Modeling with SEEP/W, (2012),GEO-SLOPE International, Ltd.**

Closing Remarks

- Suction spans a range over 6 orders of magnitude
- No single measurement technique is ideal for every application
- Measurement approach must consider:
  - Soil type
  - Range of wetting
  - Wetting direction
  - Applicability in the lab or field
- Quality measurements require careful protocol and calibration

Acknowledgments

Material from W. Likos (UW-Madison) and M. Padilla (GCTS Testing Systems), ASCE 2011 Webinar



Q&A - Fundamentals

All

NRRA Webinar
May 19, 2020

DEPARTMENT OF TRANSPORTATION

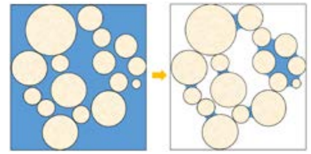
MICHIGAN STATE UNIVERSITY

Department of Civil and Environmental Engineering
UNIVERSITY OF WISCONSIN–MADISON

NRRA
National Road Research Alliance

Break (10 min)

- Welcome – Introduction – *T. Beaudry*
- Fundamental Concepts in Unsaturated Soil – *W. Likos*
- Measurement of Unsaturated Properties – *R. Velasquez*
- Q&A – Fundamentals – *All*
- Break (10 min)
- Impact of Moisture on Pavement Foundation Materials – *B. Cetin*
- Importance of Unsaturated Soil Mechanics in ME Design – *B. Cetin*
- Correlations between Unsat Soil Parameters and ME Design Input – *B. Cetin*
- Use of Unsaturated Soil Mechanics by MnDOT– *J. Siekmeier*
- Q&A –Applications – *All*
- Closing Remarks – *T. Beaudry*



Impact of Moisture on Pavement Foundation Materials

Bora Cetin, PhD
Assistant Professor
Michigan State University
cetinbor@msu.edu

NRRA Webinar
May 19, 2020

COMPACTION

- Compaction is the densification of a soil by the use of mechanical energy
  - The process of expelling _air_ from the soil
  - Improves strength
    - Increases bearing capacity of foundations
    - Increases stability of embankment slopes
  - Reduces compressibility
    - Decreases settlement of foundations
  - Reduces permeability

Compaction Principles

- The basic principle of densification is the re-arrangement of particles into a denser state, which results in

Modulus

Strength

Resistance to liquefaction

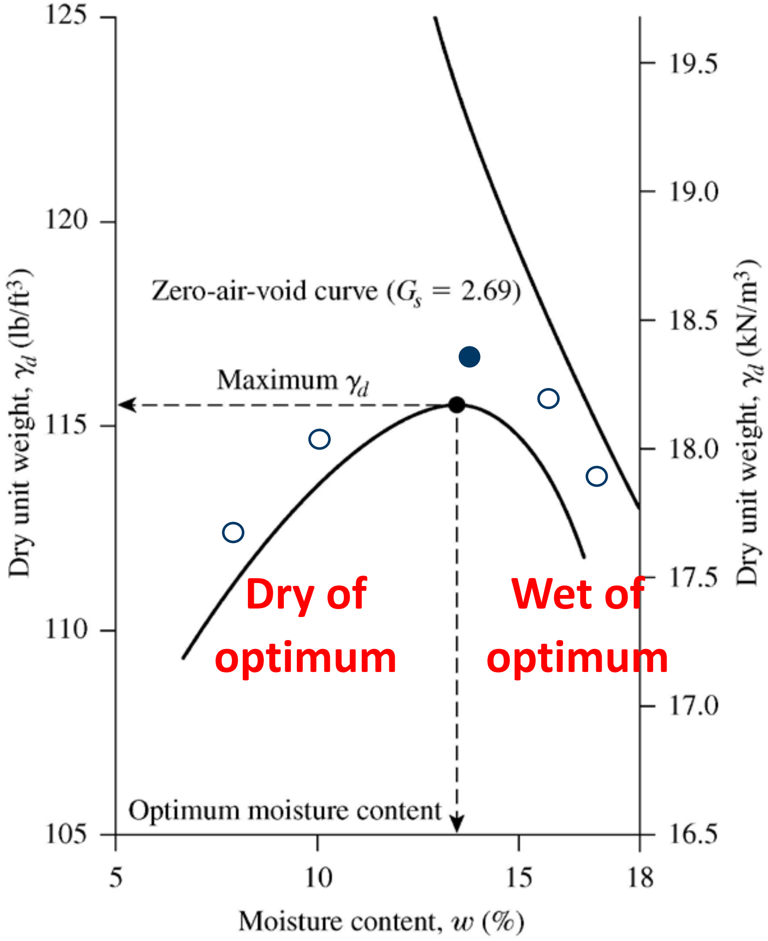
increase

Permeability

Collapsibility

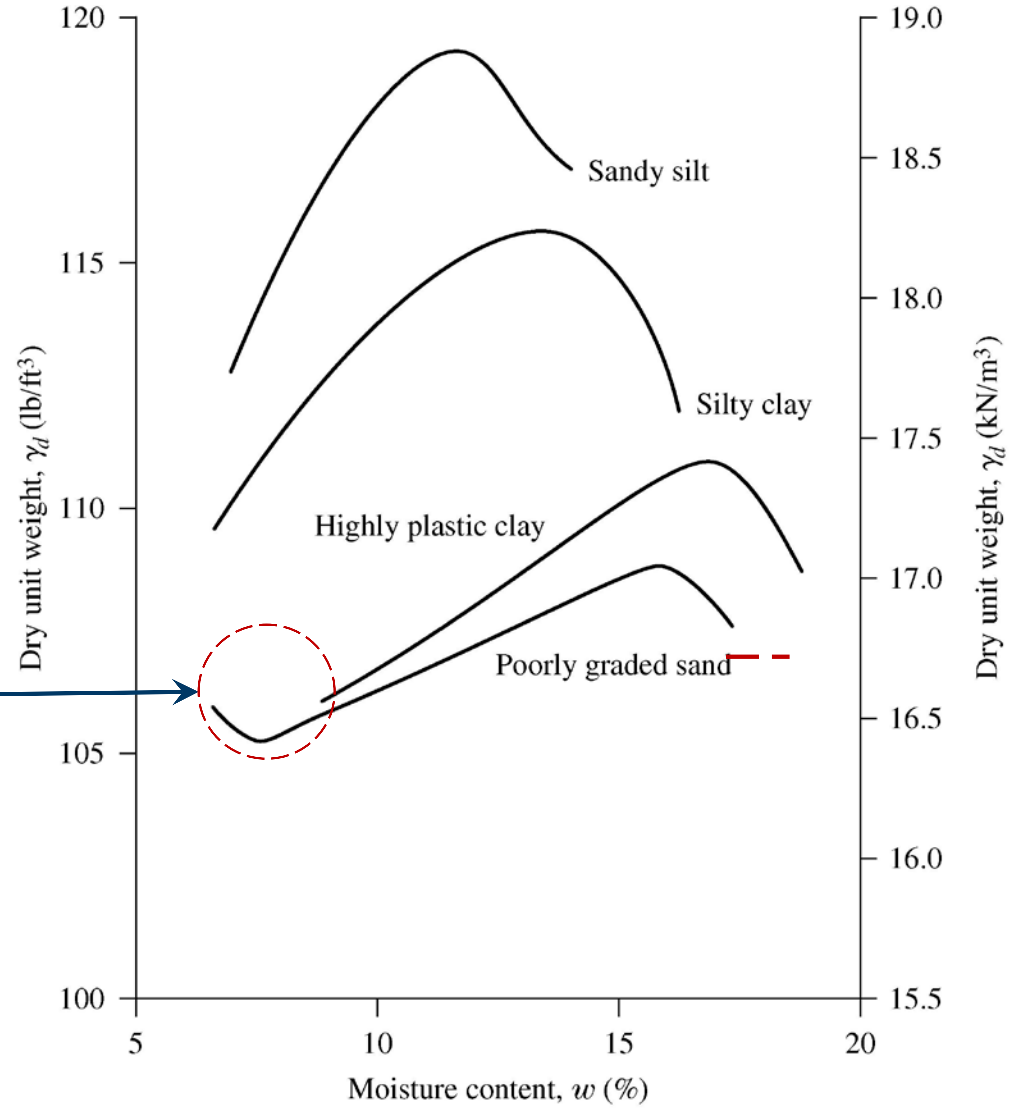
decrease

Dry Unit Weight vs. Moisture Content Curve



Effect of Soil Type

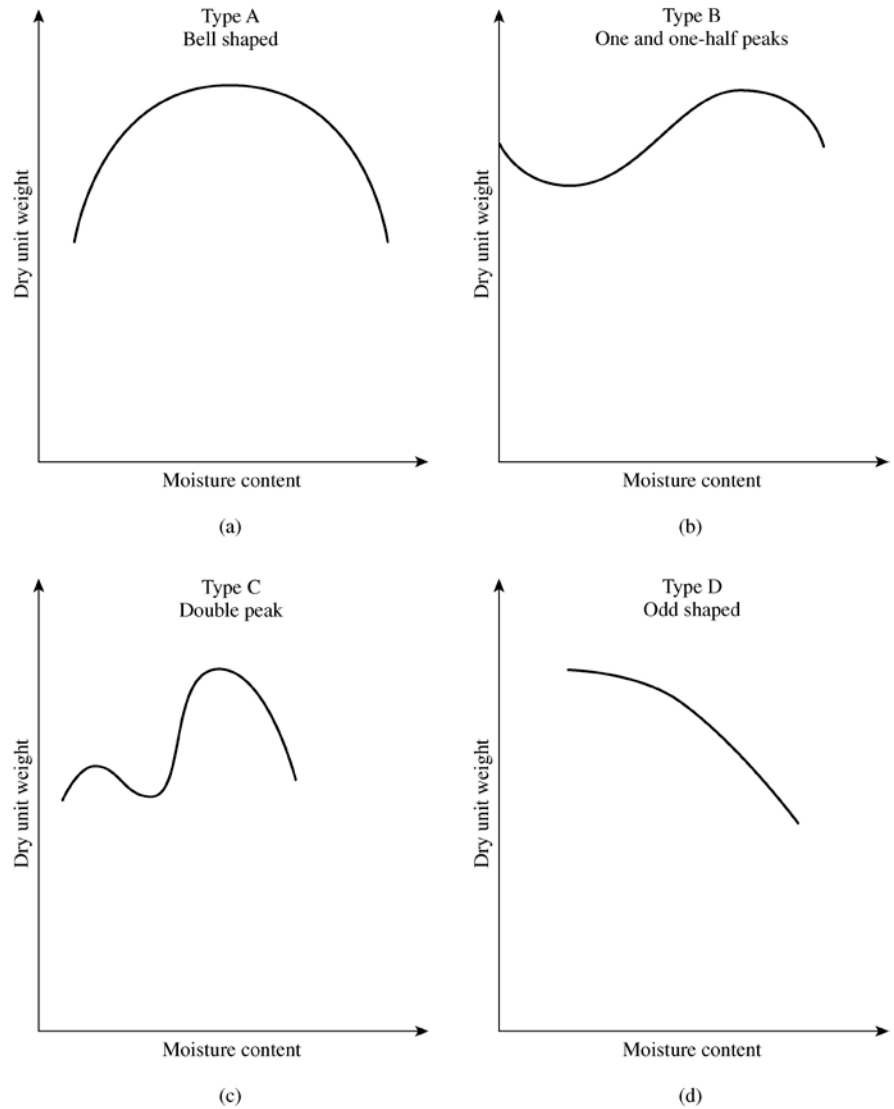
Particle rearrangement inhibited due to capillary tension



Types of compaction curves

30 < LL < 70

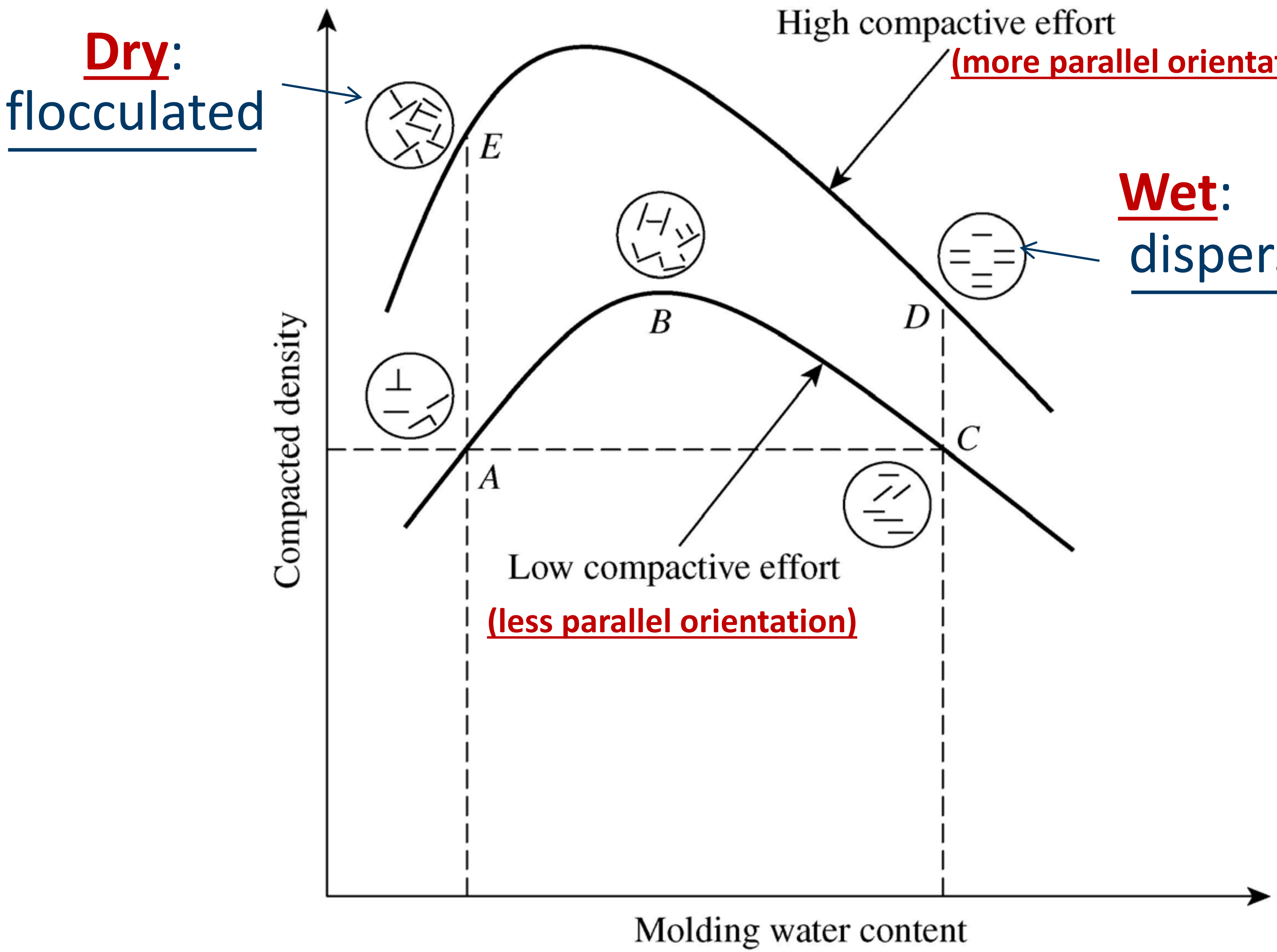
LL < 30



LL < 30 or > 70

LL >70

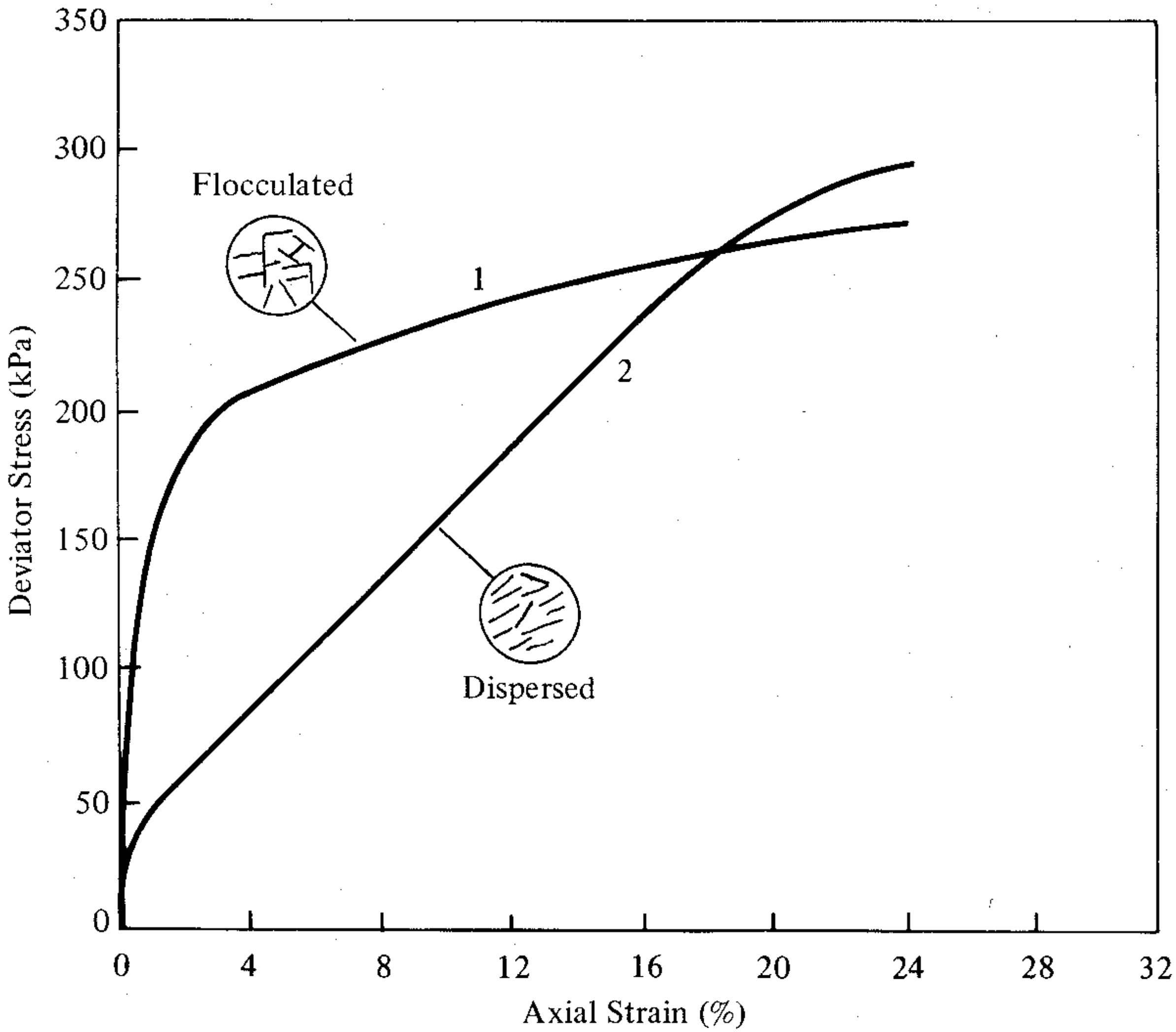
STRUCTURE OF COMPACTED CLAY SUBGRADE WITH MOISTURE



Effect of Moisture on Soil Properties

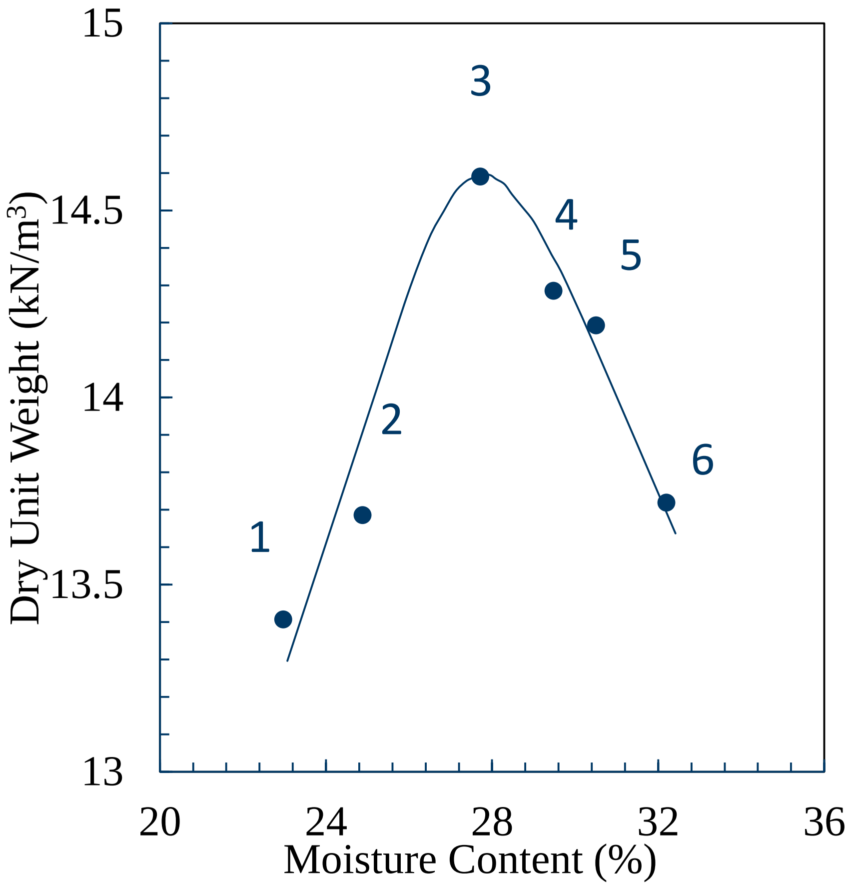
Stress-Strain

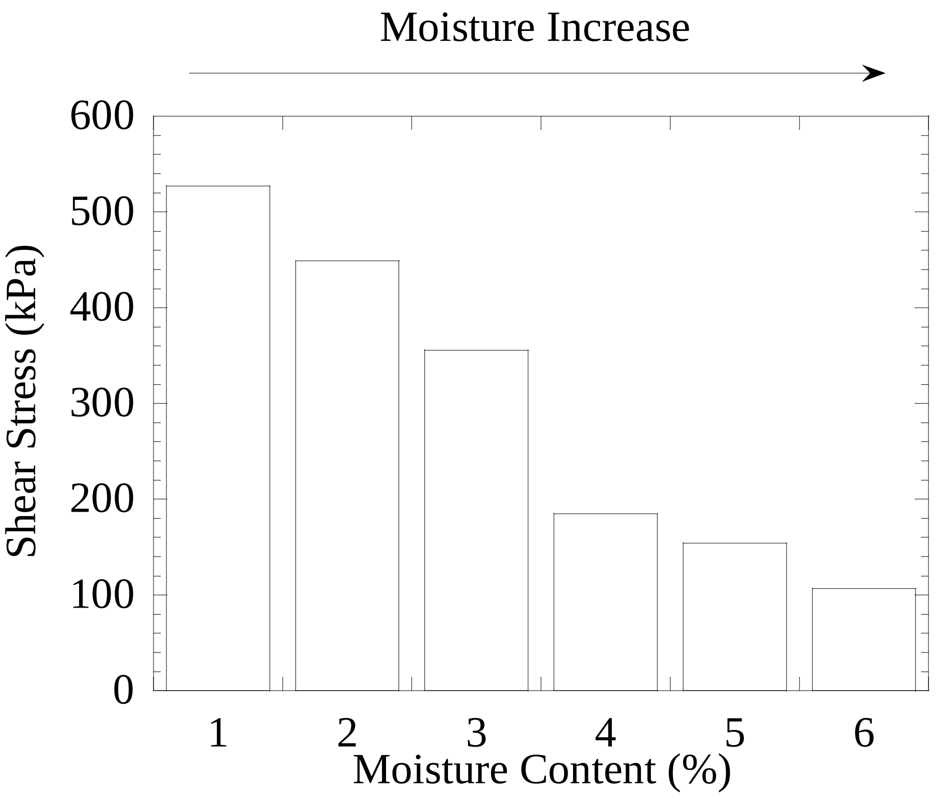
and strength



Effect of Moisture on Soil Properties

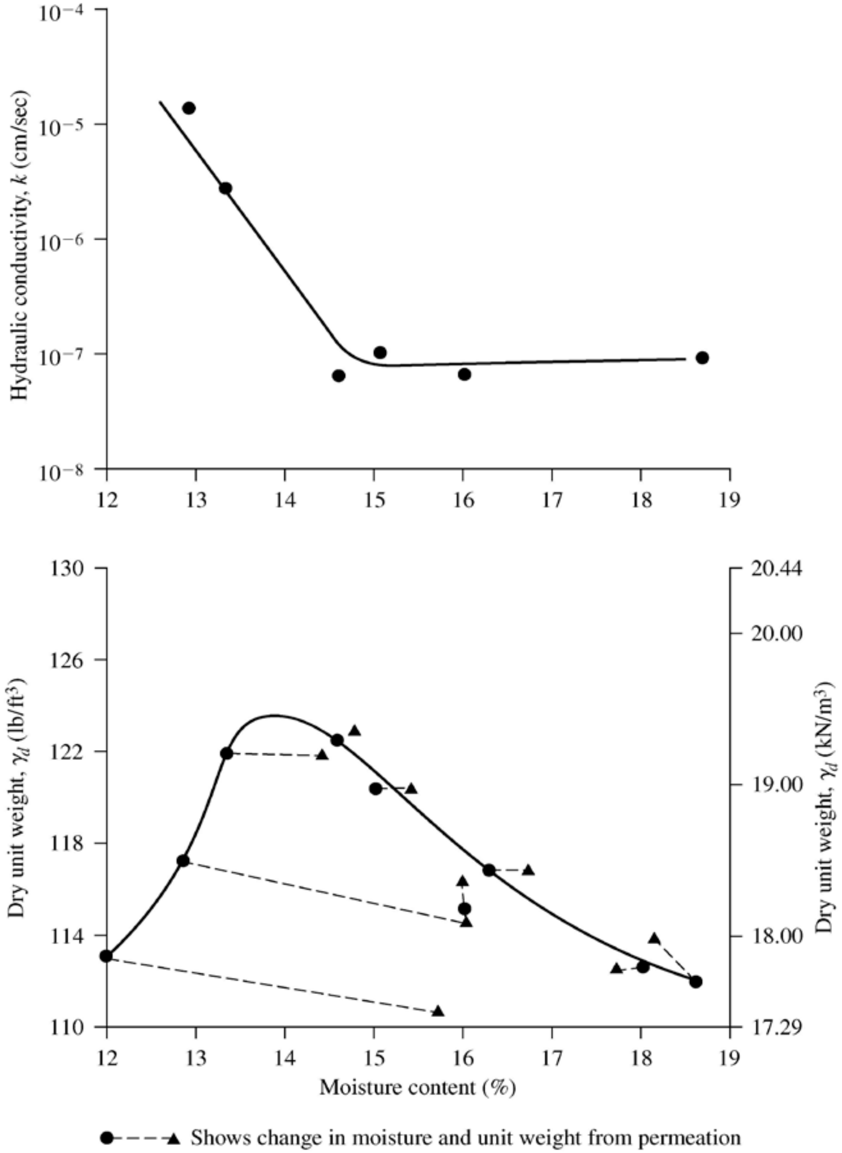
Stress-Strain and strength





Effect of Compaction on Soil Properties

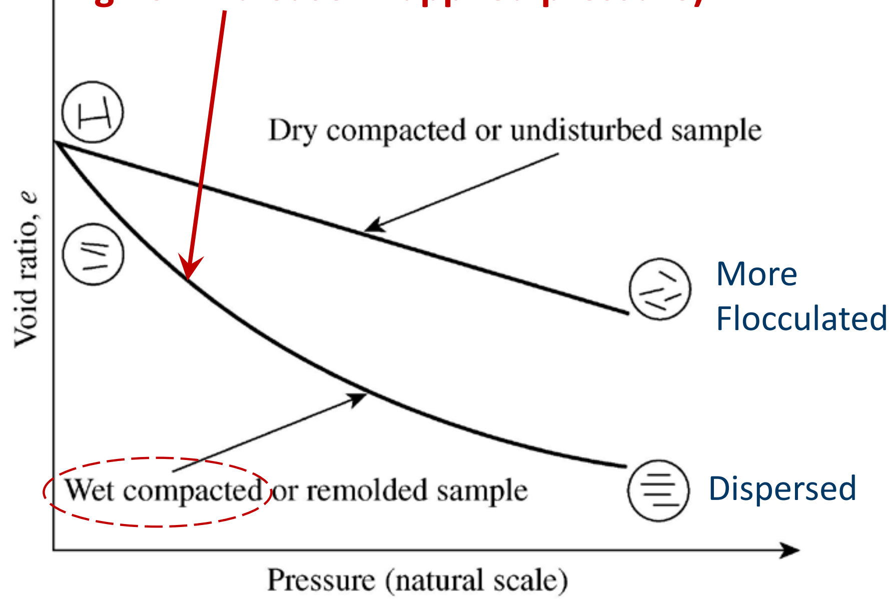
Permeability



EFFECT OF MOISTURE ON SOIL PROPERTIES

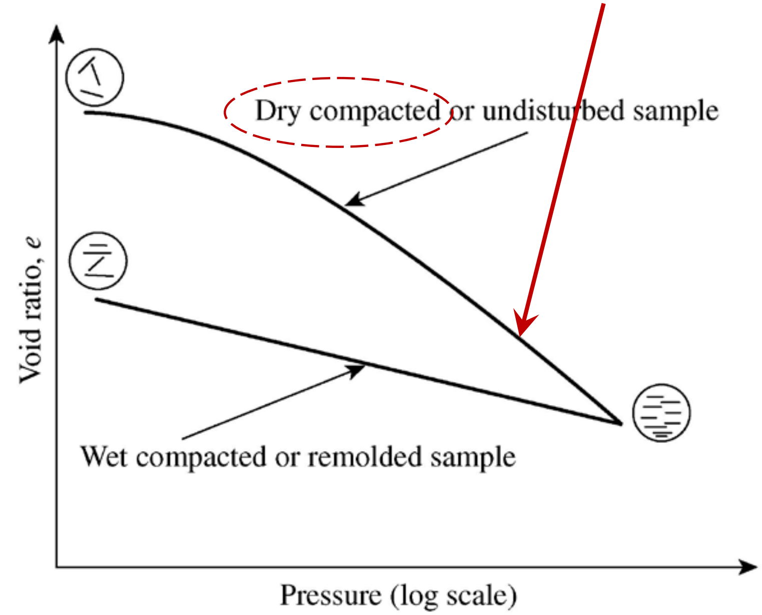
Compressibility / Settlement

If compacted Wet of optimum: more compressible at low pressure (greater slope = greater change in void ratio for given increase in applied pressure)



(a) Low-pressure consolidation

If compacted Dry of optimum: more compressible at high pressure (steeper slope)



(b) High-pressure consolidation

EFFECT OF MOISTURE ON SOIL PROPERTIES

Strength of clayey soils

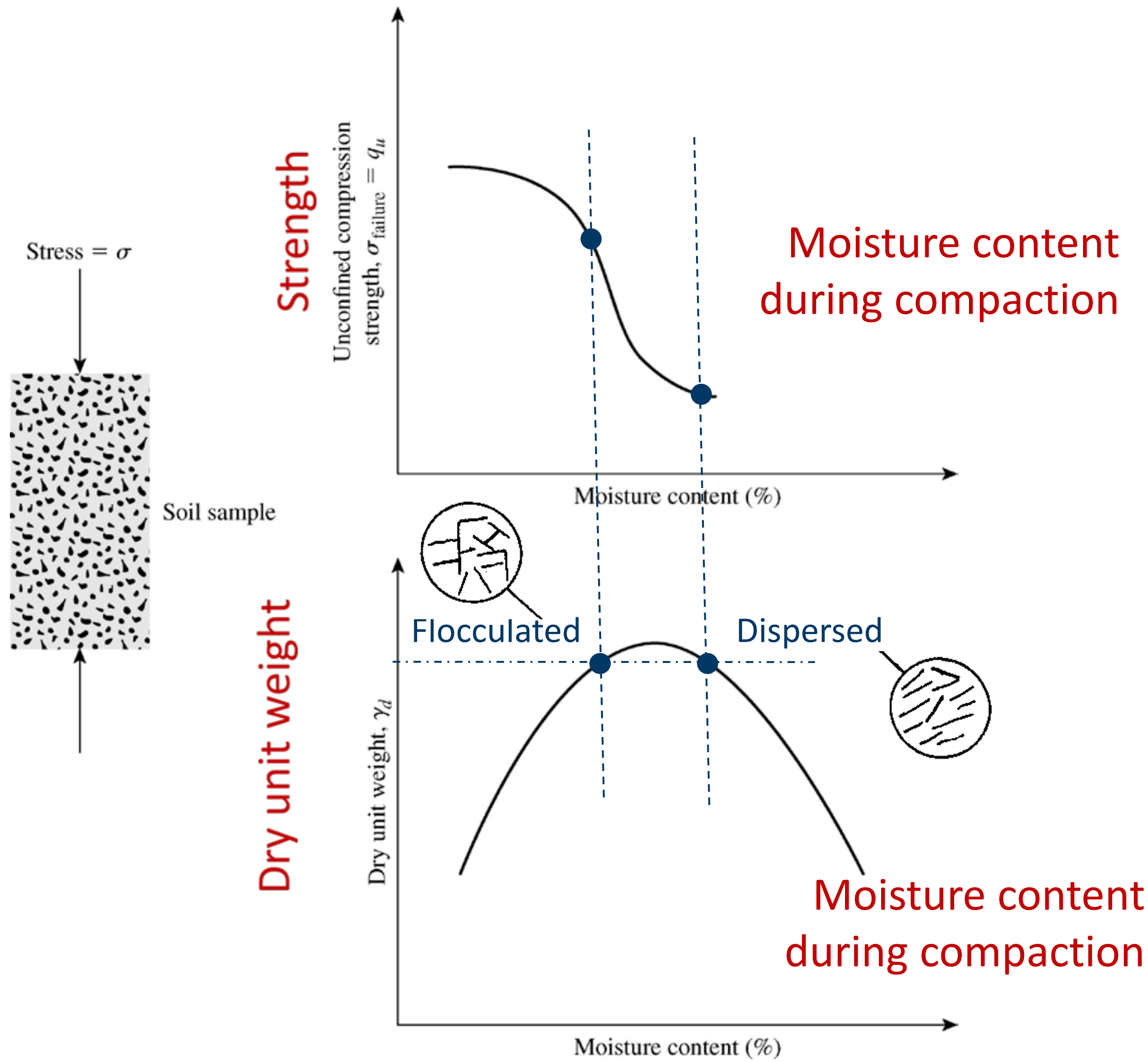
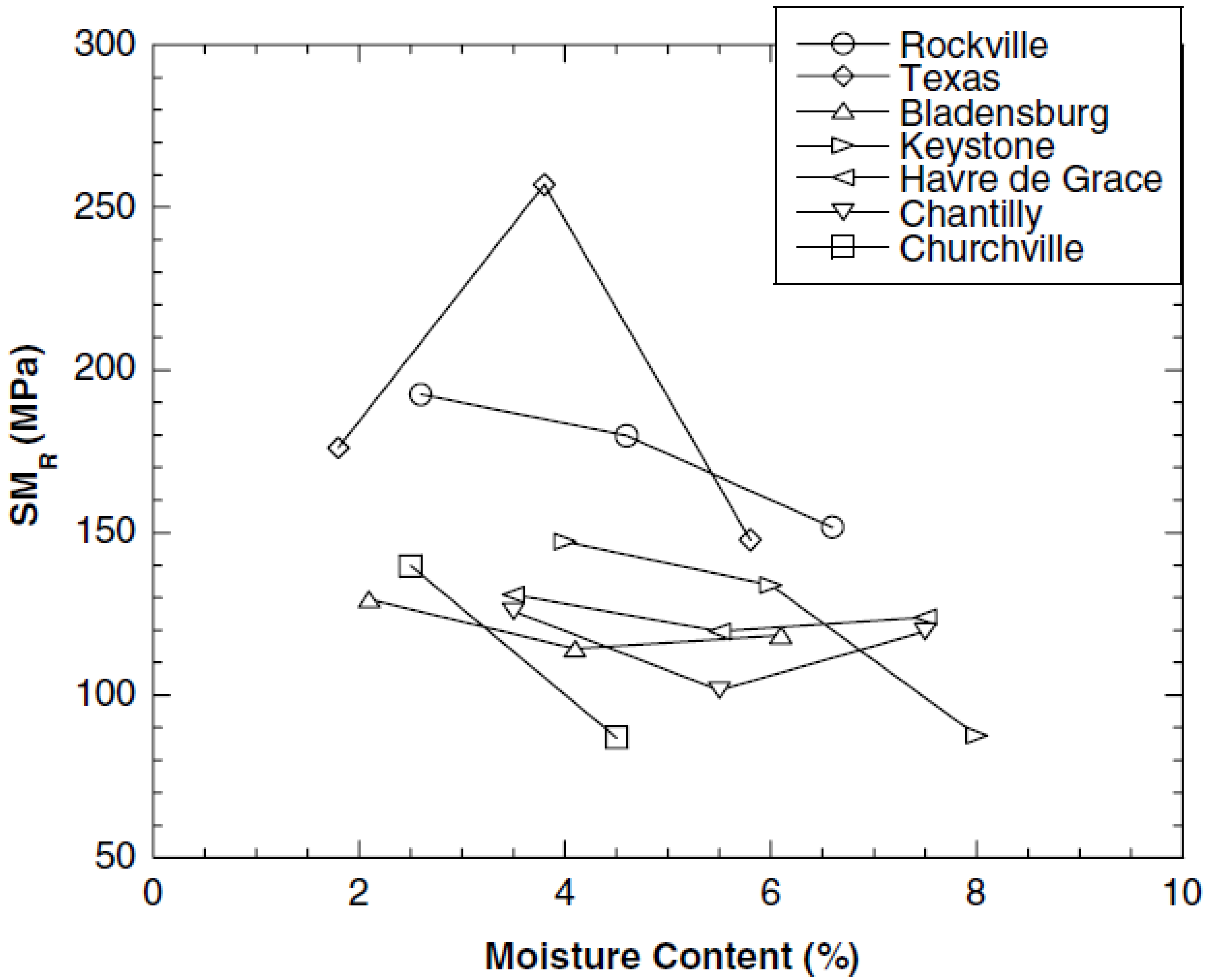


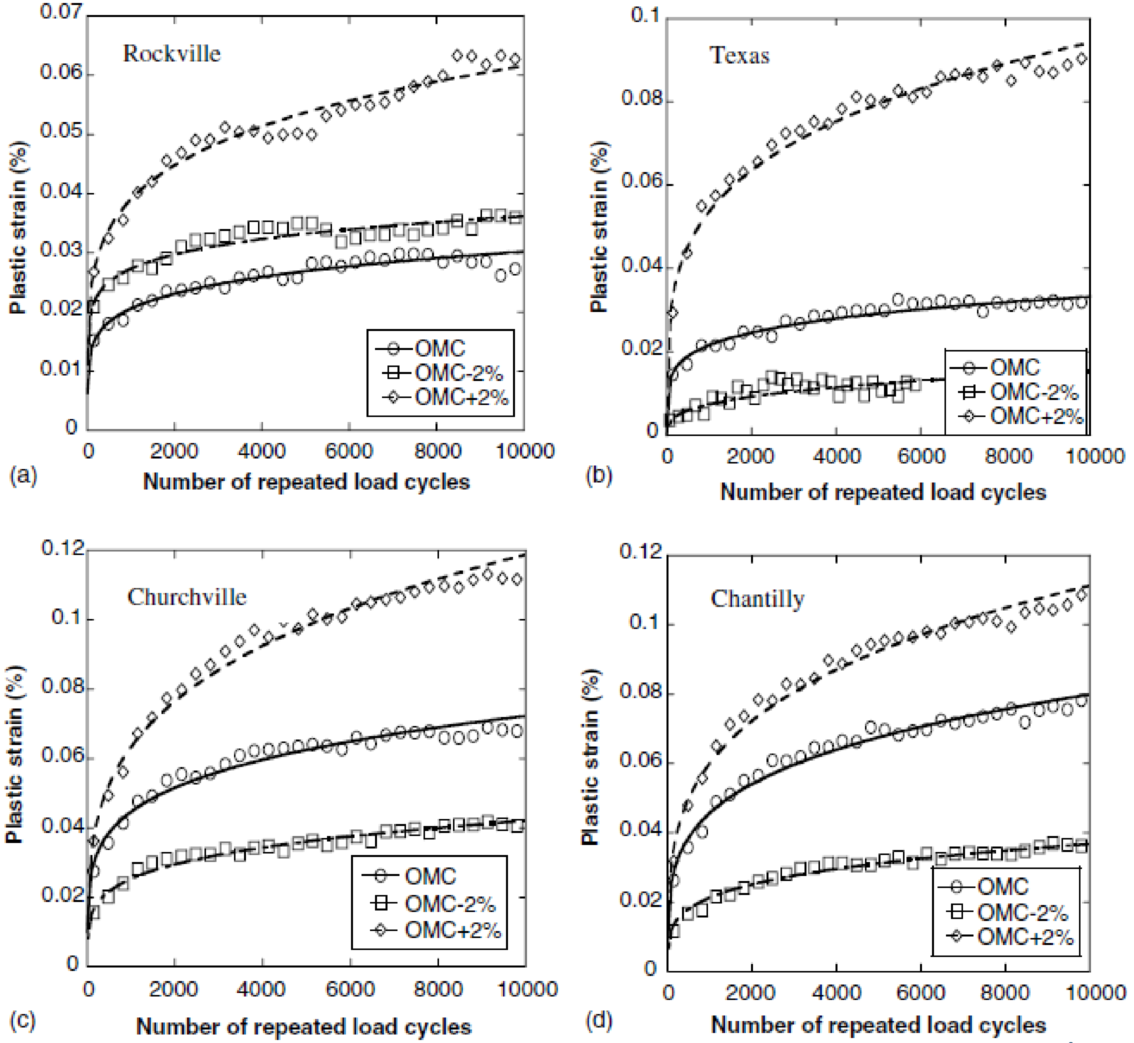
Figure 5.18 Effect of compaction on the strength of clayey soils

Effect of Moisture Content on Resilient Modulus of Granular Aggregate Base Materials



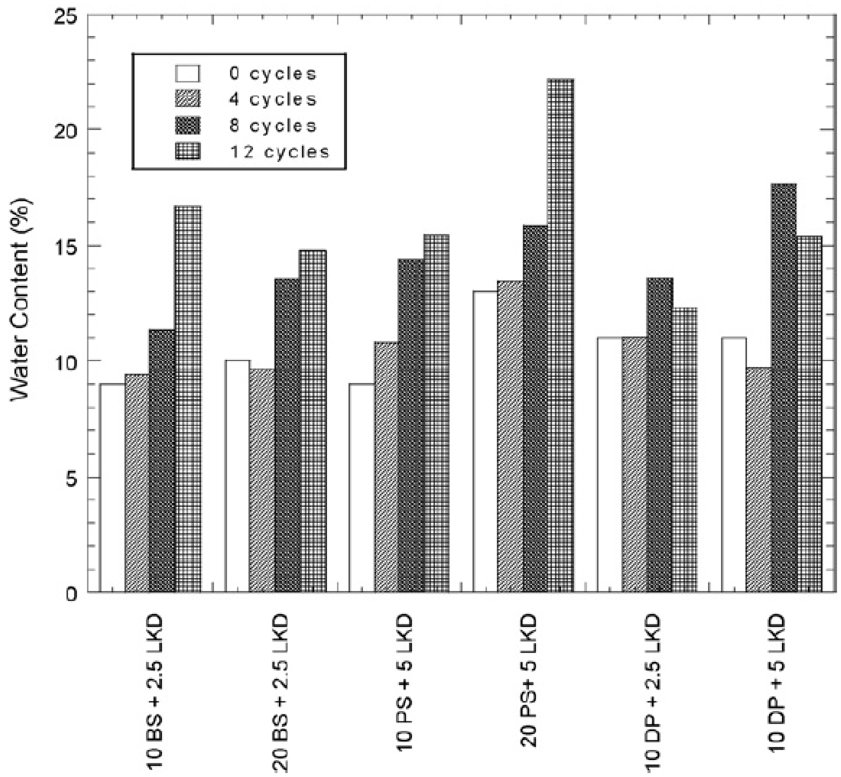
(Haider et al. 2014)

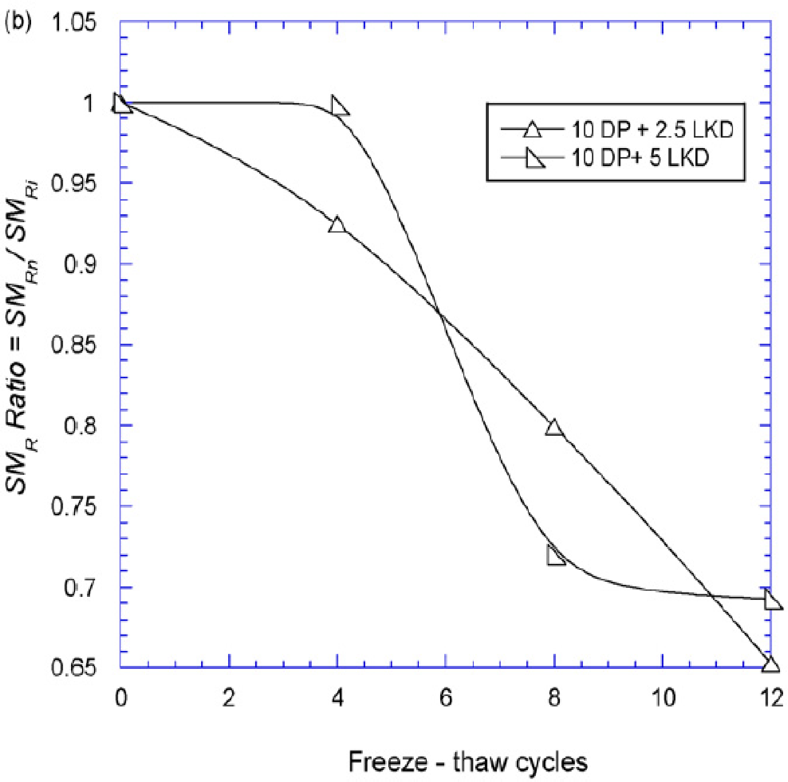
Effect of Moisture Content on Permanent Deformation of Granular Aggregate Base Materials



(Haider et al. 2014)

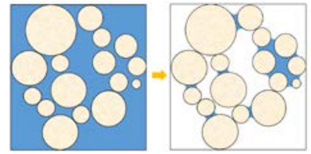
Effect of Freeze-Thaw Cycles on Moisture/Resilient Modulus





BS: Brandon Shores Power Plant Fly Ash
PS: Paul Smith Power Plant Fly Ash
DP: Dickerson Precipitator Plant Fly Ash
LKD: Lime Kiln Dust

(Cetin et al. 2010)



Importance and Integration of Unsaturated Soil Mechanics in Pavement M-E Design

Bora Cetin, PhD

Assistant Professor

Michigan State University

cetinbor@msu.edu

NRRA Webinar

May 19, 2020

Importance of Matric Suction for Pavement Structure

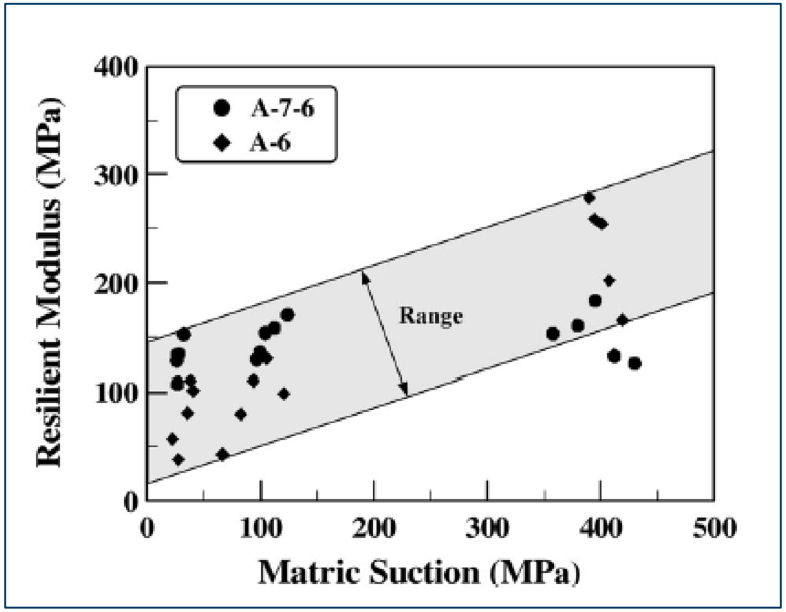
- Having unsaturated geomaterials in the pavement foundation leads many researches to focus on the behavior of the unsaturated geomaterials by investigating the relationship between:

- *Saturation degree* versus *matric suction*

- *Shear strength* versus *matric suction*

- *Stiffness (Resilient Modulus)* versus

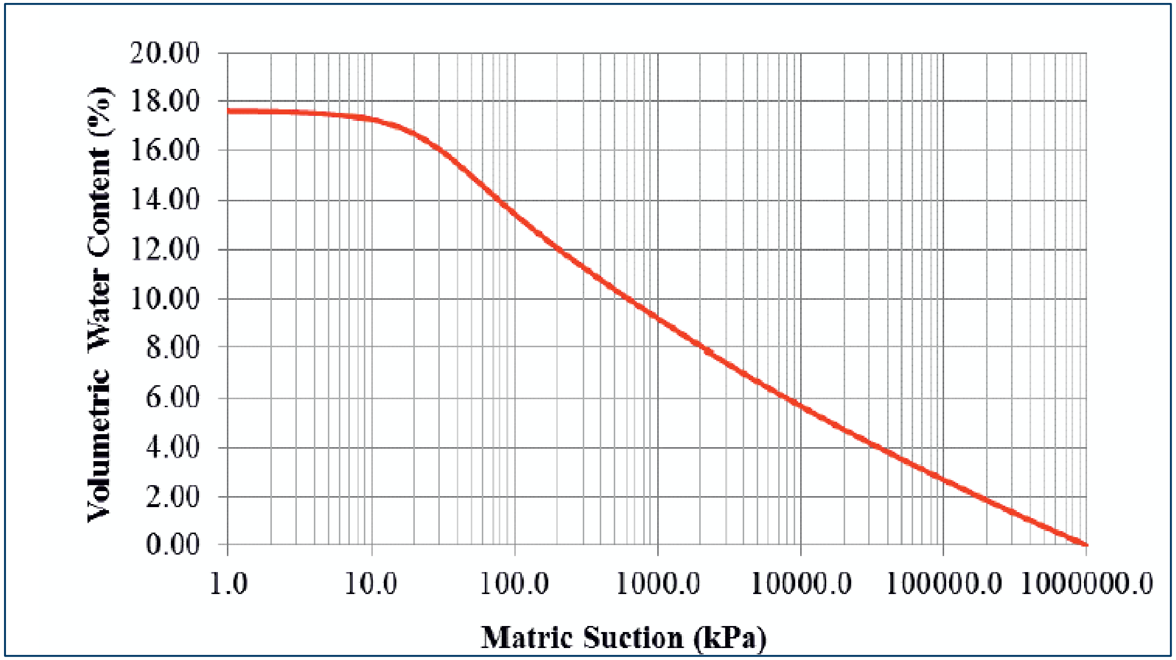
matric suction



(Yang et al. 2008)

Importance of Matric Suction for Pavement Structure

- Matric suction in a pavement structure changes as water content changes.

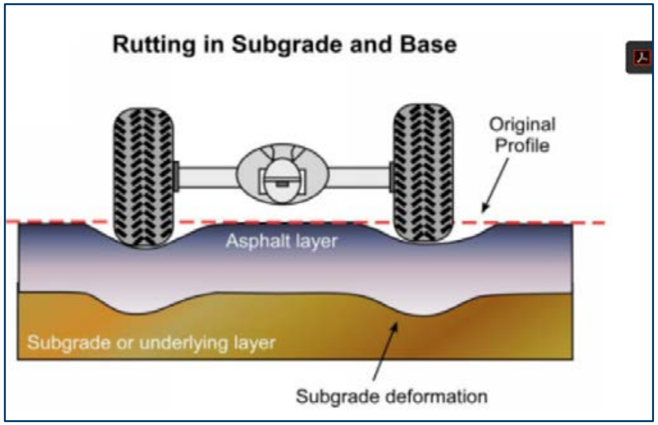


Gu et al., 2016

Importance of Matric Suction for Pavement Structure

- The increase in the matric suction has a significant effect on the shear strength and modulus of geomaterials in the pavement and it is directly related to:
  - Total Rutting: Shear strength directly affects total rutting; it decreases as shear strength increases

Rutting failure due to the weak shear strength of subgrade



Colorado Department of Transportation 2017 Pavement Design Manual

Importance of Matric Suction for Pavement Structure

- Load-related Cracking (Alligator and Longitudinal): A larger shear strength and modulus improve the integrity of supporting layers and also resistance to load-related cracking

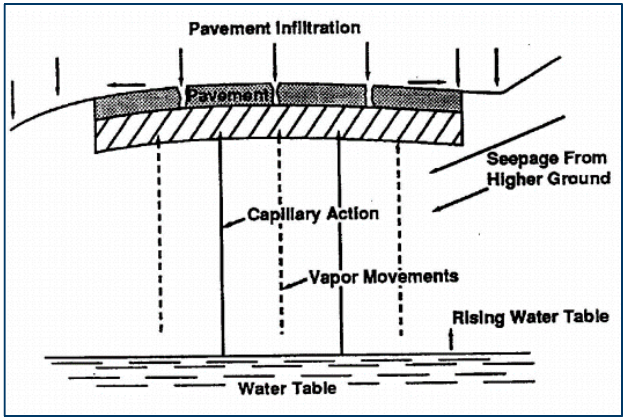
Alligator cracking

- Smoothness (IRI): High shear strength and modulus result in low IRI values

Importance of Matric Suction for Pavement Structure

- Environmental conditions such as precipitation, change in the water table level and drainage conditions, causing distress to the pavement by changing the moisture content ➡ matric suction

Climate conditions

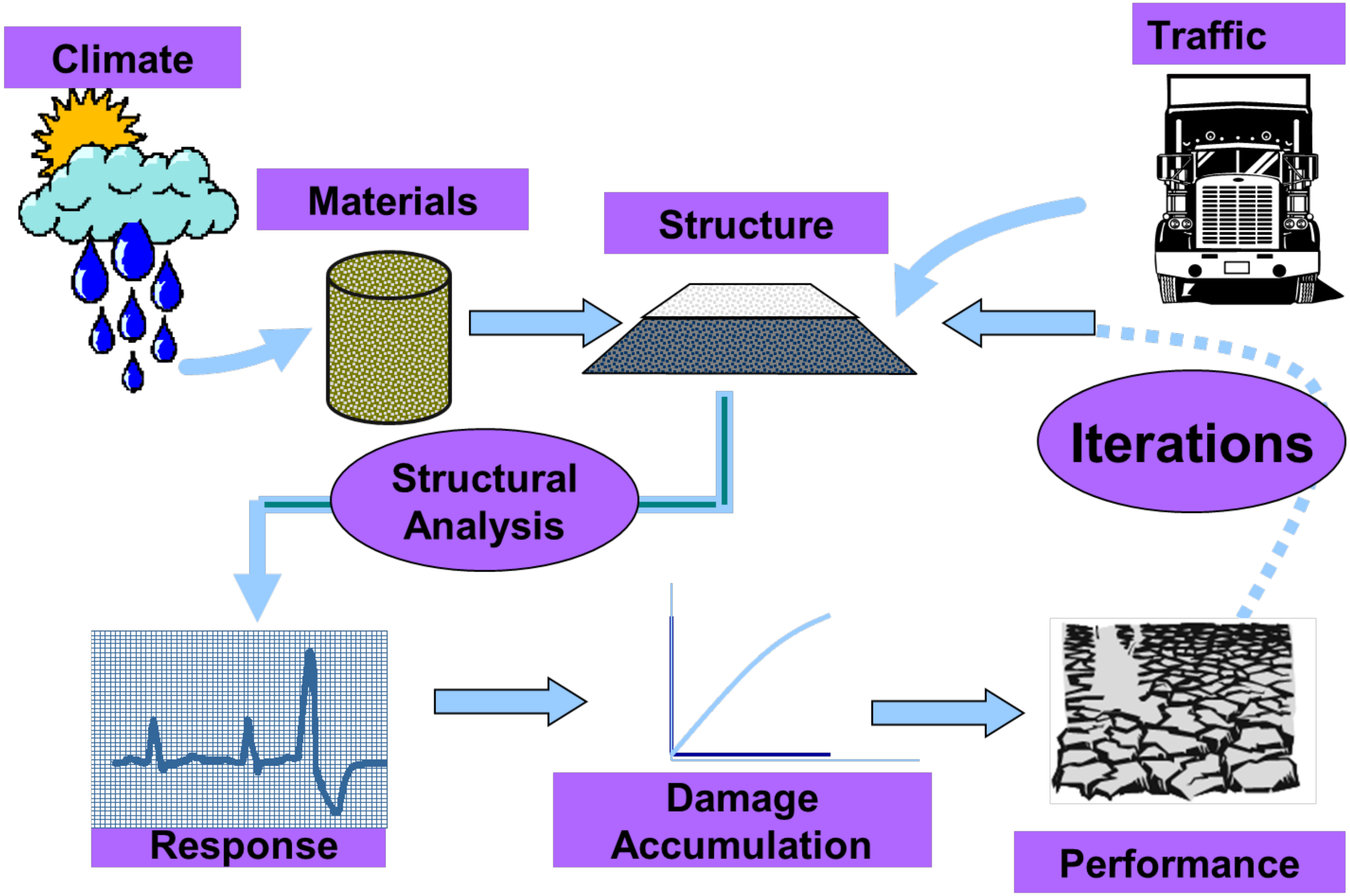


Sources of Subsurface Water in Pavements

Drainage quality

http://www.macdrain.com.br/?page_id=56

Pavement M-E Design



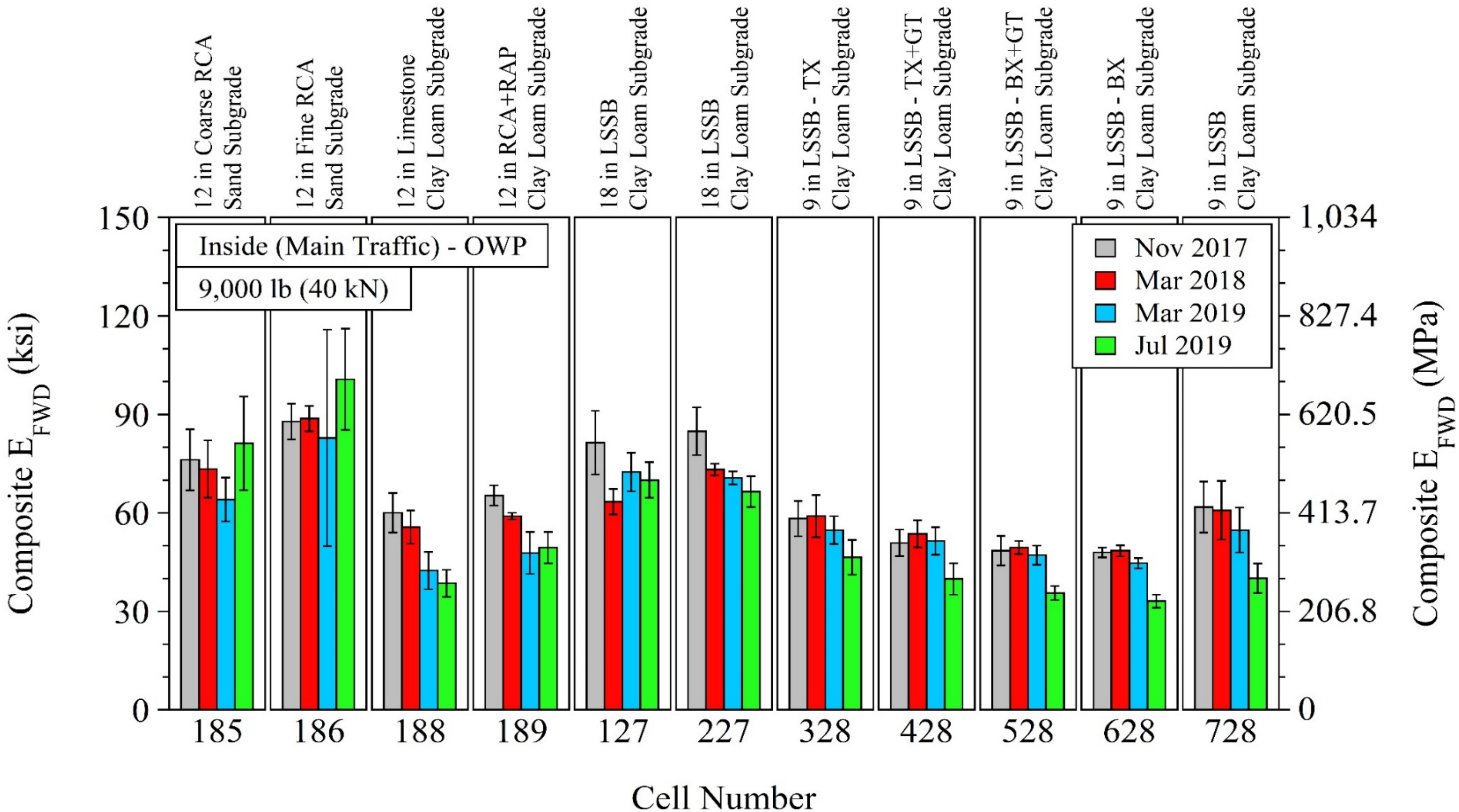
Pavement ME Design Guide Features

- Hierarchical approach to inputs
- Axle load spectra data (not ESALs)
- **Consideration of climatic effects**
- **Use of intrinsic material properties**
- Consideration of key distress types
- Incremental damage approach

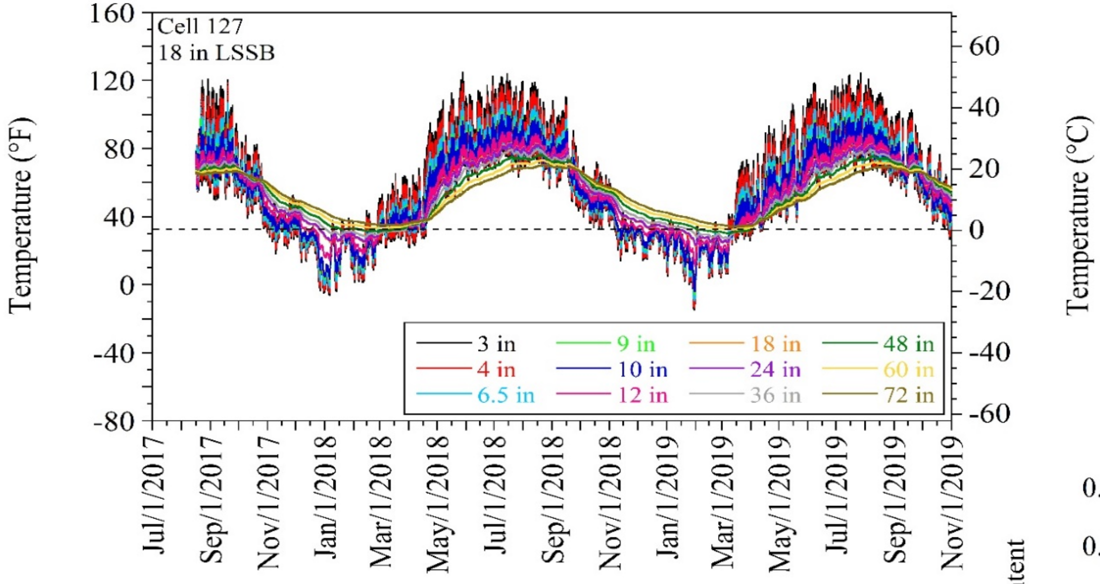
Incremental Damage

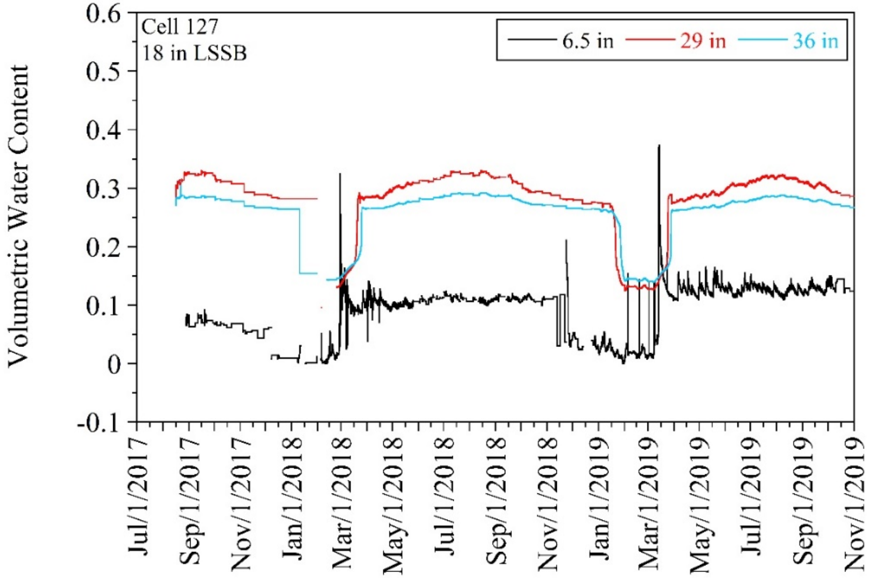
- Changes over time are addressed
  - Material strength and stiffness
  - seasonal moisture and temperature
  - variations in traffic seasonally and over time

Incremental Damage/Stiffness



Incremental Damage/Moisture & Temperature



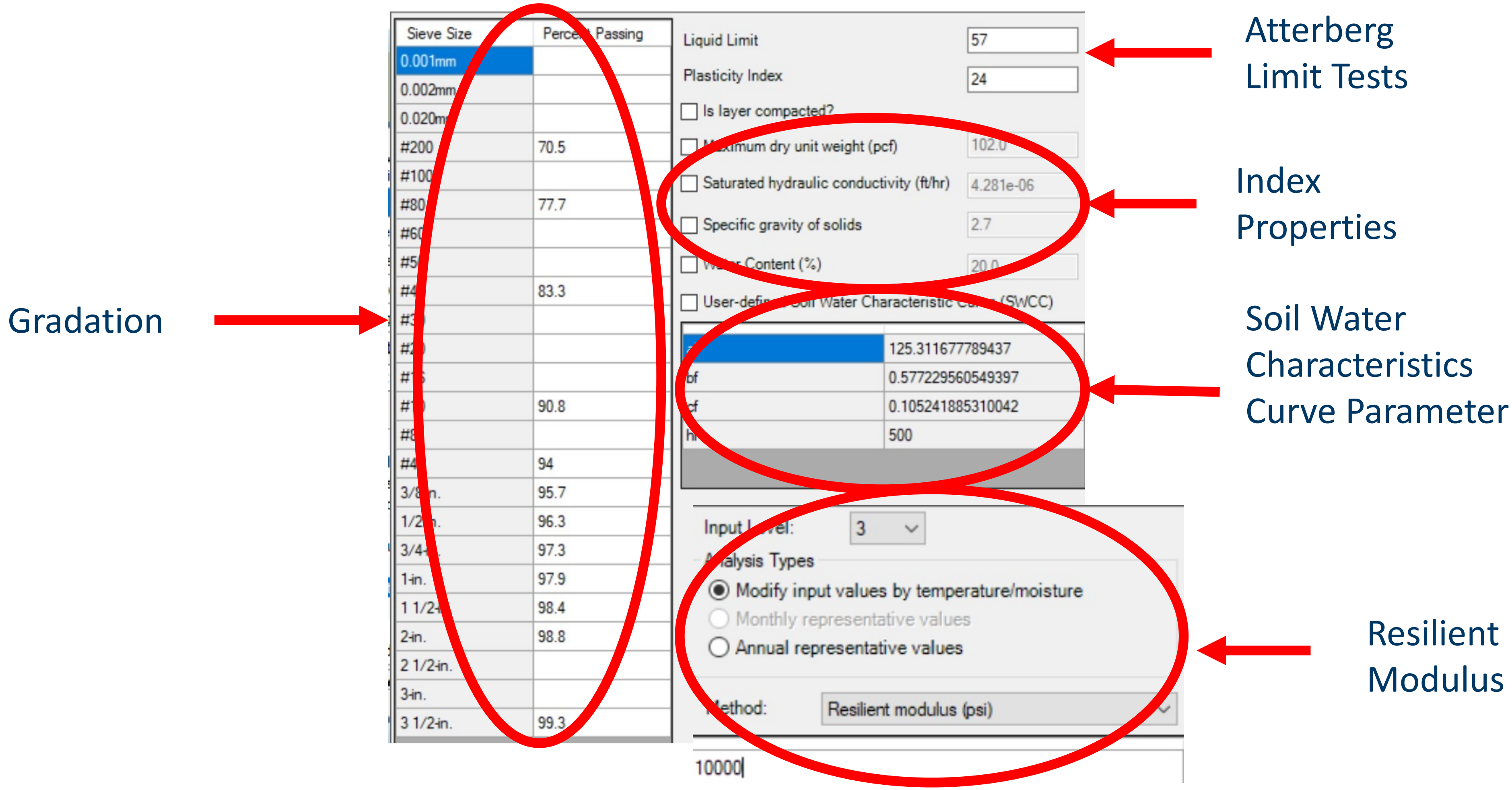


Material Characterization

Analysis Procedure in Pavement – ME

- Step 1 – Input
  - Subgrade soil properties, AASHTO classification
  - Resilient modulus at reference condition, gradation, engineering and index properties, Atterberg limit tests
- Step 2 – Background
  - Estimation of adjusted resilient modulus for varying moisture and temperature condition for each month over the design life (i.e. 20 years)
- Step 3 – Distress
  - Determination of pavement distress (i.e. cracking, rutting, IRI) for due to seasonal variation in resilient modulus

Subgrade Inputs for Pavement-ME



Soil Water Characteristics Curve (SWCC)

- SWCC determines the relationship between water content and suction for a given soil.
- Pavement-ME generates the SWCC curve based on four parameters.
  - a_f (psi)
  - b_f
  - c_f
  - h_r (psi)

Pavement – ME SWCC Flow Chart

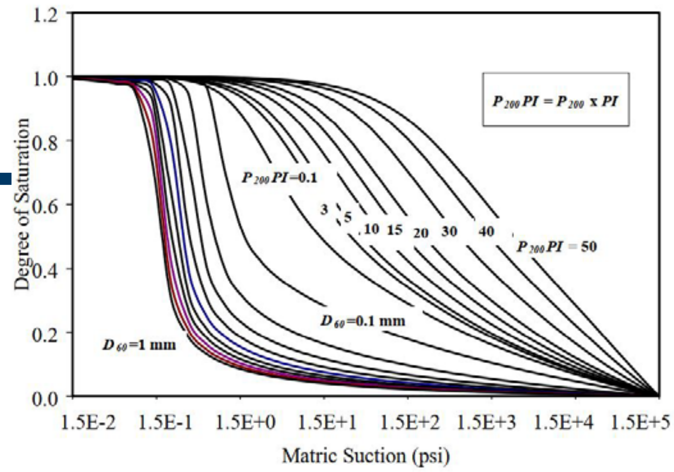
Step 1 – Inputs

- **Required**
  - P_{200} & D_{60} (AASHTO T27)
  - PI (AASHTO T90)
- **Optional**
  - W_{opt}
  - γ_{dmax} (AASHTO T180, T99)
  - G_s (AASHTO T100)

Step 2 – EICM Background

- **Mass – Volume parameters**
  - S_{opt}, θ_{opt}, θ_{sat}
  - W_{opt}, γ_{dmax}, G_s
- **SWCC parameters**
  - **a_f, b_f, c_f, h_r**

Step 3 – SWCC Formation



Step 4 – Update Initial M_r

- Equilibrium condition
- Field moisture condition
- Varying depths, nodes, time

Time (days)

Nodes	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
1	0.8	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	SUBGRADE
2	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	
3	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	
4	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	
5	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	
6	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	
7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	
8	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	

Enhanced Integrated Climatic Model (EICM)

- 1 – dimensional coupled heat and moisture flow program
- Simulates the changes in pavement layers and subgrade due to climatic condition over the years
- Determines Mass – Volume parameters, Soil Water Characteristics Curve (SWCC) parameters based on
  - P_{200} and P_4 (% passing #200 and #4)
  - D_{60} (effective grain size for 60 % passing)
  - PI (plasticity index)

Mass-Volume Parameters

$$S_{opt} = 6.752 * (P_{200} * PI)^{0.147} + 78$$

$$G_s = 0.041 * (P_{200} * PI)^{0.29} + 2.65$$

$$\gamma_{d\,(\max comp)} = \frac{G_s * \gamma_{water}}{1 + \frac{W_{opt} * G_s}{S_{opt}}}$$

where,

G_s = Oven dry specific gravity of soil

S_{opt} = Initial degree of saturation of soil

P_{200}= % passing #200 sieve

PI = Plasticity Index of soil

$\gamma_{d\,(max\,comp)}$ = Maximum dry unit weight of soil

W_{opt} = Optimum gravimetric water content of soil

Mass-Volume Parameters

$$W_{opt} = 1.3 * (P_{200} * PI)^{0.73} + 11 \qquad \text{if } P_{200} * PI > 0$$

$$W_{opt} = 8.6425 * (D_{60})^{-0.1038} \qquad \text{if } P_{200} * PI = 0$$

$$\theta_{opt} = W_{opt} * \gamma_{d\,max}$$

$$\theta_{sat} = \frac{\theta_{opt}}{S_{opt}}$$

where,

W_{opt} = Optimum gravimetric water content of soil

P_{200}= % passing #200 sieve

PI = Plasticity Index of soil

D_{60} = Effective grain size for 60% passing

θ_{opt} = Optimum volumetric water content

θ_{sat} = Saturated volumetric water content

$\gamma_{d\,(max\,comp)}$ = maximum dry unit weight of soil

Soil-Water Characteristic Curve Parameters

$$a_f = \frac{0.00364(P_{200}PI)^{3.35} + 4(P_{200}PI) + 11}{6.895}$$

$$\frac{b_f}{c_f} = -2.313(P_{200}PI)^{0.14} + 5$$

$$c_f = 0.0514(P_{200}PI)^{0.465} + 0.5$$

$$\frac{h_r}{a_f} = 32.44e^{0.0186(P_{200}PI)}$$

if $P_{200} * PI > 0$

where,

P_{200}= % passing #200 sieve

PI = Plasticity Index of soil

Soil-Water Characteristic Curve Parameters

$$a_f = \frac{0.8627(D_{60})^{-0.751}}{6.895}$$

$$b_f = 7.5$$

$$c_f = 0.1772 \ln(D_{60}) + 0.7734$$

$$\frac{h_r}{a_f} = \frac{1}{D_{60} + 9.7e^{-4}}$$

if $P_{200} * PI = 0$

where,

P_{200}= % passing #200 sieve

PI = Plasticity Index of soil

D_{60} = Effective grain size for 60% passing

Soil-Water Characteristic Curve Parameters

$$S_{equil} = C(h) * \frac{1}{\left(\ln\left(EXP(1)+\left(\frac{h}{a_f}\right)^{bf}\right)\right)^{cf}}$$

$$C(h) = 1 - \frac{\ln\left(1+\frac{h}{h_r}\right)}{\ln\left(1+\frac{1.45*10^5}{h_r}\right)}$$

where,

$h = y_{GWT} * \ \gamma_{water}$

S_{equil} = Equilibrium degree of saturation

Effect of Soil Moisture on Resilient Modulus

$$\log\frac{M_r}{M_{Ropt}} = a + \frac{b-a}{1+EXP(\ln\frac{-b}{a}+k_m(S-S_{opt}))}$$

$$\log\frac{M_{R\,equil}}{M_{Ropt}} = a + \frac{b-a}{1+EXP(\ln\frac{-b}{a}+k_m(S_{equil}-S_{opt}))}$$

where,

M_r= Resilient modulus at a given time

M_{Requil} = Equilibrium resilient modulus

M_{Ropt}= Resilient modulus at a reference condition

a, b = Min & max of $\log\frac{\mathrm{M_r}}{\mathrm{M_{Ropt}}}$

k_m = Regression parameter

$S - S_{opt}$= Variation in degree of saturation

Importance of Matric Suction for Pavement Structure

- The Pavement ME Design incorporated the suction in the MR model through NCHRP Project 9-23A:

$$M_R = k_1 P_a \left(\frac{\theta + wc * matric\_suction}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3}$$

where θ is bulk stress, w_c is water content.

Integration of Matric Suction in Pavement ME

- Sensitive models for determination of the Resilient Modulus (Proposed Enhancements to Pavement ME Design, 2019)

Model Type	Model Formulation (detailed definitions of parameters in Appendix B)	Material Type
Moisture-sensitive Model	$\log\frac{M_R}{M_{Ropt}} = a + \frac{b-a}{1+\exp\left[\ln\frac{-b}{a} + k_m\left(S - S_{opt}\right)\right]}$	Granular Base/ Subgrade Soil
Moisture-sensitive and Stress-dependent Model	$M_R = k_2 + k_3\left(k_1 - \sigma_d\right) + k_s\left(u_a - u_w\right)$ $M_R = k_2 + k_4\left(\sigma_d - k_1\right) + k_s\left(u_a - u_w\right)$	Subgrade Soil
Moisture-sensitive and Stress-dependent Model	$M_R = k_1 Pa\left(\frac{I_1 - 3k_4}{Pa}\right)^{k_2}\left(\frac{\tau_{oct}}{Pa}\right)^{k_3}$	Granular Base/ Subgrade Soil

Integration of Matric Suction in Pavement ME

- The Pavement ME suggests the Moisture - sensitive models for determination of the Resilient Modulus (Proposed Enhancements to Pavement ME Design, 2019) (cont.)

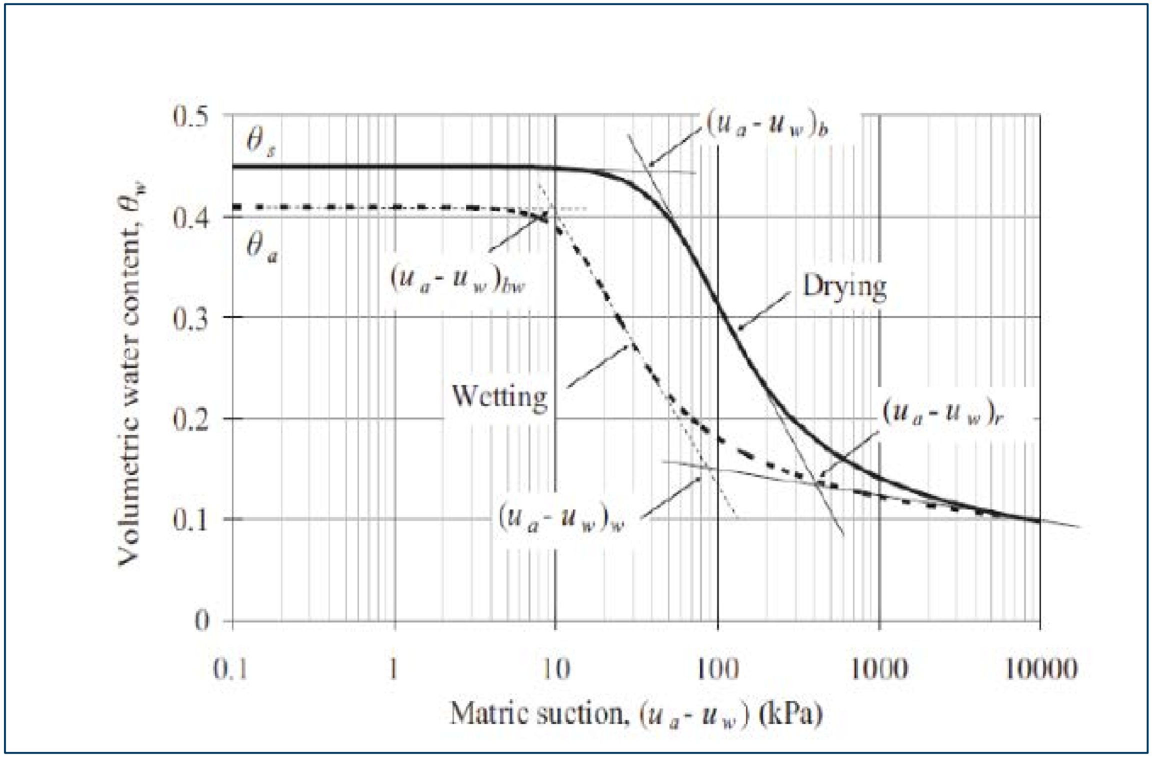
Model Type	Model Formulation (detailed definitions of parameters in Appendix B)	Material Type
Moisture-sensitive and Stress-dependent Model	$M_R = k_1 Pa \left(\frac{I_1 - 3\theta f h_m}{Pa} \right)^{k_2} \left(\frac{\tau_{oct}}{Pa} \right)^{k_3}$	Granular Base/ Subgrade Soil
Moisture-sensitive and Stress-dependent Model	$M_R = k_1 Pa \left[\frac{I_1 - 3\theta f \left(h_m + \beta \frac{I_1}{3} + \alpha \tau_{oct} \right)}{Pa} \right]^{k_2} \left(\frac{\tau_{oct}}{Pa} \right)^{k_3}$	Granular Base/ Subgrade Soil
Moisture-sensitive and Stress-dependent Model	$M_R = k_1 \left(\sigma_d + \chi_w \psi_m \right)^{k_2}$	Subgrade Soil

Integration of Matric Suction in Pavement ME

- The Pavement ME suggests the Moisture - sensitive models for determination of the Resilient Modulus (Proposed Enhancements to Pavement ME Design, 2019) (cont.)

Model Type	Model Formulation (detailed definitions of parameters in Appendix B)	Material Type
Moisture-sensitive and Stress-dependent Model	$M_R = k_1 P_a \left(\frac{\theta + \chi_w \psi_m}{P_a} \right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1 \right)^{k_3}$	Subgrade Soil
Moisture-sensitive and Stress-dependent Model	$M_R = k_1^{'} P_a \left(\frac{\theta_{net} - 3\Delta u_{w-sat}}{P_a} \right)^{k_2^{'}} \left(\frac{\tau_{oct}}{P_a} + 1 \right)^{k_4} \left(\frac{\psi_{m_o} - \Delta \psi_m}{P_a} + 1 \right)^{k_4}$	Granular Base
Moisture-sensitive and Stress-dependent Model	$M_R = k_1 p_a \left(\frac{\sigma_b - 3k_6}{p_a} \right)^{k_2} \left(k_7 + \frac{\tau_{oct}}{p_a} \right)^{k_3} + k_{us} p_a \Theta^{\kappa} \left(\mu_a - \mu_w \right)$	Subgrade Soil

Importance of Matric Suction for Pavement Structure During Freeze-Thaw Cycles



(Albadri et al., 2020)

Effect of Freeze – Thaw Action in Resilient Modulus

- Three factors are introduced to account for base/subgrade resilient modulus due to freeze – thaw action
  - Reduction Factor (RF)
  - Recovery Ratio (RR)
  - Environmental Adjustment Factor (F_{env})

Environmental Adjustment Factor (F_{env})

$$F_F = \frac{M_{Rfzr}}{M_{Ropt}}$$

$$F_R = RF + R_{equil} * RR - RR * RF \qquad \text{if } S_{equil} - S_{opt} < 0$$

$$F_R = R_{equil} * (RF + RR - RR * RF) \qquad \text{if } S_{equil} - S_{opt} > 0$$

$$\log \mathrm{F_U} = \log \frac{M_R}{M_{Ropt}} = a + \frac{b - a}{1 + EXP(\ln \frac{-b}{a} + k_m(S - S_{opt}))}$$

where,

M_R= Resilient modulus at unfrozen / normal condition

M_{Ropt}= Resilient modulus at a reference condition

M_{Rfzr}= Resilient modulus at a frozen condition

Environmental Adjustment Factor (F_{env})

$$M_R = F_{env} * k_1 * p_a * \left(\frac{\theta}{p_a}\right)^{k2} * \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k3}$$

where,

M_R = stress dependent resilient modulus

F_{env} = composite environmental adjustment factor

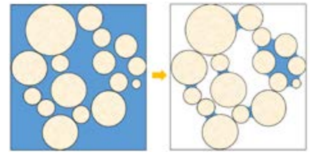
k_1, k_2, k_3= regression coefficients

p_a = atmospheric pressure

θ = bulk stress

τ_{oct} = octahedral shear stress

THANK YOU



Correlations between Unsaturated Soil Parameters and Pavement-ME Design Input

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Assistant Professor
Michigan State University
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NRRA Webinar
May 19, 2020

DEPARTMENT OF TRANSPORTATION

MICHIGAN STATE UNIVERSITY

Department of Civil and Environmental Engineering
UNIVERSITY OF WISCONSIN–MADISON

NRRA
National Road Research Alliance

Relationship between Matric Suction and Stiffness Properties of Materials

- Maximum Shear Modulus – G_{max} (G_o):

Measurement of Shear Wave Velocity ➡ **Shear Modulus**

$$G = \rho \times v_s^{2}$$

where ρ is density and v_s is shear wave velocity.

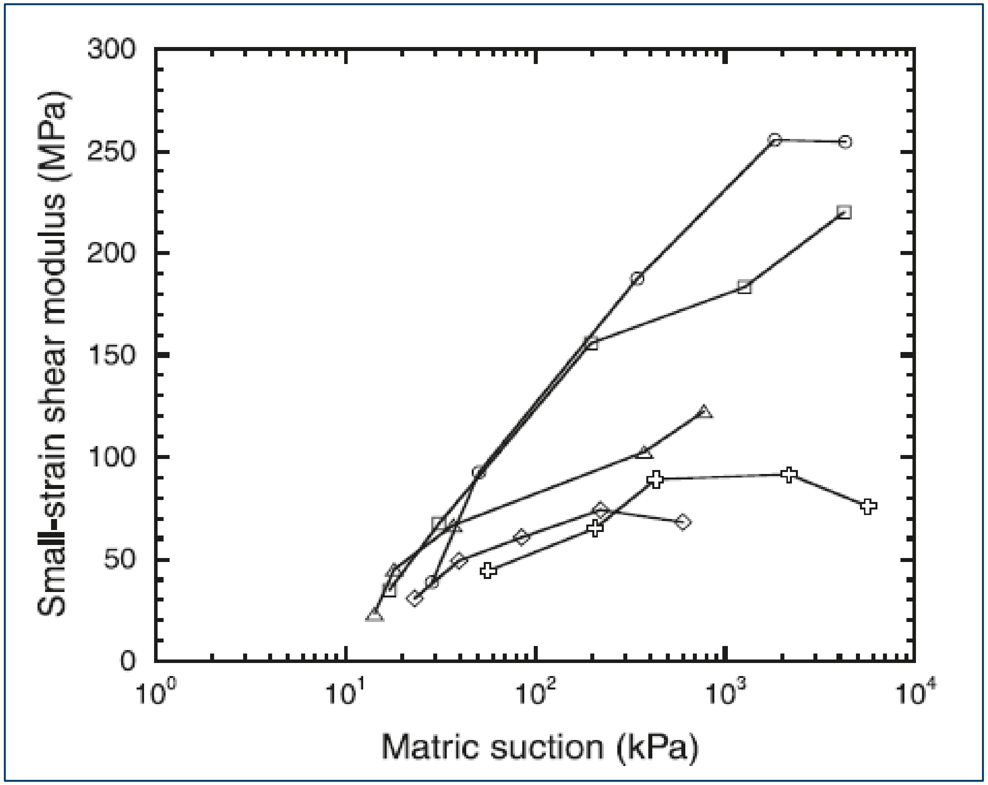
Bender Element

Ultrasonic Velocity Test

Resonant Column

Relationship between Matric Suction and Stiffness Properties of Materials

- Four key factors that directly influence the magnitude of G_{max}
- Void ratio
- Net stress
- **Matric Suction**
- **Saturation degree**



(Sawangsuriya et al. 2008)

Relationship between Matric Suction and Stiffness Properties of Materials

- Effect of wetting and drying cycles on Maximum shear modulus

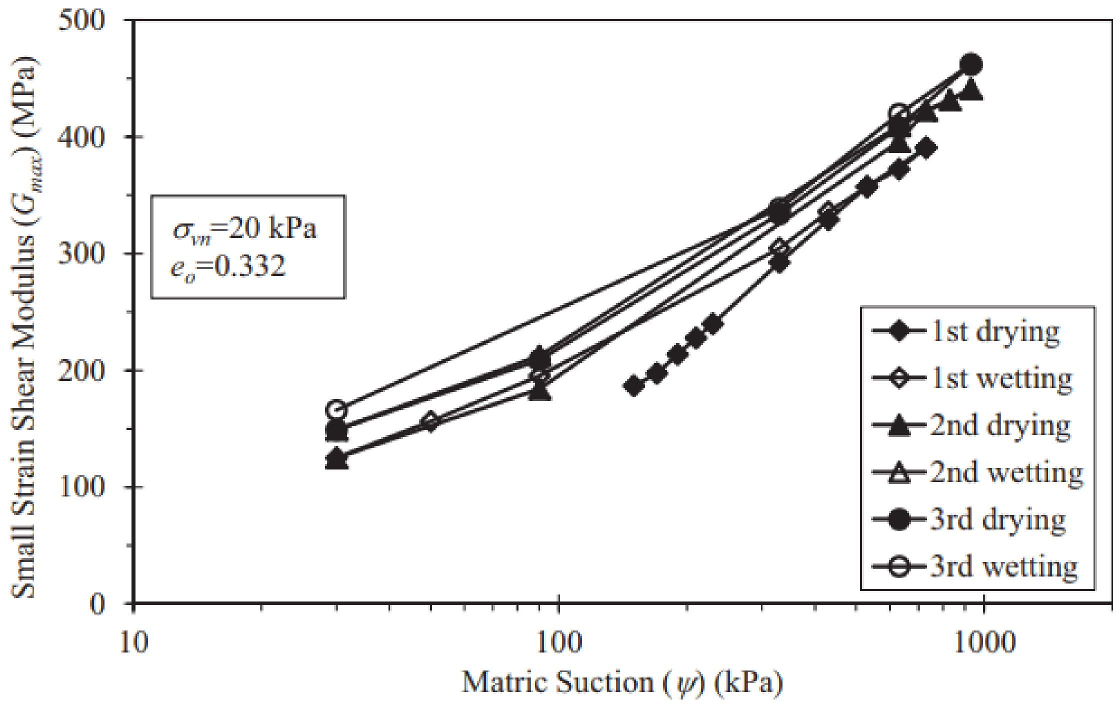


Fig. 11. G_{max}–ψ relationship during the three drying-wetting cycles.

(Ngoc et al., 2019)

Relationship between Matric Suction and Stiffness Properties of Materials

- Correlations between Maximum Shear Modulus and Matric Suction

$$G_{max} = p_r f(e)\left[b_1\left(\frac{\psi S_r}{p_r}\right)^{m_1} + c(1-S_r)^k\right] \text{ for } S_r \geq S_{rs}$$

$$G_{max} = p_r f(e)\left[b_2\left(\frac{\psi S_r}{p_r}\right)^{m_2} + c(1-S_r)^k\right] \text{ for } S_r < S_{rs}$$

Ngoc et al., 2020

$$\frac{G_o}{w\xi\omega} = \alpha \log\psi - \beta$$

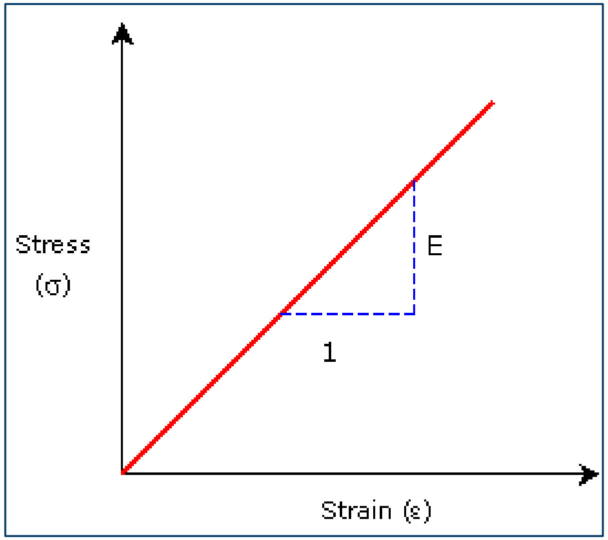
$$G_o = \left(w\frac{E}{E_{std}}\frac{w_{opt}}{w_{opt,std}}\right)(\alpha \log \psi - \beta)$$

Sawangsuriya et al., 2008

Relationship between Matric Suction and Stiffness Properties of Materials

- Young's Modulus - E

Uniaxial test ➡ Stress(σ) – strain relationship(ε) ➡ **Young's Modulus**

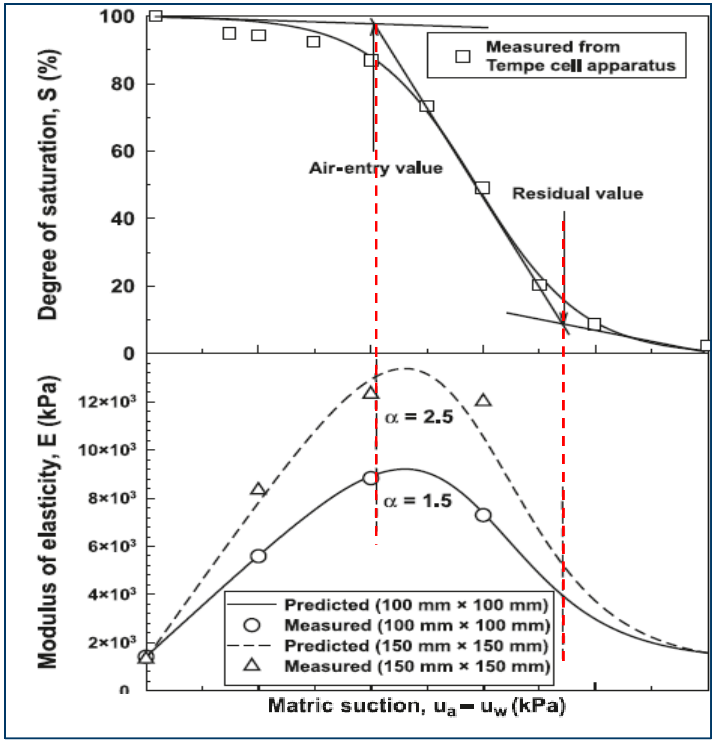


$$E = \frac{\sigma}{\varepsilon}$$

Triaxial Testing

Relationship between Matric Suction and Stiffness Properties of Materials

- Relationship between Young's Modulus and Matric Suction

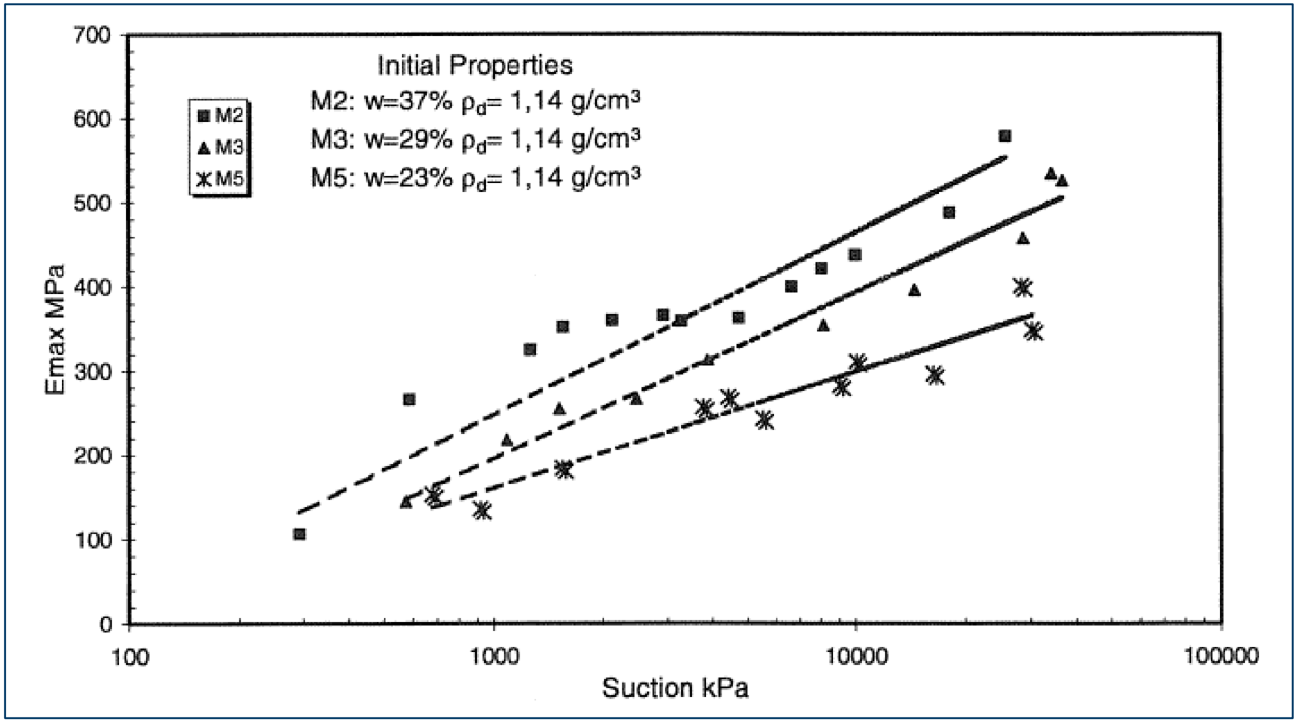


(Oh et al., 2009)

- Moduli of elasticity behavior is different in the three stages of desaturation: the boundary effect zone, transition zone, and residual zone (Vanapalli et al. 1999).
    - Boundary effect zone
    - Transition zone
    - Residual zone

Relationship between Matric Suction and Stiffness Properties of Materials

- Relationship between Young's Modulus and Matric Suction



(Mendoza and Colmenares 2006)

Relationship between Matric Suction and Stiffness Properties of Materials

- Correlations between Modulus of Elasticity and Matric Suction

$$E_{\text{unsat}} = E_{\text{sat}} + E_{\text{sat}}\alpha \frac{(u_{\text{a}} - u_{\text{w}})}{(P_{\text{a}}/100)}(S^{\beta})$$

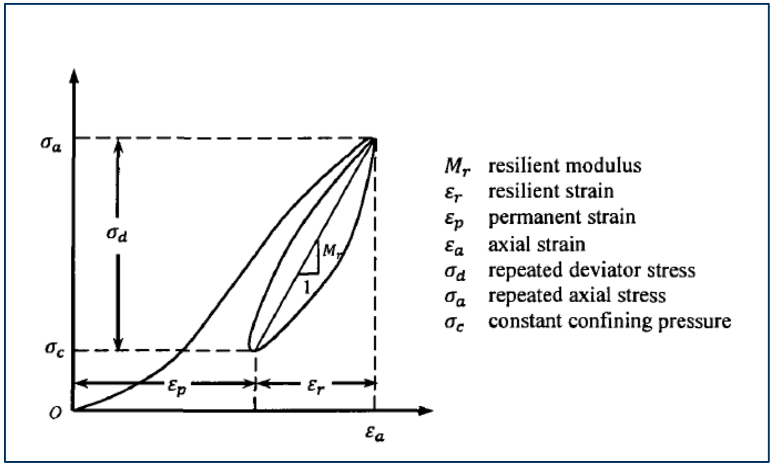
(Oh et al. 2009)

$$E_{max(unsat)} = 30000\,\frac{(2.3-e)^2}{1+e}\left[\ln(u_a - u_w)\right]^{1.35}$$

(Mendoza et al. 2005)

Relationship between Matric Suction and Stiffness Properties of Materials

- Resilient Modulus -M_R



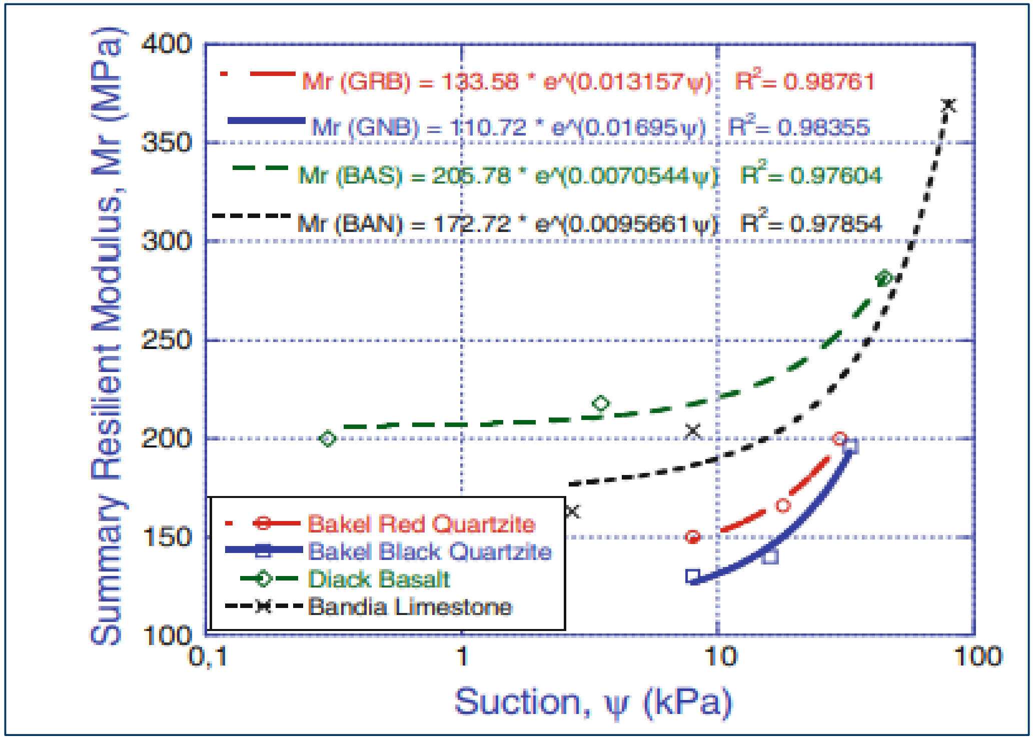
$$M_R = \frac{\sigma_d}{\varepsilon_r}$$

Resilient Modulus Testing Systems

(Yingliu 2010)

Relationship between Matric Suction and Stiffness Properties of Materials

- Relationship between Resilient Modulus and Matric Suction



(Ba et al. 2013)

Relationship between Matric Suction and Stiffness Properties of Materials

- Correlations between Resilient Modulus and Matric Suction

$$M_R/M_{ROPT} = 0.385 + 0.267\log(\psi)$$

Ba et al., 2013

$$M_R = 142 + 16.9\psi$$

Ceratti et al., 2004

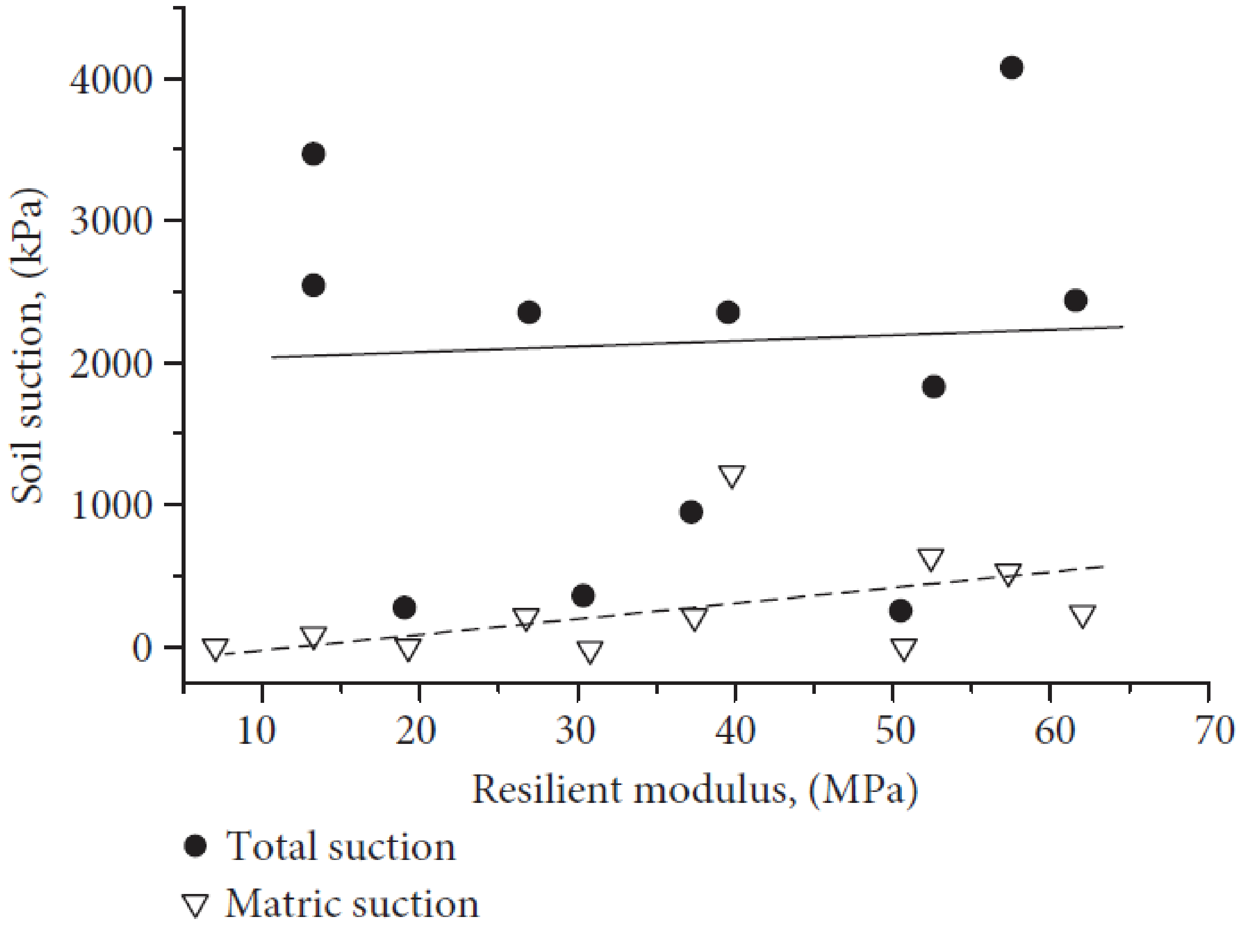
$$M_R = k_1 p_a \left(\frac{\theta_b}{p_a}\right)^{k_2}\left(k_4 + \frac{\tau_{oct}}{p_a}\right)^{k_3} + \alpha_1 \psi^{\beta_1}$$

Khoury et al., 2009

$$M_R = k_1 p_a \left(\frac{\theta_b - 3f\theta\psi}{p_a}\right)^{k_2}\left(\frac{\tau_{oct}}{p_a}\right)^{k_3}$$

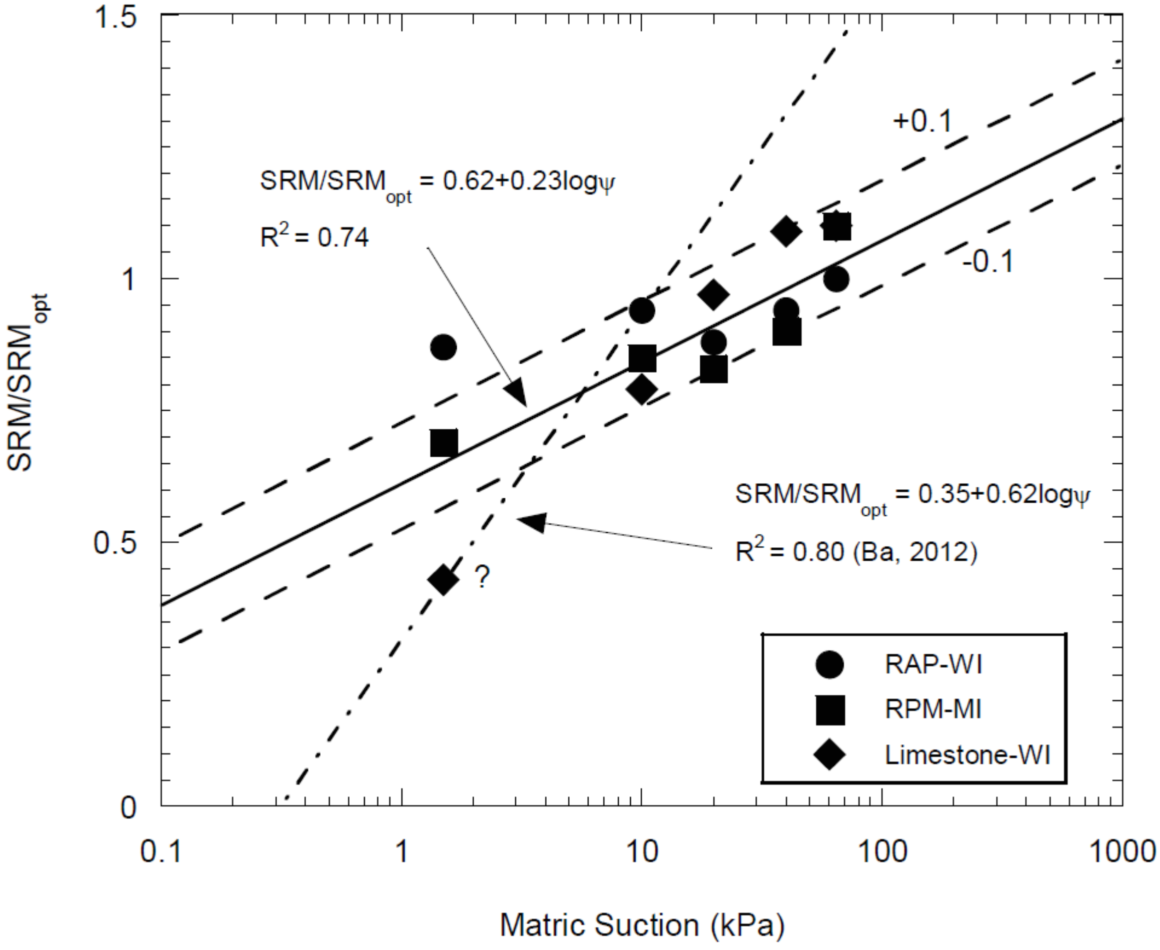
Lytton, 1995

Matric Suction - Modulus



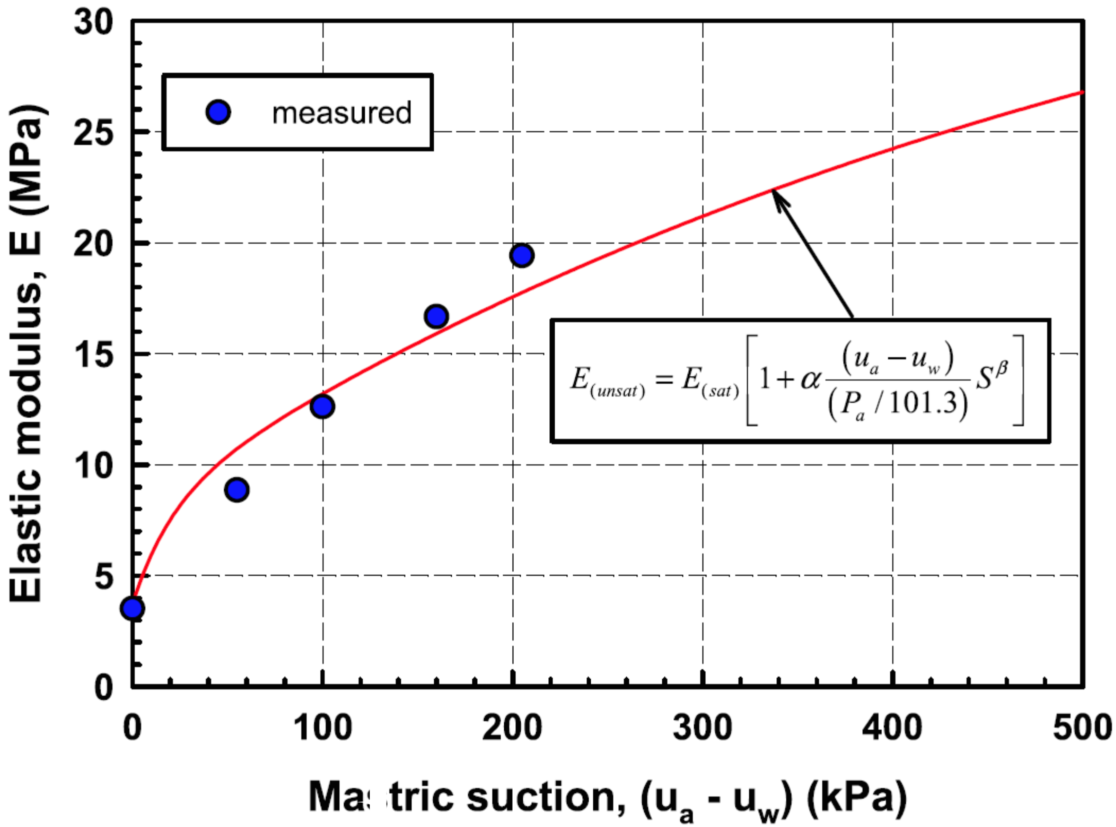
(Chu 2020)

Matric Suction - Modulus



(Nokkaew et al. 2013)

Matric Suction - Modulus



(Oh and Vanapalli 2018)

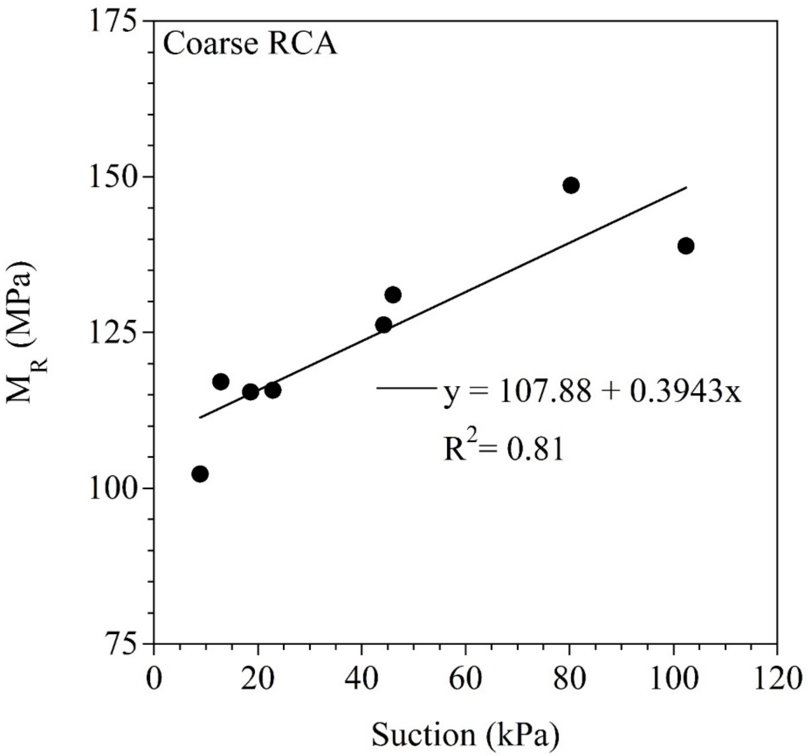
NRRA Funded Project Results

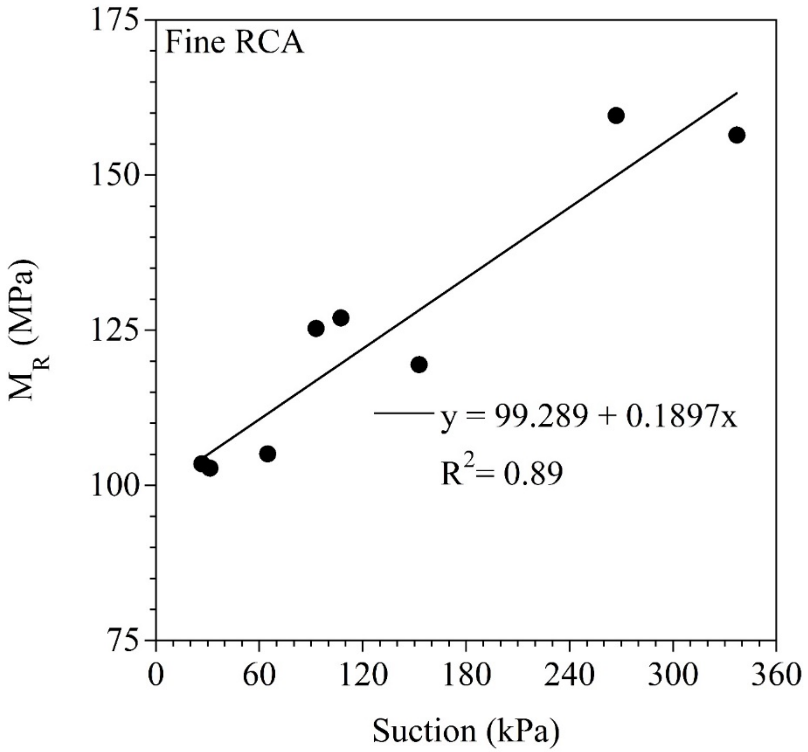
Recycled Aggregate Base				Large Stone Subbase		Large Stone Subbase with Geosynthetics				
185	186	188	189	127	227	328	428	528	628	728
3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave
12 in Coarse RCA	12 in Fine RCA	12 in Limestone	12 in RCA+RAP	6 in Class 6 Aggregate	6 in Class 6 Aggregate	6 in Class 5Q Aggregate	6 in Class 5Q Aggregate	6 in Class 5Q Aggregate	6 in Class 5Q Aggregate	6 in Class 5Q Aggregate
3.5 in S. Granular Borrow	3.5 in S. Granular Borrow	3.5 in S. Granular Borrow	3.5 in S. Granular Borrow	18 in LSSB (1 lift)	18 in LSSB (1 lift)	9 in LSSB TX	9 in LSSB TX+GT	9 in LSSB BX+GT	9 in LSSB BX	9 in LSSB
Sand	Sand	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam

S. Granular Borrow = Select Granular Borrow

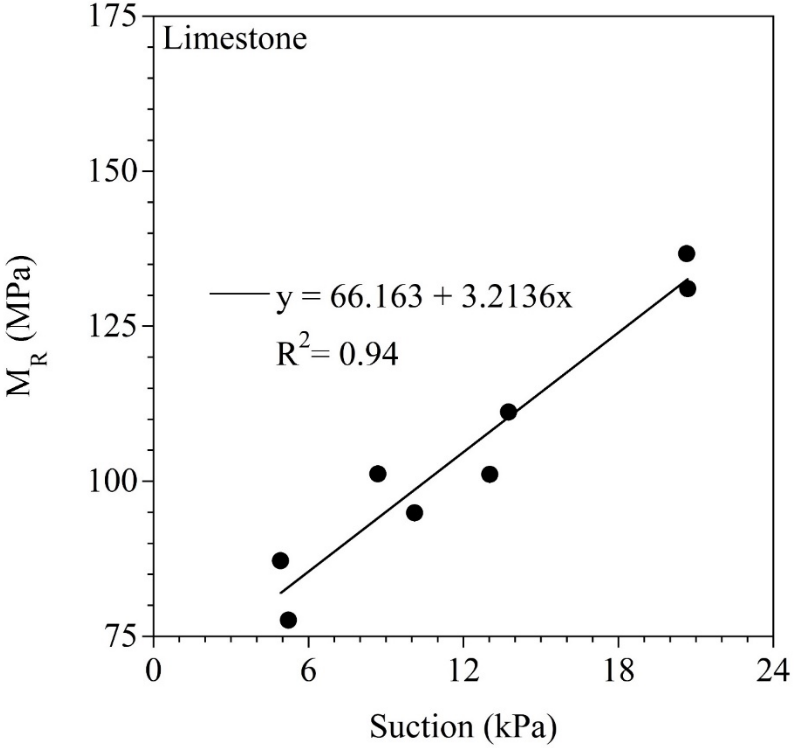
TX = Triaxial Geogrid
BX = Biaxial Geogrid
GT = Nonwoven Geotextile

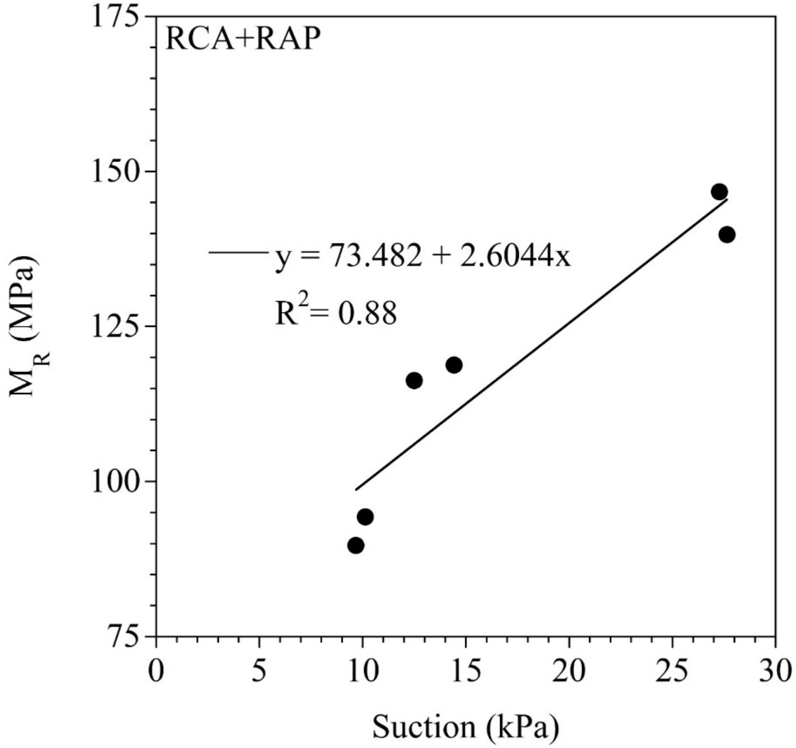
Matric Suction - Modulus





Matric Suction - Modulus





SUMMARY

- Determination of the Resilient Modulus for various **matric suctions / water contents / saturation degree** has a significant effect on the design process of long - lasting pavement structures.
    - The effect of various climate and traffic conditions
    - The moisture-sensitive models

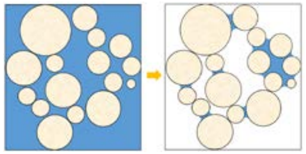
Improved Prediction of the Pavement Response

SUMMARY

- In various engineering designs such as compacted subgrades and support fills for highways, railroads, airfields, parking lots, earthquake resistant structures and foundations the **Soil Modulus** is required.

- Soil Modulus (G_{max}, E, M_R) which represents the stiffness of geomaterials for different cases is related to **Matric Suction.**

Knowing the Effect of Matric Suction will Increase the Accuracy of the Design of Engineering Structures!



Unsaturated Soil Mechanics at MnDOT

John Siekmeier P.E.

NRRA Webinar
May 19, 2020

DEPARTMENT OF TRANSPORTATION
MICHIGAN STATE UNIVERSITY
Department of Civil and Environmental Engineering
UNIVERSITY OF WISCONSIN–MADISON
NRRA National Road Research Alliance

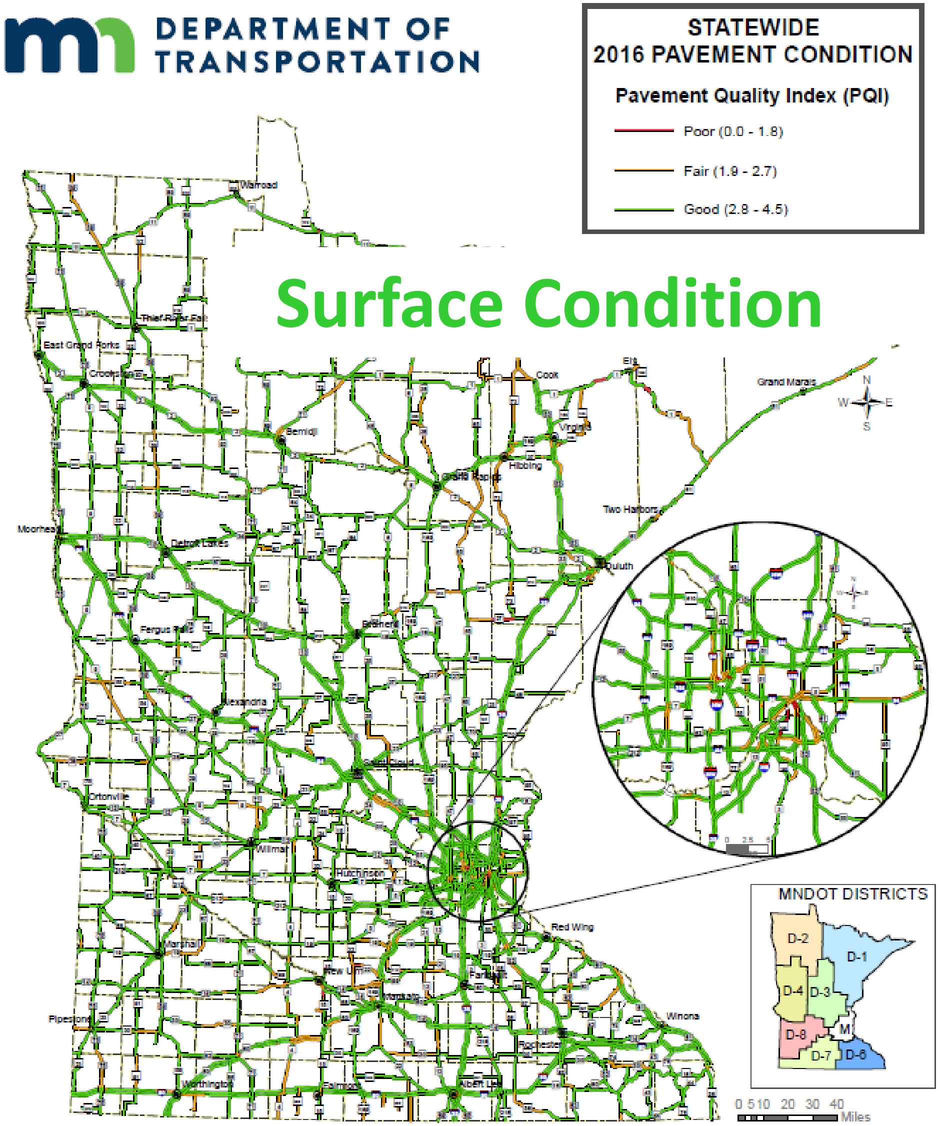
Acknowledgements

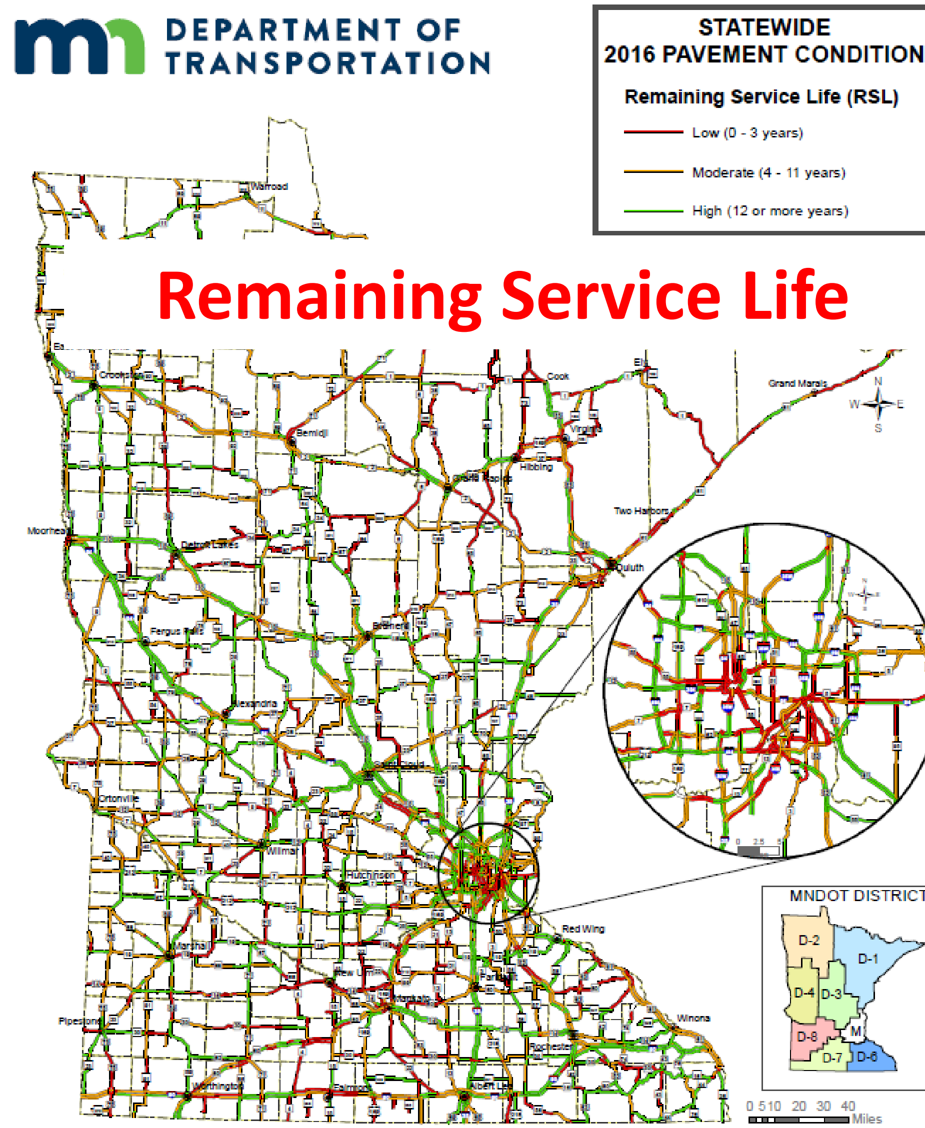
- Counties, Cities and MnDOT Districts
- Federal Highway Administration and State DOTs
- Manufacturers, Contractors and Consultants
- Universities and the National Academies

Outline

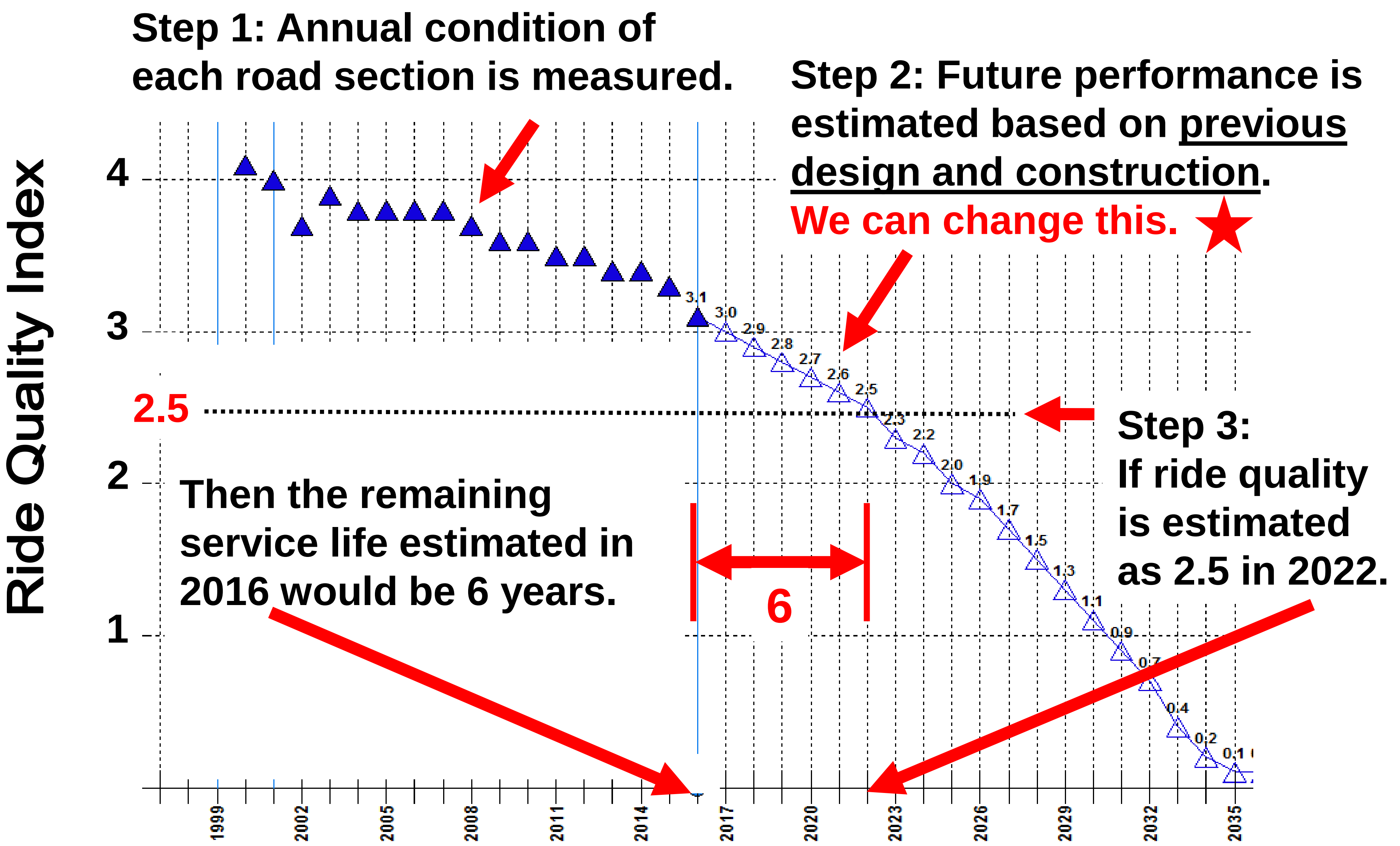
- Pavement Foundations are Important
- Pavement Design Framework
- Performance Based Specifications
- Lessons Learned

Pavement Foundations are Important

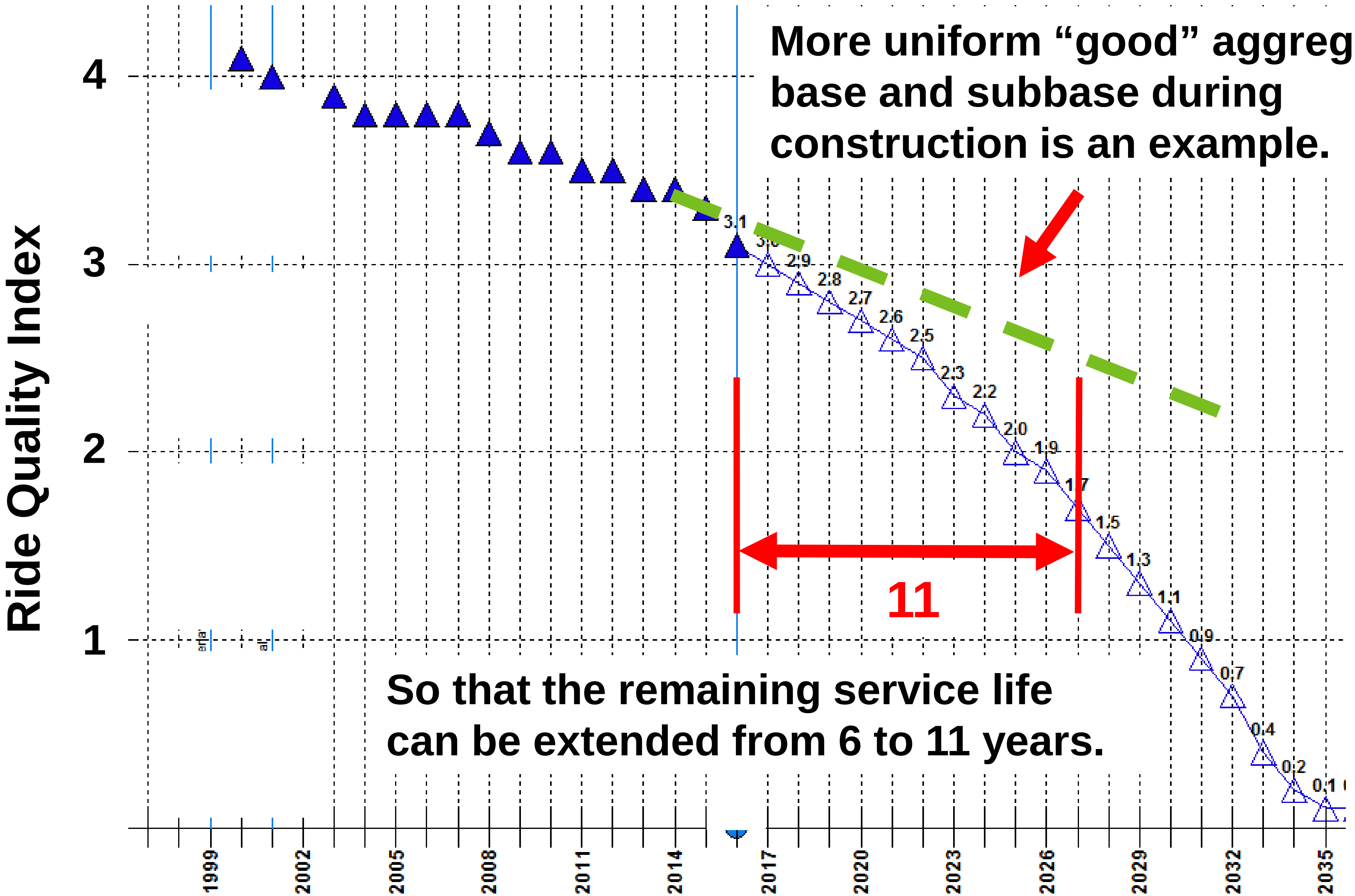




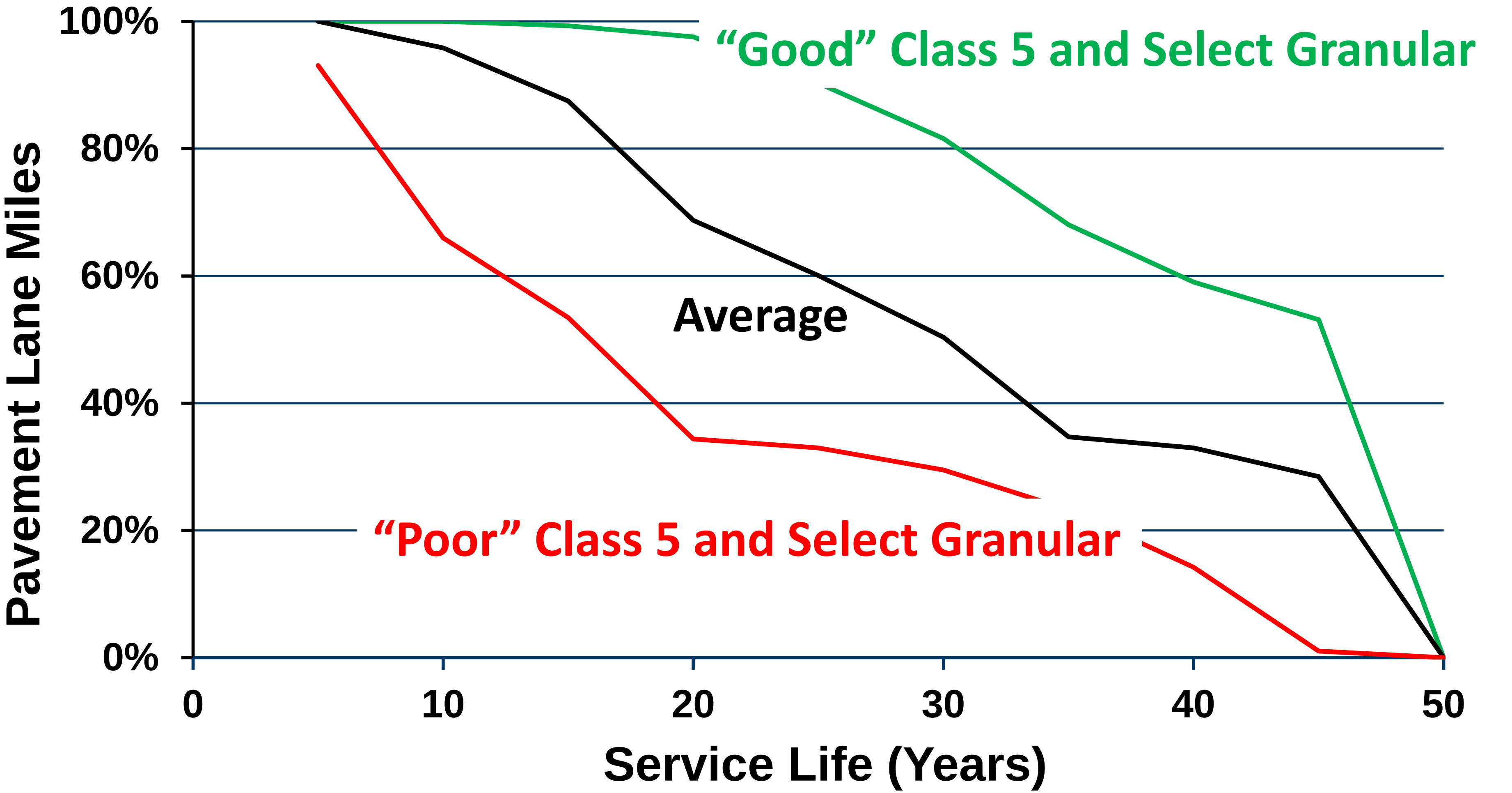
What is Remaining Service Life?



Need to Construct Better Foundations



Importance of Good Base and Subbase



Courtesy of Erol Tutumluer, Best Value Granular Project, July 20, 2010

Cost Effective Pavement Design 2002

DATE: March 20, 2002

TO: District Engineers (DISTENG), District Materials Engineers, District State Aid Engineers (DSAE)
VIA Groupwise

FROM: Gerald J. Rohrbach, Director
Office of Materials & Road Research

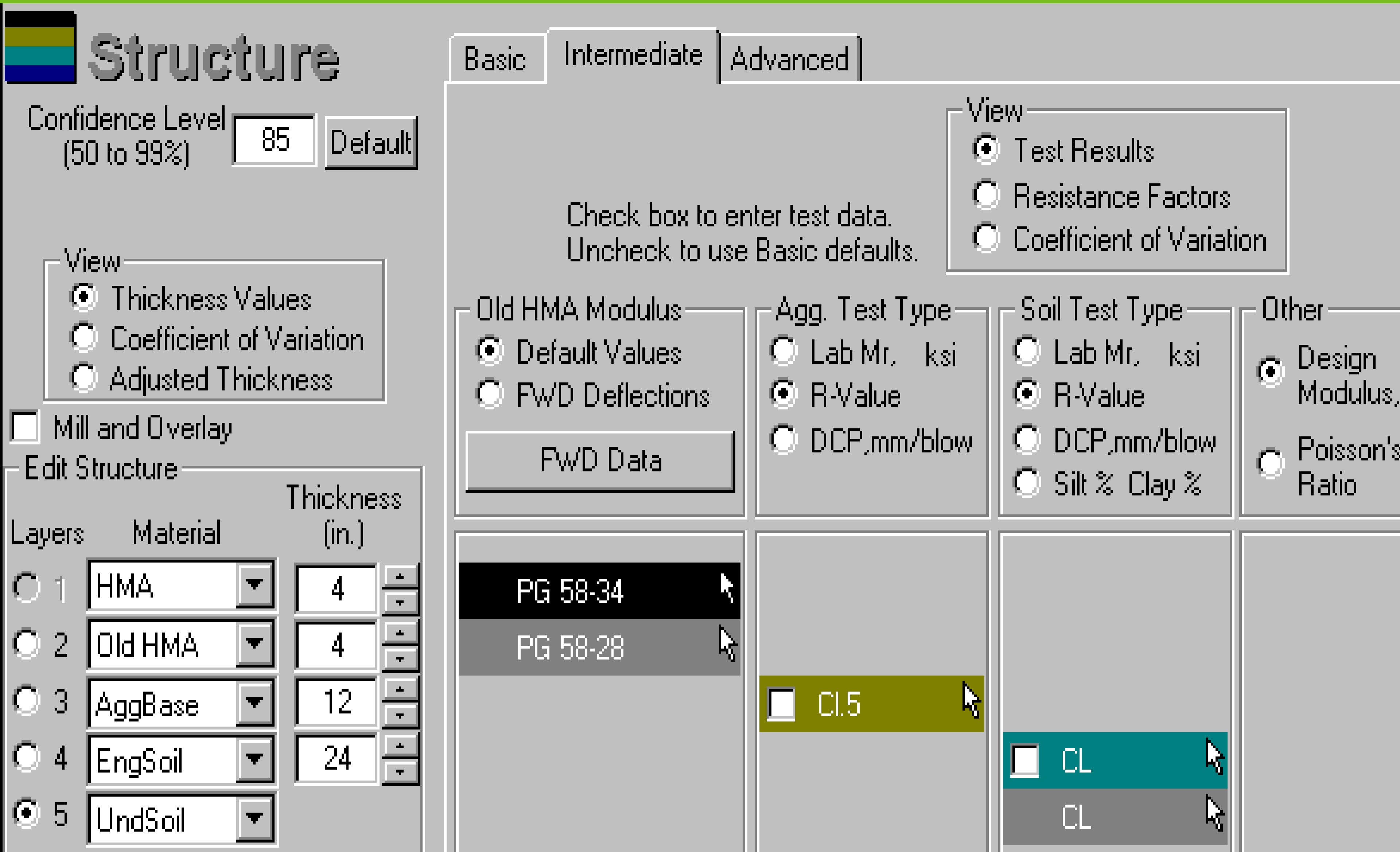
PHONE: 651-779-5590

SUBJECT: **Mn/PAVE – Mechanistic-Empirical Thickness Design Procedure for Flexible Pavements.**

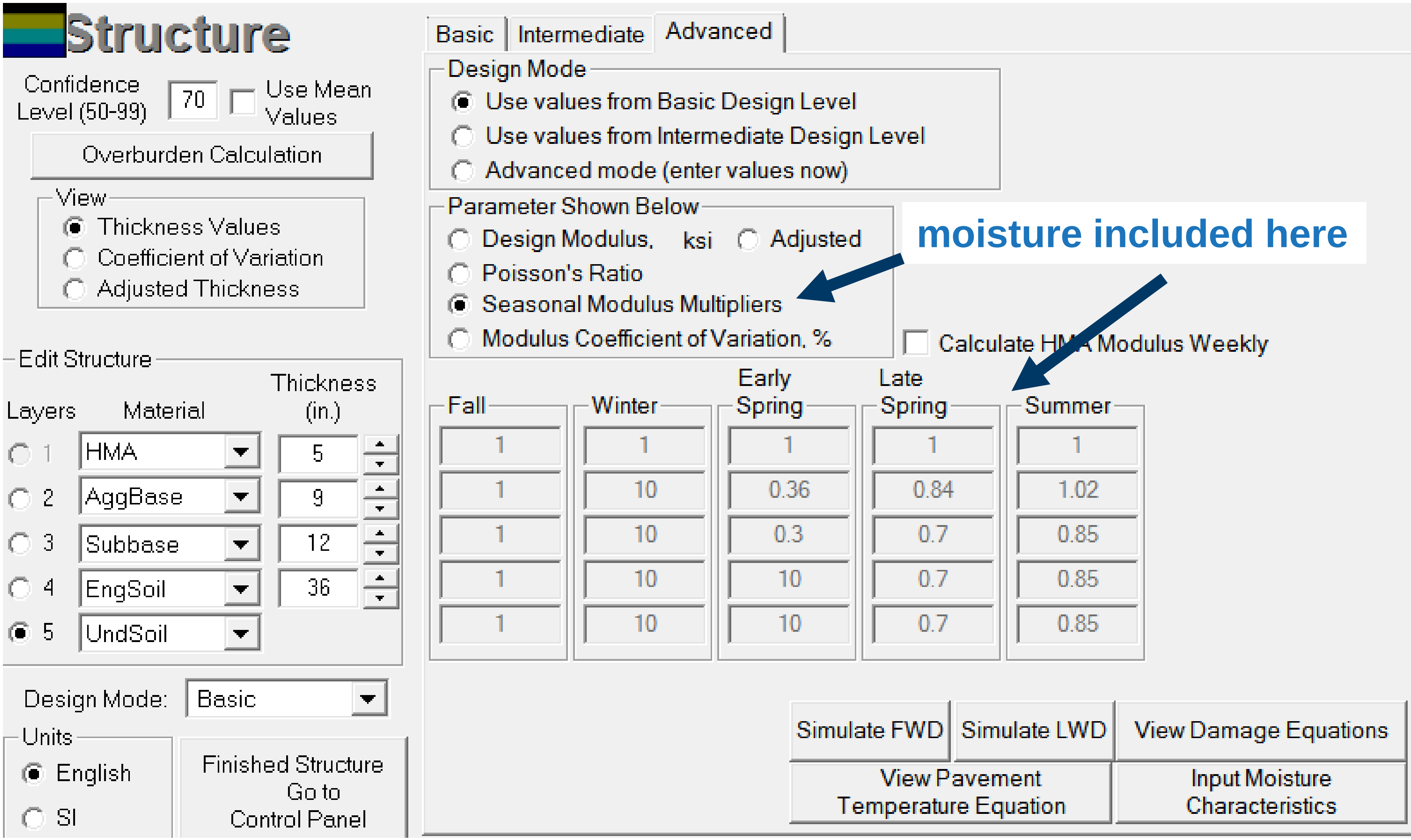
Through cooperative efforts with the University of Minnesota and the Local Road Research Board, the Minnesota Department of Transportation has developed a software program entitled MnPAVE. MnPAVE is a mechanistic-empirical design procedure based on structural analysis of a layered pavement system and is intended for use by state and local agencies. It is now time to move into the training/implementation phase and begin using the design procedure on a trial basis.

MnPAVE has several key advantages over our current Mn/DOT design procedures. These include the capability to 1) adapt to different distress modes, 2) implement better materials tests, 3) adapt to changing load limits and configurations, and 4) achieve agreement between structural and material design. In short, MnPAVE will allow agencies to design and construct more cost-effective flexible pavements.

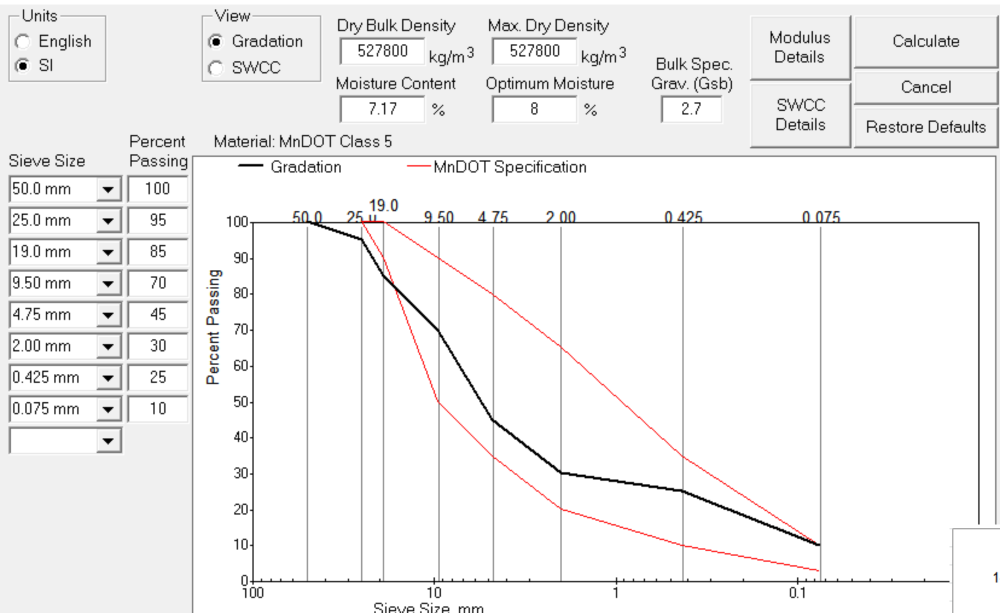
MnPAVE Design Inputs are Layer Thickness and Stiffness

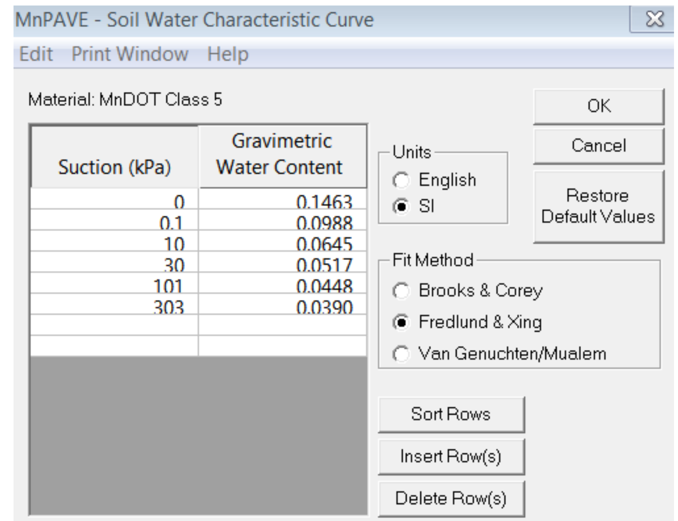


MnPAVE also Requires Moisture Inputs

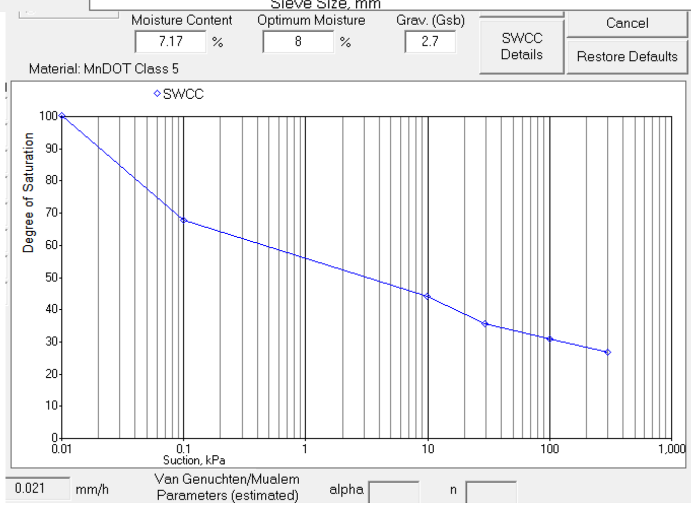


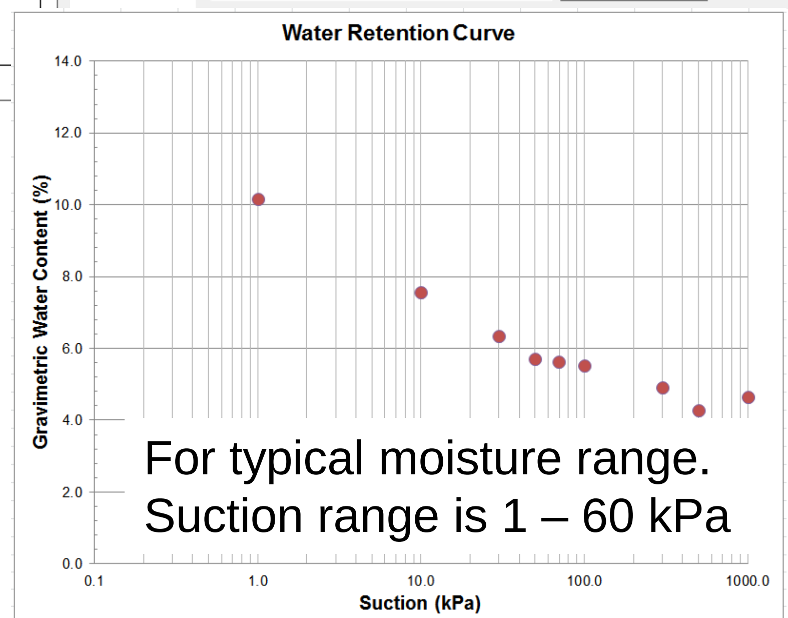
Gradation used to Estimate Suction





Suction (kPa)	Gravimetric Water Content
0	0.1463
0.1	0.0988
10	0.0645
30	0.0517
101	0.0448
303	0.0390





For typical moisture range.
Suction range is 1 – 60 kPa

Moisture Condition Case Studies

Jill Ovik Thesis, 1998
seasonal properties

Ruth Roberson Thesis, 2007
unsaturated geomechanics

Lessons Learned from Case Studies

- Modulus and strength are greatly affected by the moisture between the particles, which causes a suction or tensile stress between the particles.
- Tensile stress between particles depends on:
  - Gradation (quantity of sand, silt, and clay)
  - Particle shape (roughness)
  - Porosity (void space “openness”)
  - Moisture content (how much water is in the voids)

Construction request.
Need to eliminate unsafe Testing

MnPAVE Outputs are Pavement Life and Moisture Corrected LWD Deflections

Plate Diameter 200 mm LWD Resistance Factor 0.67

Applied Load 6.3 kN

Restore Default Values

Units
- English
- SI

Input Data

Exit

Estimated Target Values

Surface Material	Field Modulus (MPa)	Field Resistance Factor	LWD Deflection (mm) at top of Surface Material — Degree of Saturation: Opt.-20%	Opt.-10%	Optimum	Opt.+10%	Opt.+20%
AggBase	180.5	1.15	0.52	0.55	0.60	0.66	0.71
EngSoil	29.98	0.96				X	
UndSoil	19.23	0.75			X		

Simulated using material properties from Intermediate design level.

Performance Based Specifications

Ralph Proctor reminds us.

- Density does not determine strength.
- Optimum moisture is for compaction.
- Need to avoid rutting during construction.

Photo courtesy of Dr. J. David Rogers
Missouri University Science & Technology

Bouquet Canyon Dam 1932-34

Photo courtesy of Dr. J. David Rogers
Missouri University Science & Technology

Ralph Proctor, 1945, Trans 110, ASCE

- “No use is made of the actual peak dry weight.”
- “Methods for hand compaction, such as dropping various weight tampers from different heights and mechanical tampers, were tried and discarded.”
- “The measure of soil compaction used is the indicated saturation penetration resistance.”

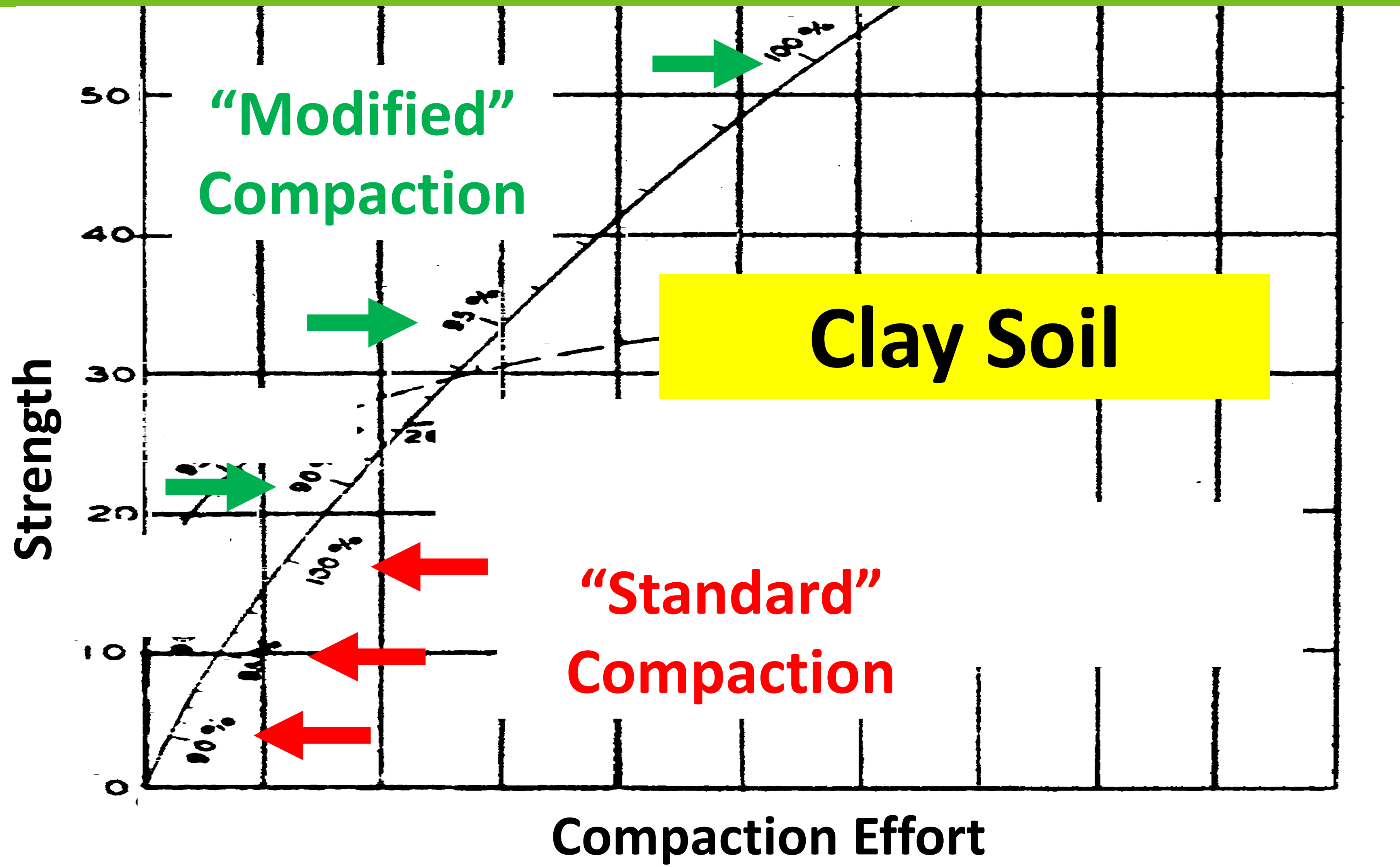
Proctor Penetrometer Performance Test

Photo courtesy of Humboldt

What went wrong during WWII ?
Density was used, not penetration test.

Photo courtesy of Dr. J. David Rogers
Missouri University Science & Technology

Strength Compared to Density, Proctor 1948



Density Does Not Determine Strength

Need Correct Moisture for Compaction

Moisture Content

Dry Density (pcf)	5%	7%	9%	11%	13%	15%	17%	19%	21%	23%	25%
90	15%	22%	28%	34%	40%	46%	53%	59%	65%	71%	77%
95	17%	24%	31%	38%	45%	52%	59%	66%	72%	79%	86%
99	19%	27%	35%	43%	50%	58%	66%	74%	81%	89%	97%
104	22%	31%	39%	48%	57%	66%	74%	83%	92%	101%	109%
109	25%	35%	45%	55%	65%	75%	85%	95%	105%	115%	125%
115	29%	40%	52%	64%	75%	87%	98%	110%	121%	133%	145%
121	34%	48%	61%	75%	88%	102%	116%	129%	143%	156%	170%
127	41%	57%	74%	90%	106%	123%	139%	155%	172%	188%	204%
133	51%	71%	91%	111%	131%	152%	172%	192%	212%	233%	253%
140	65%	91%	118%	144%	170%	196%	222%	248%	274%	300%	327%
147	90%	127%	163%	199%	235%	271%	308%	344%	380%	416%	452%
154	143%	200%	257%	314%	371%	428%	486%	543%	600%	657%	714%

Percent Saturation
120
115
110
105
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20

Courtesy of Soheil Nazarian, 2018 NRRA Pavement Workshop, May 23-24, 2018

Construction Tests Verify Design Properties

Dynamic Cone Penetrometer

ASTM D 6951-03

Grading and Base Manual, MnDOT

Light Weight Deflectometer

ASTM E 2583 07
(includes load measurement)

ASTM E 2835 11
(no load measurement)

Grading and Base
Manual, MnDOT

DCP and LWD
Aggregate Base Target Values

Grading Number	Moisture Content	Dynamic Cone Penetrometer Target Value	Light Weight Deflectometer Target Value
	%	mm / drop	mm
3.1-3.5	5 - 7	10	0.38
	7 - 9	12	0.45
	9 - 11	16	0.60
3.6-4.0	5 - 7	10	0.38
	7 - 9	15	0.56
	9 - 11	19	0.71
4.1-4.5	5 - 7	13	0.49
	7 - 9	17	0.64
	9 - 11	21	0.79

Minnesota LWD Specification

S-47.3 CONSTRUCTION REQUIREMENTS

Compact the entire lift to achieve the LWD-TV per Table 1. Either LWD-TV parameter (Maximum Allowable Deflection or Minimum Allowable Elastic Modulus) may be used, unless specifically designated in the contract. Ensure the same LWD-TV parameter is used throughout the entire project.

Re-evaluate the selected LWD-TV, and contact the Grading and Base Engineer, when failing results consistently occur and adequate compaction is observed through quality compaction.

Table 1: LWD Target Values

Specification	Material Type	Maximum Allowable Deflection (mm)	Minimum Allowable Elastic Modulus (MPa)
2105 or 2106	Granular	0.78	40
	Clay and Clay Loam	1.47	20
2211	Base	0.55	50

MnDOT Detroit Lakes

Indiana LWD Specification

Table 1. Chemically Modified Soils and Aggregate over Chemically Modified Soils

Material Type	Average	Maximum at a Single Location
Lime Modified Soil	≤ 0.30	0.35
Cement Modified Soil	≤ 0.27	0.31
Aggregate over Lime Modified Soil	≤ 0.30	0.35
Aggregate over Cement Modified Soil	≤ 0.27	0.31

Table 2. Aggregate over Untreated Soils Where Proofrolling Can Be Performed

Material Type	Average	Maximum at a Single Location
6 in. Thick Coarse Aggregate No. 53	≤ 0.51	0.57
12 in. Thick Coarse Aggregate No. 53	≤ 0.34	0.40
18 in. Thick Coarse Aggregate No. 53	≤ 0.31	0.35

Table 3. Aggregate over Untreated Soils Where Proofrolling Cannot Be Performed

Material Type	Average	Maximum at a Single Location
6 in. Thick Coarse Aggregate No. 53	≤ 0.60	0.65
12 in. Thick Coarse Aggregate No. 53	≤ 0.47	0.52
18 in. Thick Coarse Aggregate No. 53	≤ 0.44	0.49

AASHTO Draft Specifications

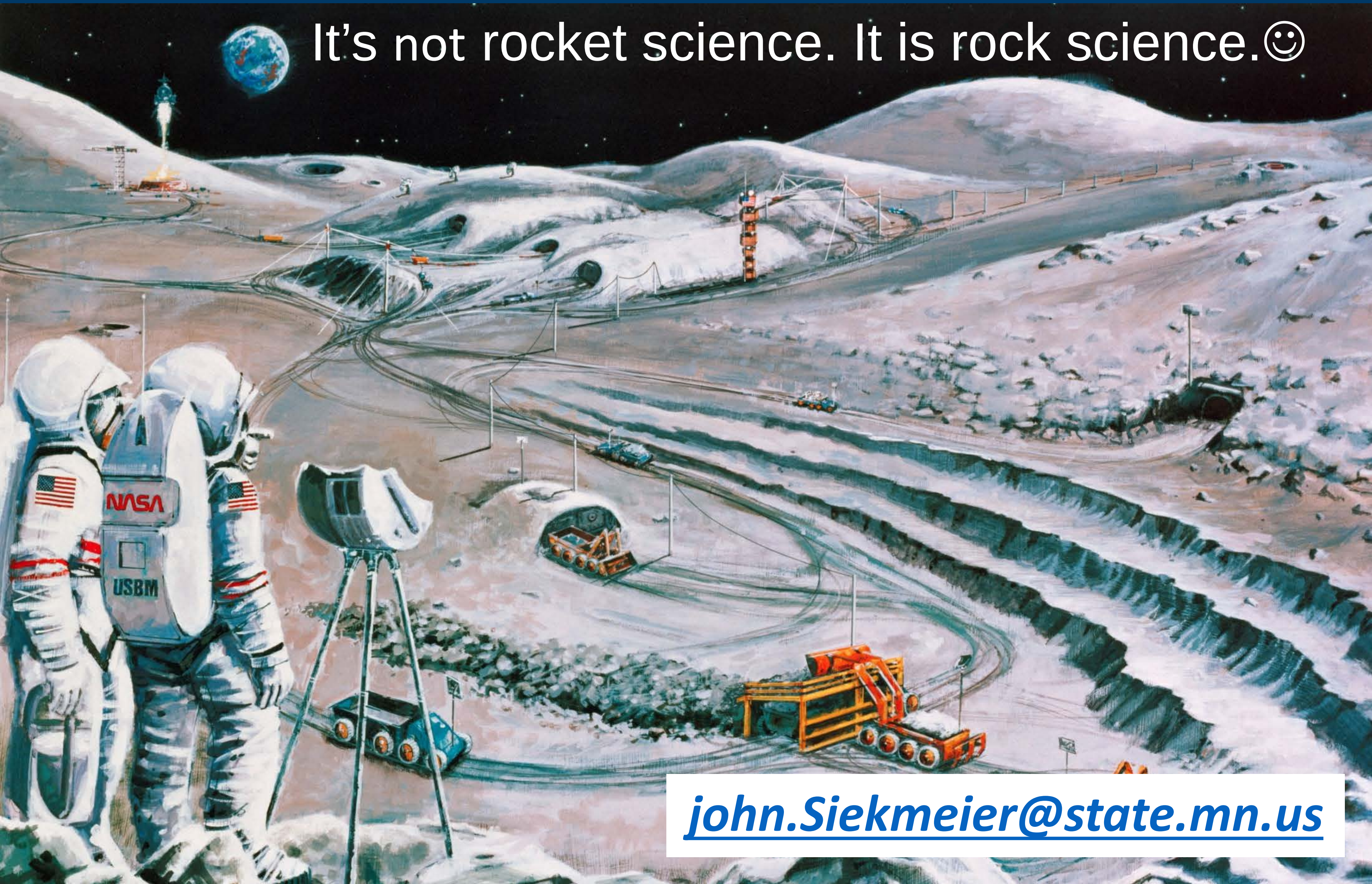
- Just Google “NRRA Geotechnical Team”
- Standard Specification for Quality Management of Earthwork and Pavement Foundation Layers using Modulus
- Acknowledgements
  - Maryland DOT Transportation Pooled Fund 5-285
  - University Texas El Paso NCHRP 10-84
    - NCHRP 24-45 new April 2020

Lessons Learned and Next Steps

- DCPs and LWDs can be used during construction to verify design values.
- It is important to measure moisture because both our ability to compact soils and aggregates, and their long term performance requires knowledge of the moisture content.
- Implementation continues so that the people’s investments are well spent.

Thanks for Listening. Please ask questions.

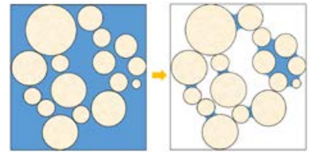
It’s not rocket science. It is rock science.☺



john.Siekmeier@state.mn.us

Moisture Tension in Sand

https://www.youtube.com/watch?v=a-6YbkZJ5UY



Q&A – Applications

All

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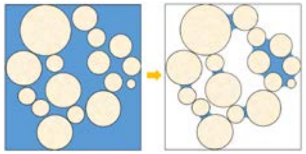

Closing Remarks

Terry Beaudry P.E.

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May 19, 2020

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THANK YOU!