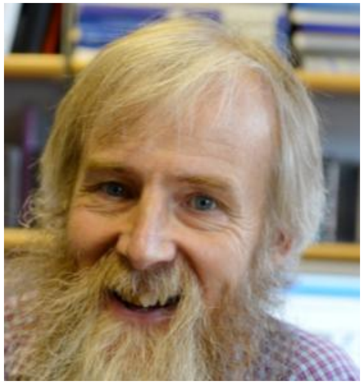
# Moisture & Compaction Measurement during Unbound Aggregate Layer Construction

Hosted by
**Andrew Dawson**
University of Nottingham, UK



*chair, TRB Committee AFP70 "Aggregates"*

# Your presenters

- John Siekmeier
  - Office of Road Research, MnDOT

- Erol Tutumluer
  - University of Illinois, Urbana-Champaign

- Claudia Zapata
  - Arizona State University

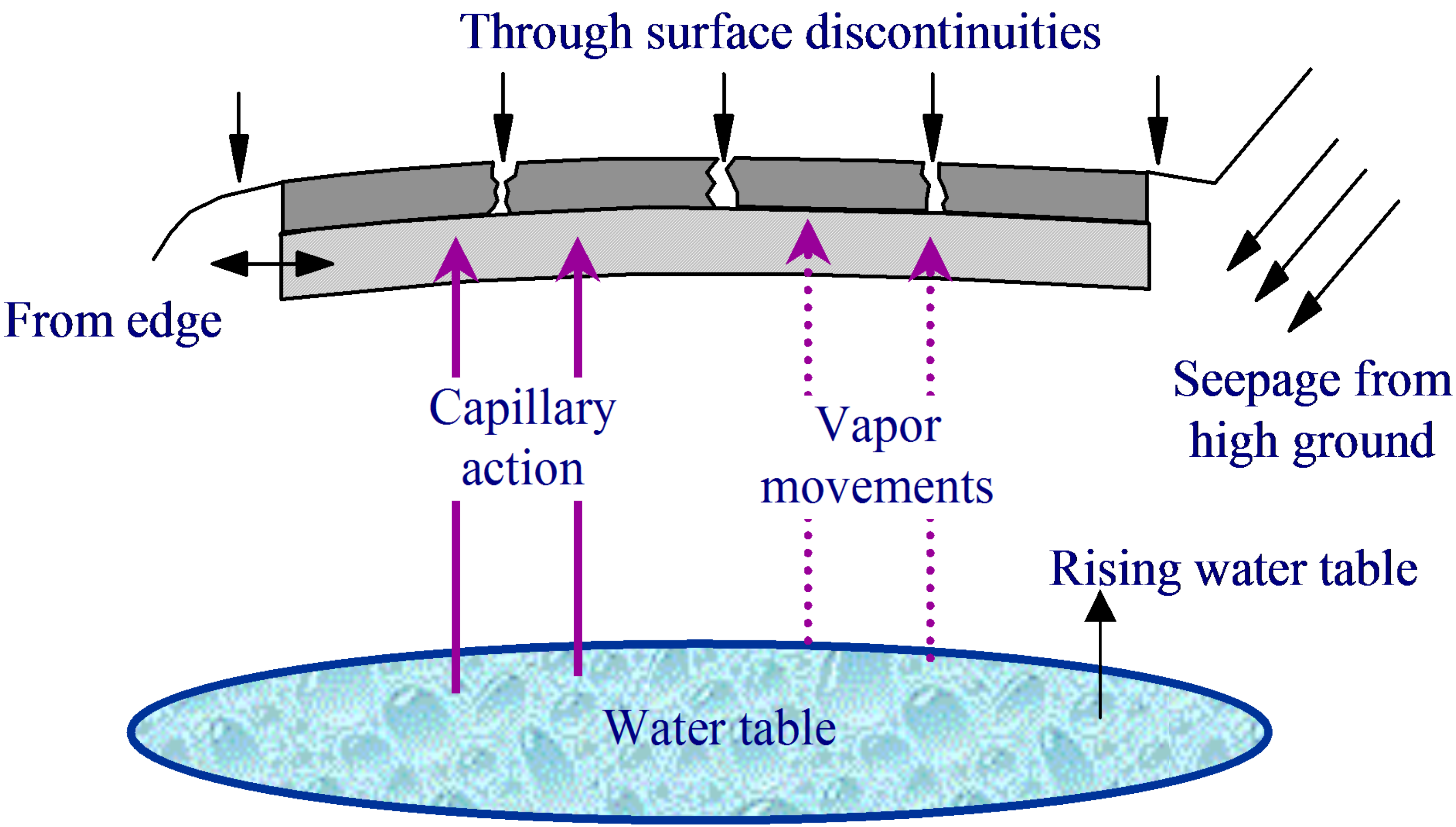
# Today's Content

- Unsaturated Geomechanical First Principles
  - Claudia Zapata 5
- Case Study & Relationship to Pavement Design
  - John Siekmeier 15
- Suction & Moisture Collected at Field Sites
  - Claudia Zapata 9
- Laboratory Measurement of Suction & Relating it to Resilient Modulus
  - Claudia Zapata 10
- Moisture & Compaction Measurement & Field Performance
  - Erol Tutumluer 19

# Unsaturated Geomechanical First Principles

**Claudia Zapata**
Arizona State University

# Sources of Moisture in Pavements

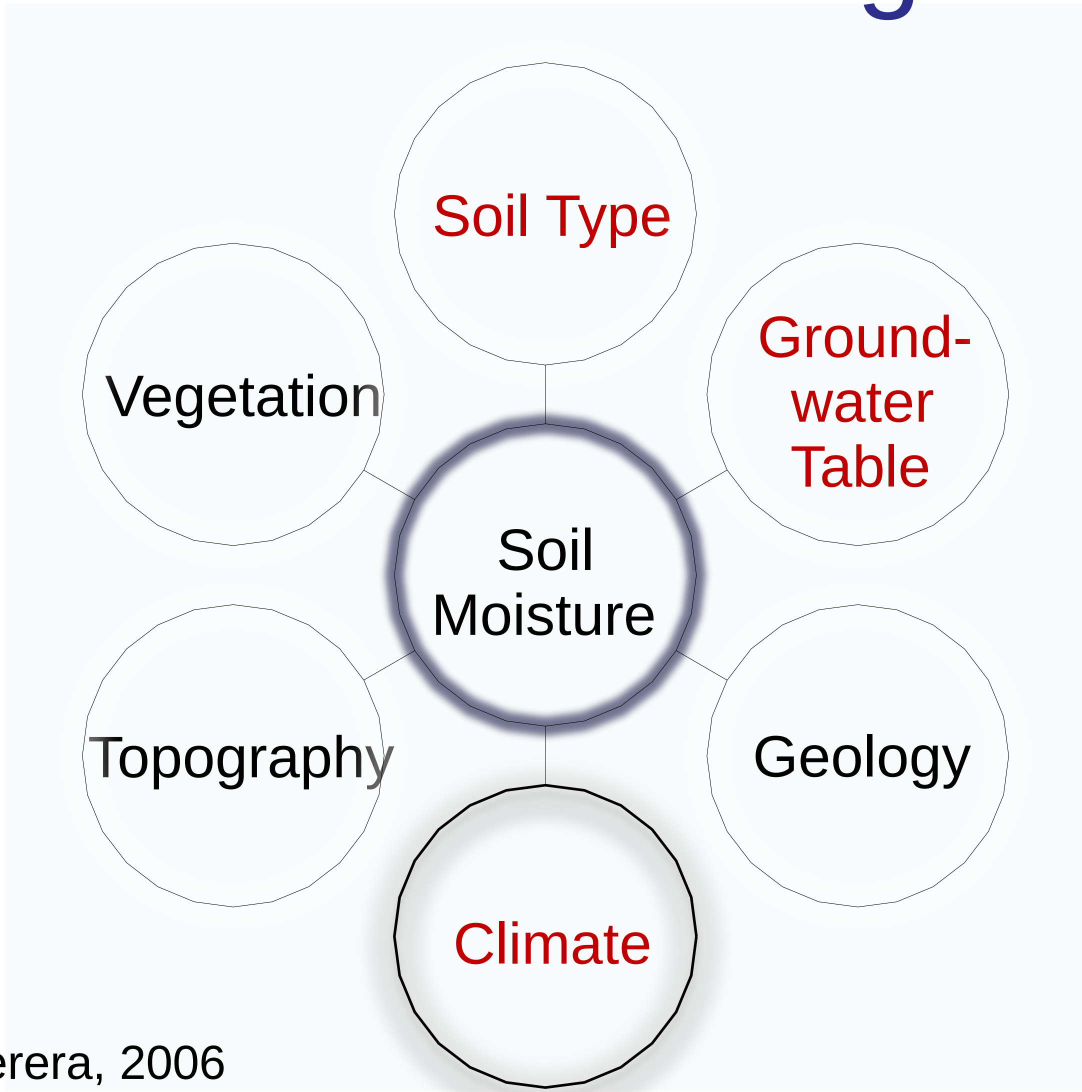


# Key Findings Related to Moisture Effects on Resilient Modulus

Field evidence and numerous numerical modeling studies have shown that even though the pavement structure acts as a cover for the unbound material...

… its moisture content eventually reaches an equilibrium condition, fact that it is greatly influenced by climate and soil properties.

# Controlling Factors

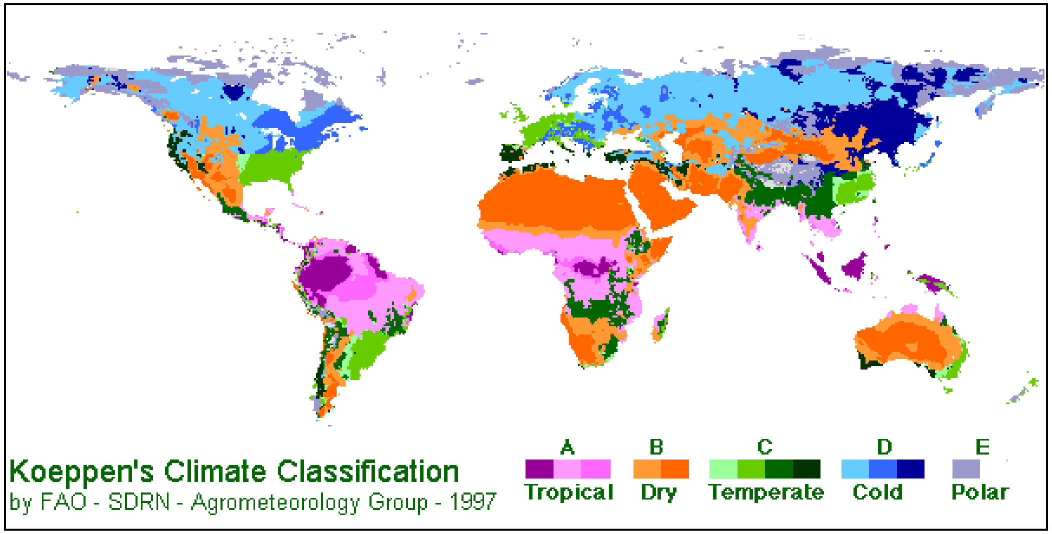


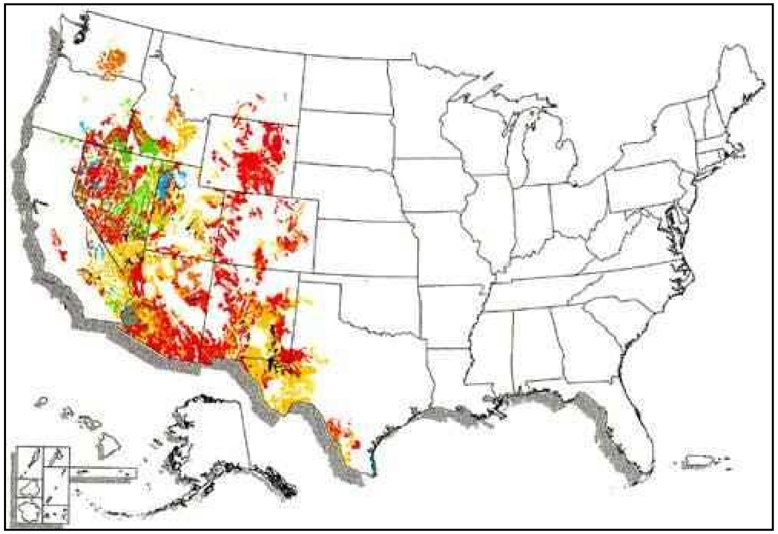

Perera, 2006

- Unbound material reaches an equilibrium condition
  - Climate
  - Soil properties
- Microclimate controls flux boundary conditions

# Unsaturated Soils

- One-third of earth's surface is considered arid or semi arid
- Unbound materials under pavements are generally unsaturated



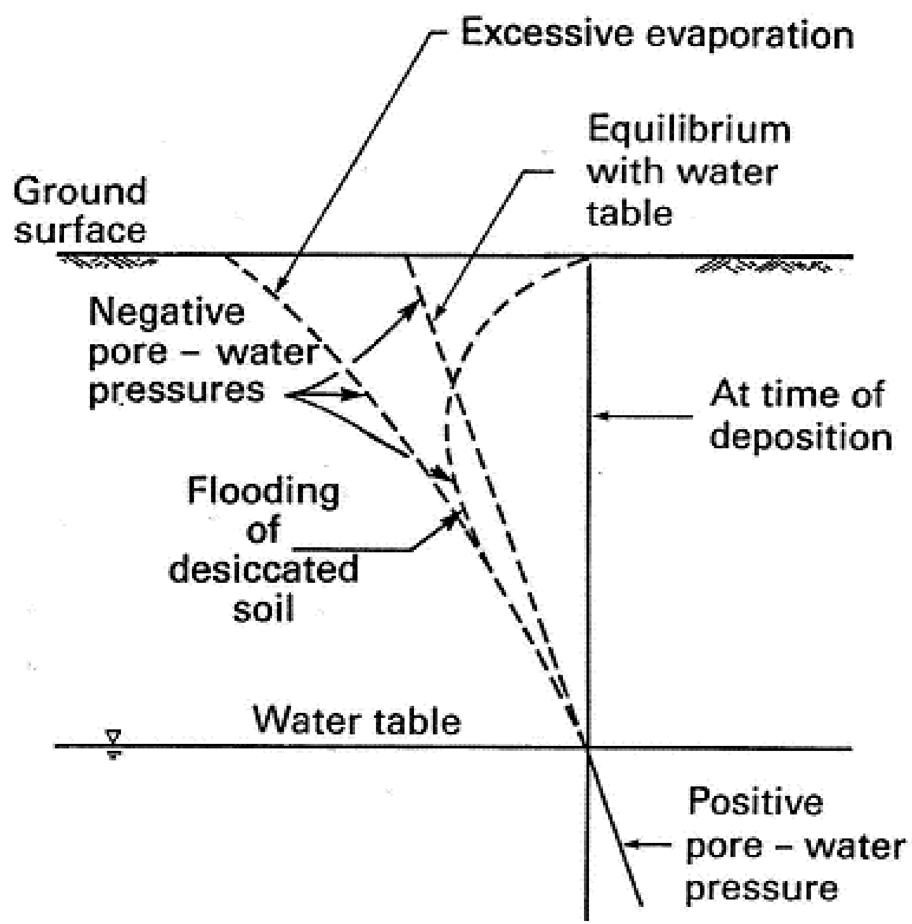
- After decades of focus on saturated soils, the Geotechnical profession has begun to turn its attention to unsaturated soils.

- Construction in unsaturated soils is preferred when practical, due to reduced costs and effort.

- Research community has made substantial advances in understanding fundamental aspects of unsaturated soil behavior.

# Typical Pore Water Pressure Profile

- Matric suction controls the water content in the soil
- If we know the suction at equilibrium, we can approximate the water content at which the soil will try to equilibrate



# Some Case Study & Relationship to Pavement Design

**John Siekmeier**
Office of Materials & Road Research
MnDOT

# Acknowledgements


- Local Agencies and MnDOT Districts
- Other DOTs and Federal Agencies
- Private Sector Consultants
- Product Manufacturers and Contractors
- Universities

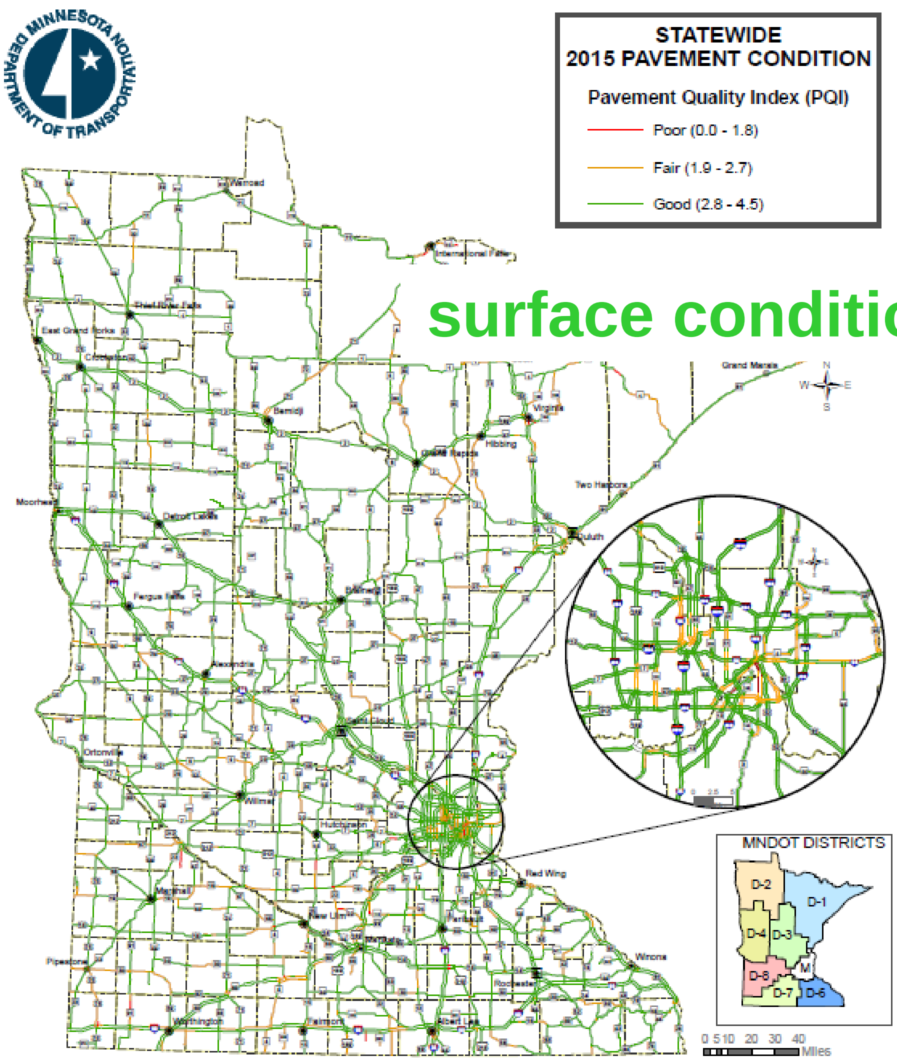
# Current Situation

- Pavement foundations are important and are constructed to avoid saturation where possible.
- MnPAVE is MnDOT's mechanistic pavement design method used to quantify performance.
- Unsaturated geomaterials have greater moduli, which can be used to optimize pavement designs.

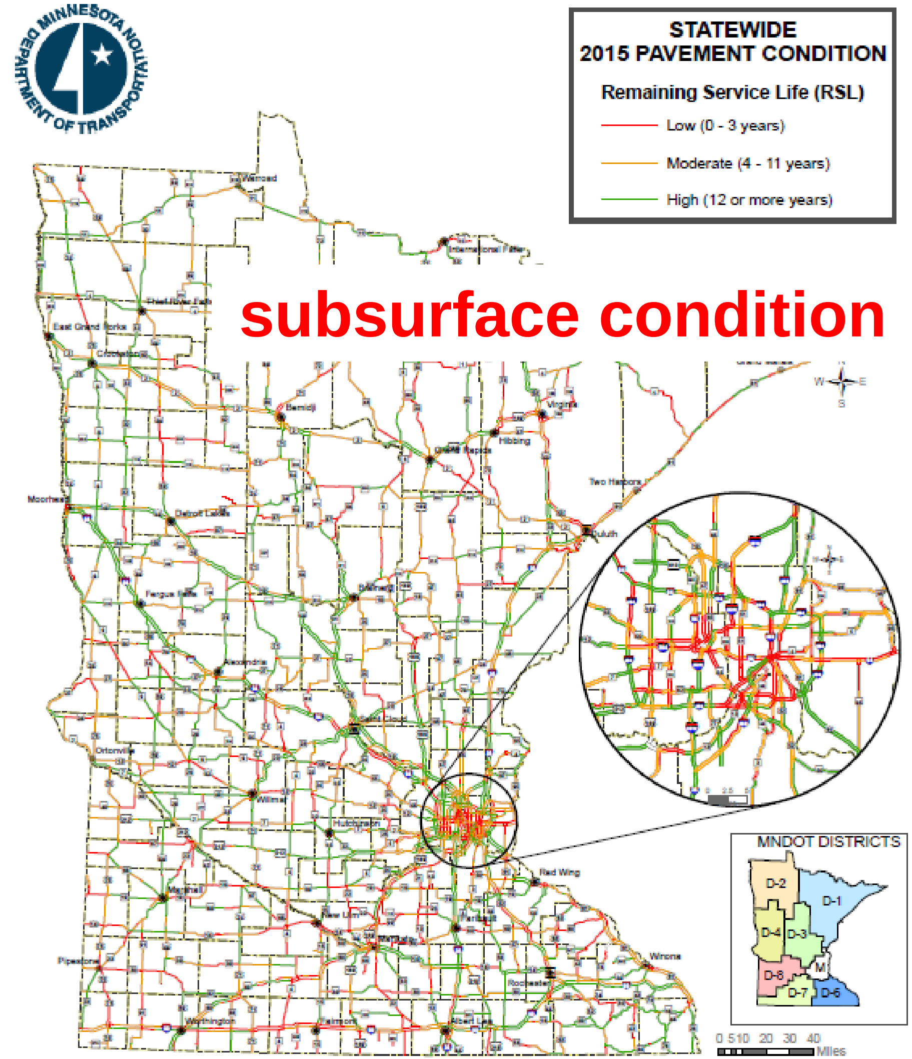
# Project Objective

- Pavement design procedures are modified to better utilize unsaturated geomechanics so that we build more financially effective roadways.

# Pavement Foundations are Important




surface condition




subsurface condition

**Minnesota Department of Transportation**
Office of Materials & Road Research
1400 Gervais Avenue, MS 645
Maplewood, MN 55109

# Memo

TO: PCMG, CMG, MnDOT Districts, Materials Engineers, Soils Engineers, State Aid

FROM: Glenn M. Engstrom, Director
Office of Materials & Road Research

DATE: October 31, 2014

SUBJECT: Pavement Design Manual Publication

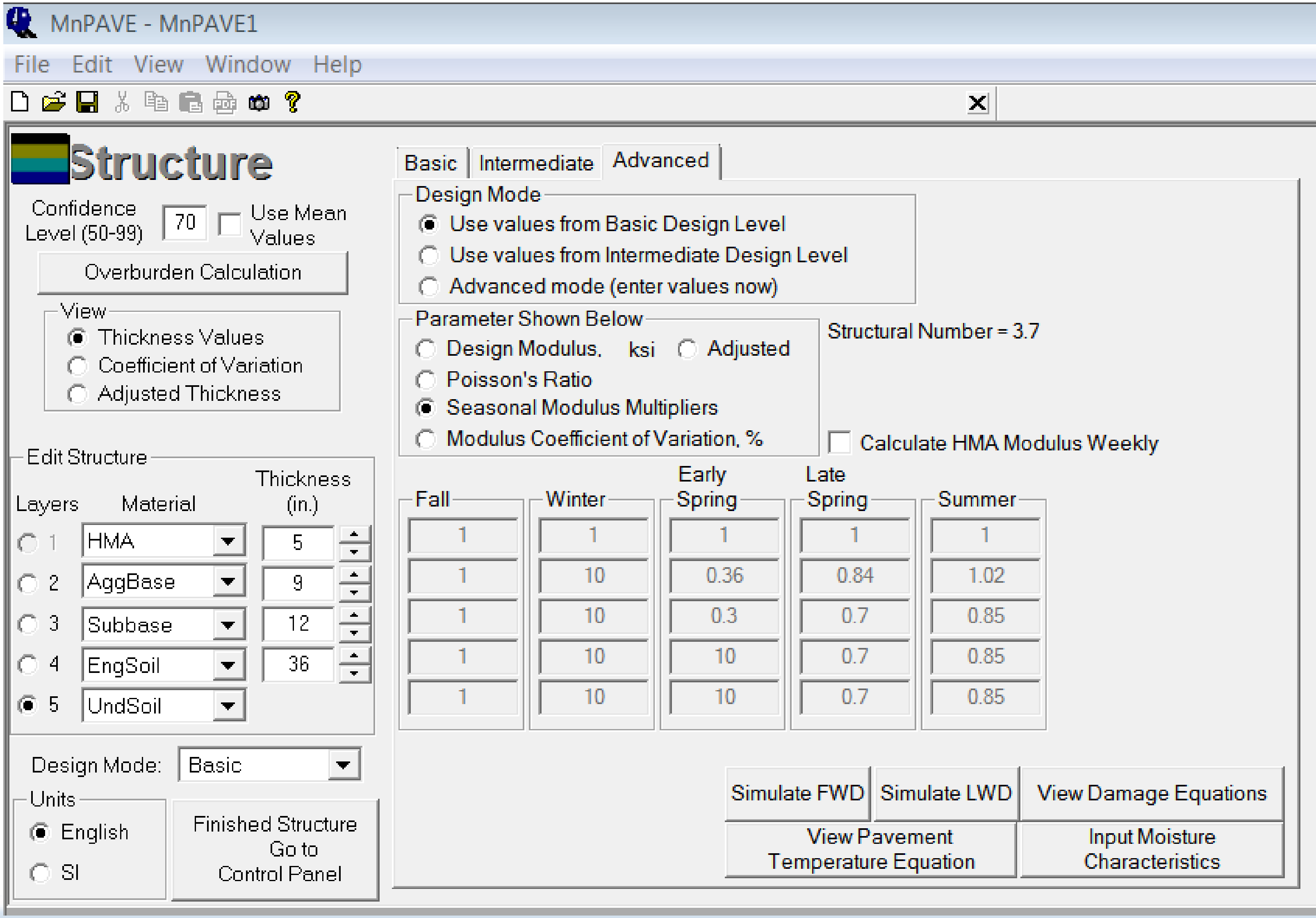
I am pleased to announce the publication of the MnDOT Pavement Design Manual.

This publication represents a significant effort to update pavement design procedures and codify existing documents into a single point of reference. As of November 1, 2014, all MnDOT pavement designs shall follow the pavement design, pavement-type selection, LCCA, and alternate bidding as laid out in the Pavement Design Manual. To view the manual, please follow http://www.dot.state.mn.us/materials/pvmtdesign/newmanual.html

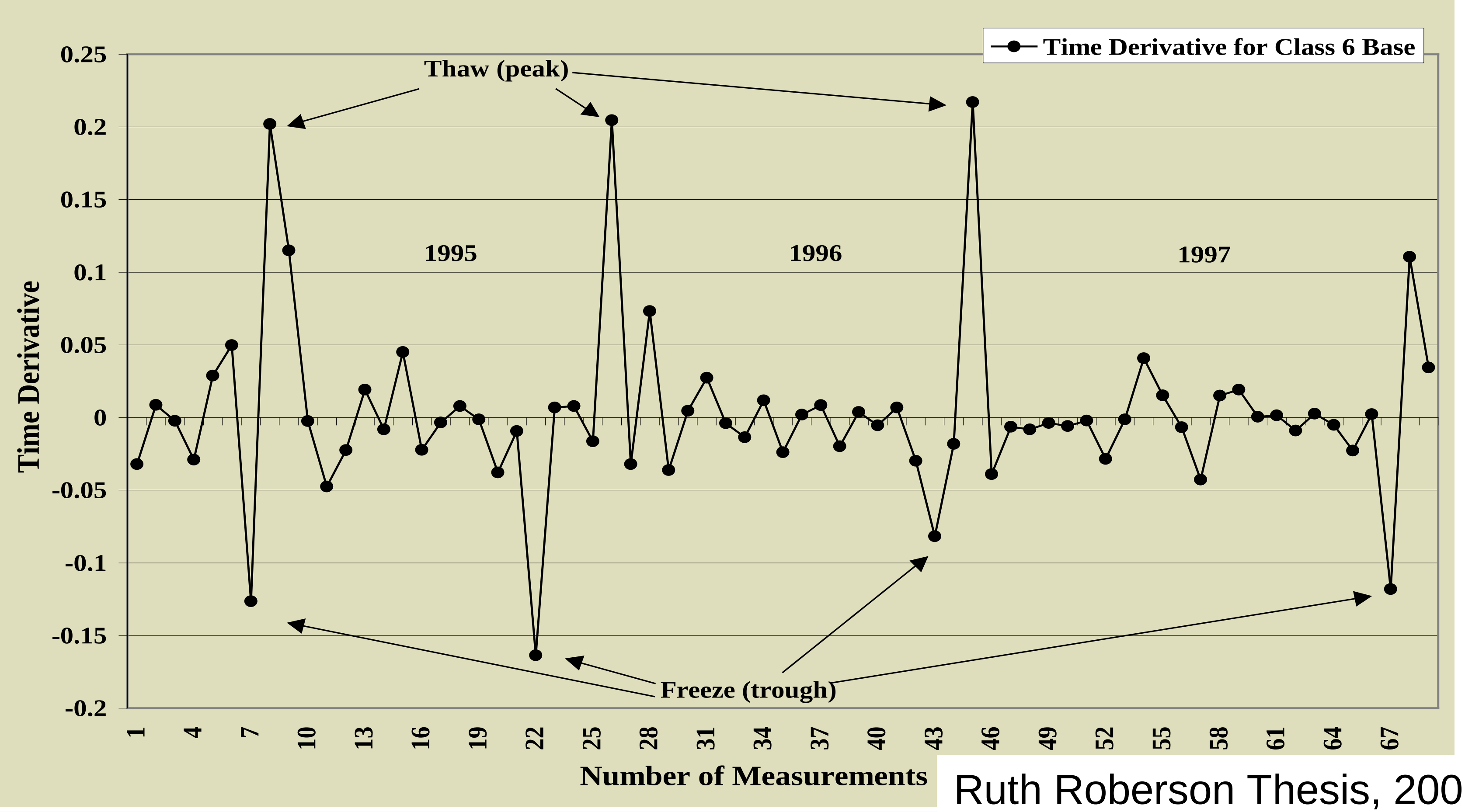
# Mechanistic Pavement Design

- Provides the framework for using performance based material properties
- Free pavement design software available http://www.dot.state.mn.us/app/mnpave/index.html
- Just Google "MnPAVE"

# Need Mechanistic Design Inputs



# Need Seasonal Change in Aggregate Water Content



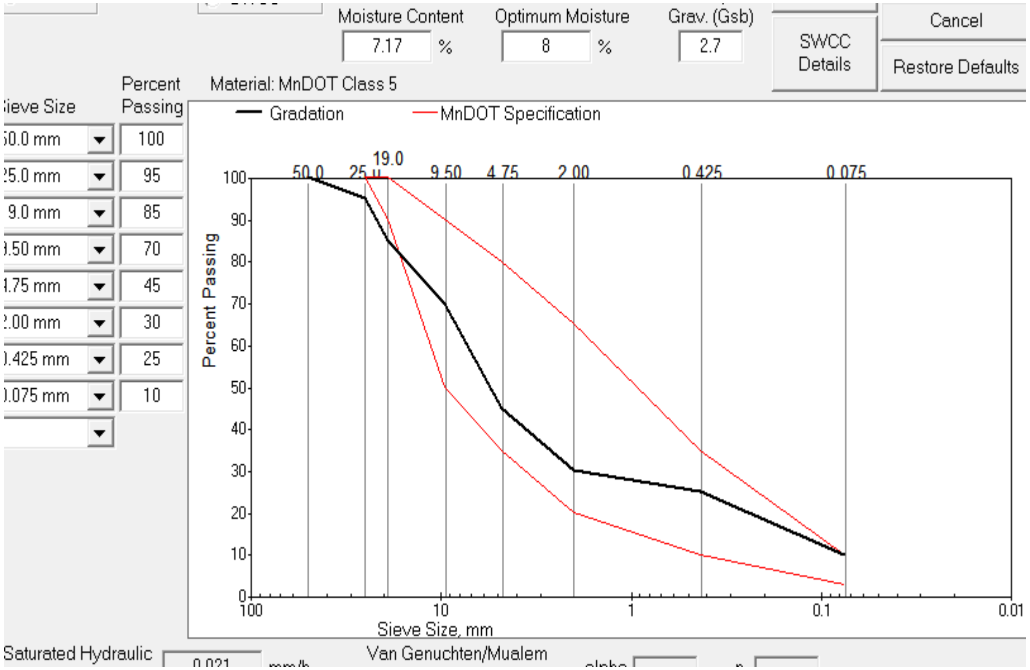

Ruth Roberson Thesis, 2007

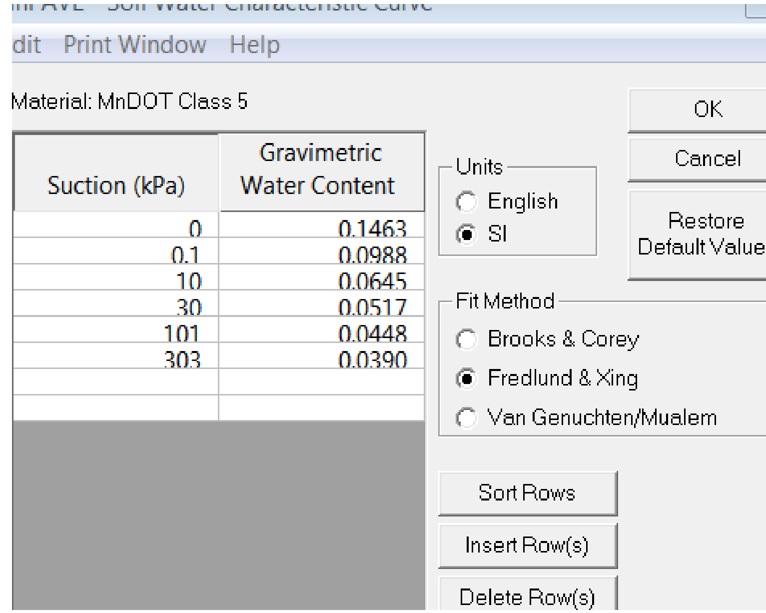
# MnROAD Test Section Case Studies

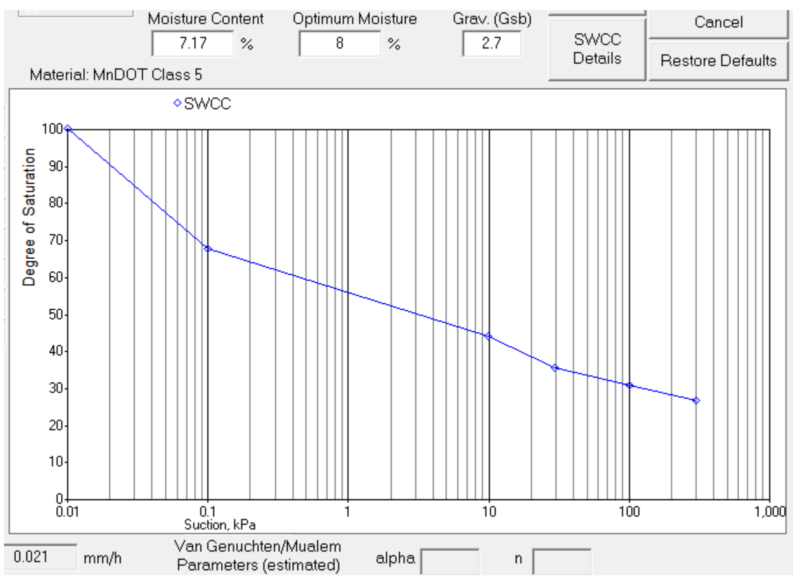
Ruth Roberson Thesis, 2007

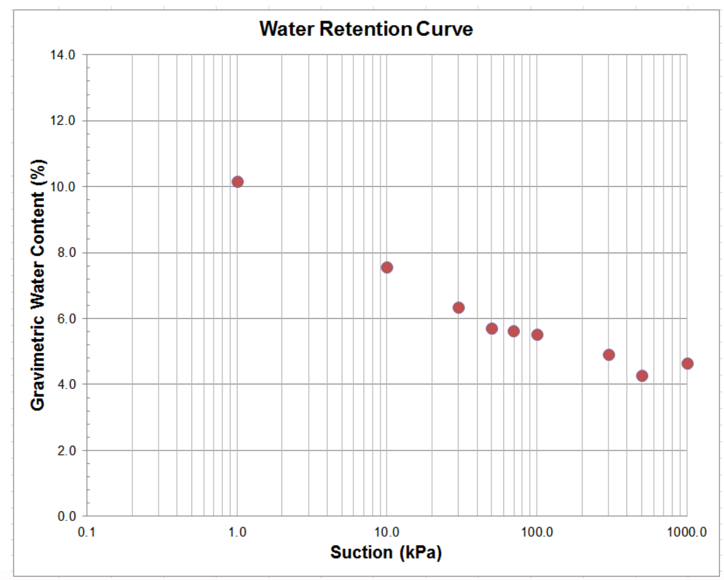
# Lessons Learned from Case Studies

- Modulus greatly affected by moisture suction (tensile stress between aggregate particles)
- Suction tensile stress depends on:
  - Quantity of sand, silt, and clay particles
  - Distribution of particles and voids
  - Particle shape and void shape
  - Porosity (measure of void space)
  - Moisture content (measure of water in voids)

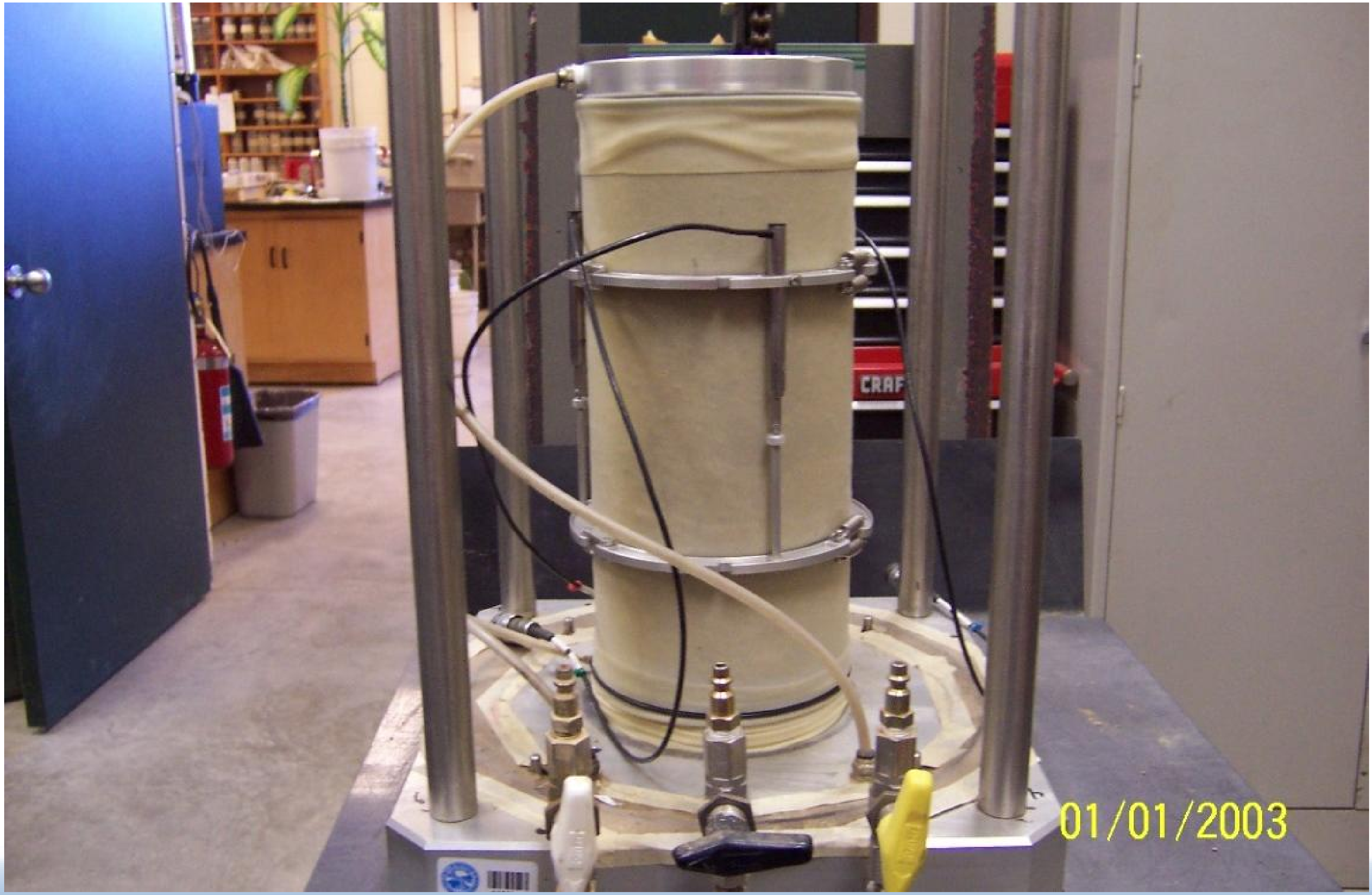

Moisture Content
7.17 %
Optimum Moisture
8 %
Grav. (Gsb)
2.7
SWCC Details
Cancel
Restore Defaults
Percent Passing
Material: MnDOT Class 5
Gradation
MnDOT Specification
100
95
85
70
45
30
25
10
Percent Passing
Sieve Size, mm
Saturated Hydraulic
Van Genuchten/Mualem


Print Window
Help
Material: MnDOT Class 5
Suction (kPa)
Gravimetric Water Content
0 0.1463
0.1 0.0988
10 0.0645
30 0.0517
101 0.0448
303 0.0390
OK
Cancel
Restore Default Values
Units
English
SI
Fit Method
Brooks & Corey
Fredlund & Xing
Van Genuchten/Mualem
Sort Rows
Insert Row(s)
Delete Row(s)

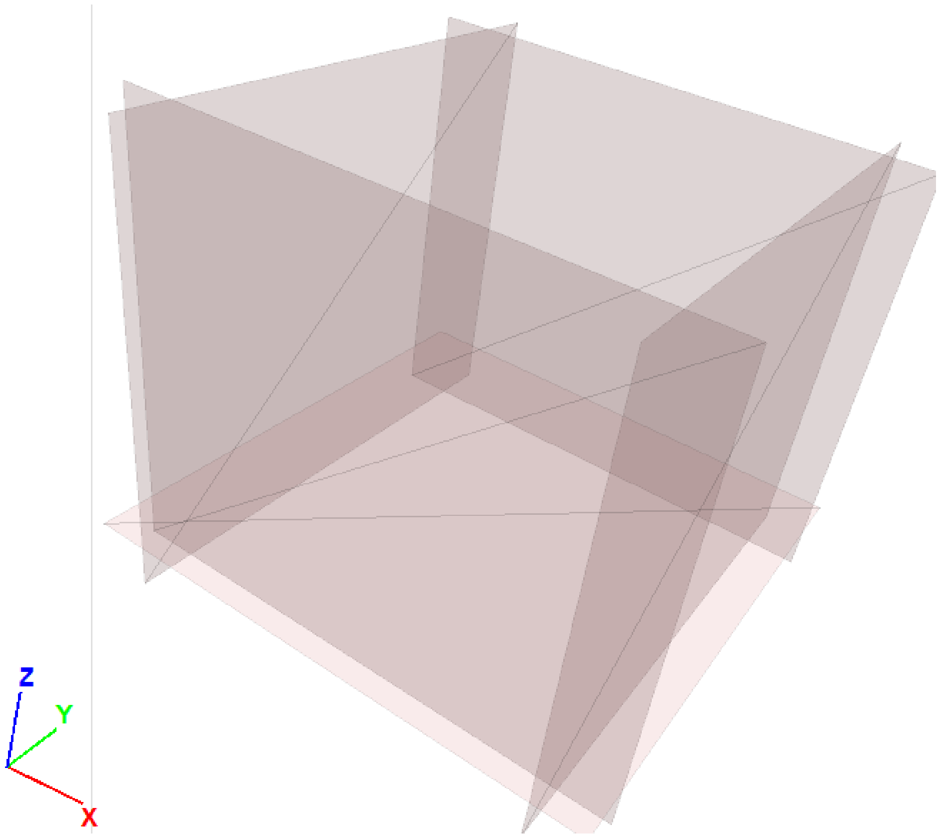

Moisture Content
7.17 %
Optimum Moisture
8 %
Grav. (Gsb)
2.7
SWCC Details
Cancel
Restore Defaults
Material: MnDOT Class 5
SWCC
Degree of Saturation
Suction, kPa
0.021
mm/h
Van Genuchten/Mualem Parameters (estimated)
alpha
n

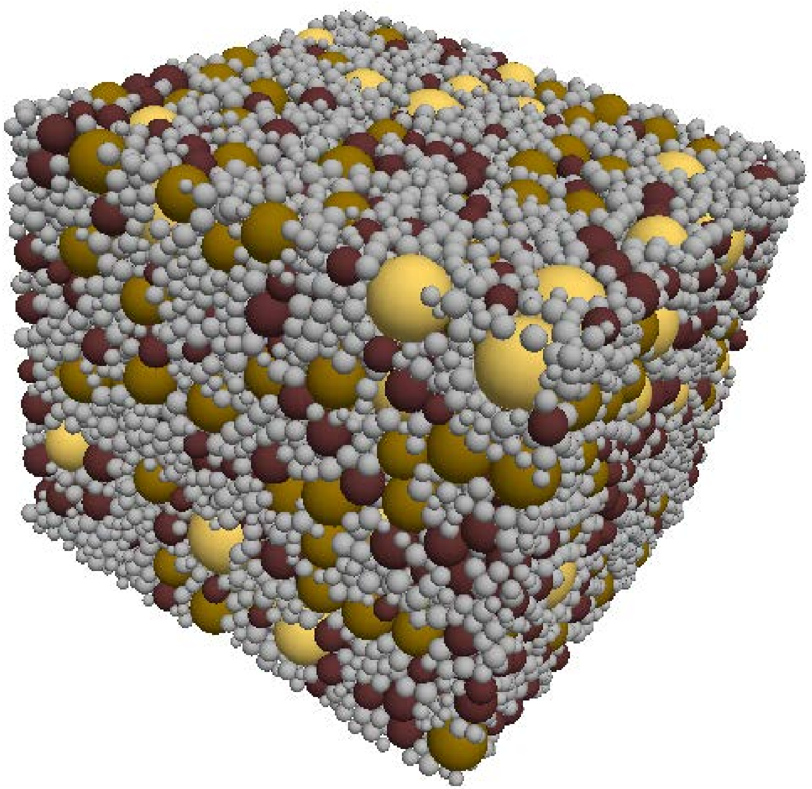

Water Retention Curve
Gravimetric Water Content (%)
Suction (kPa)

# Lab Resilient Modulus



# Numerical Simulation

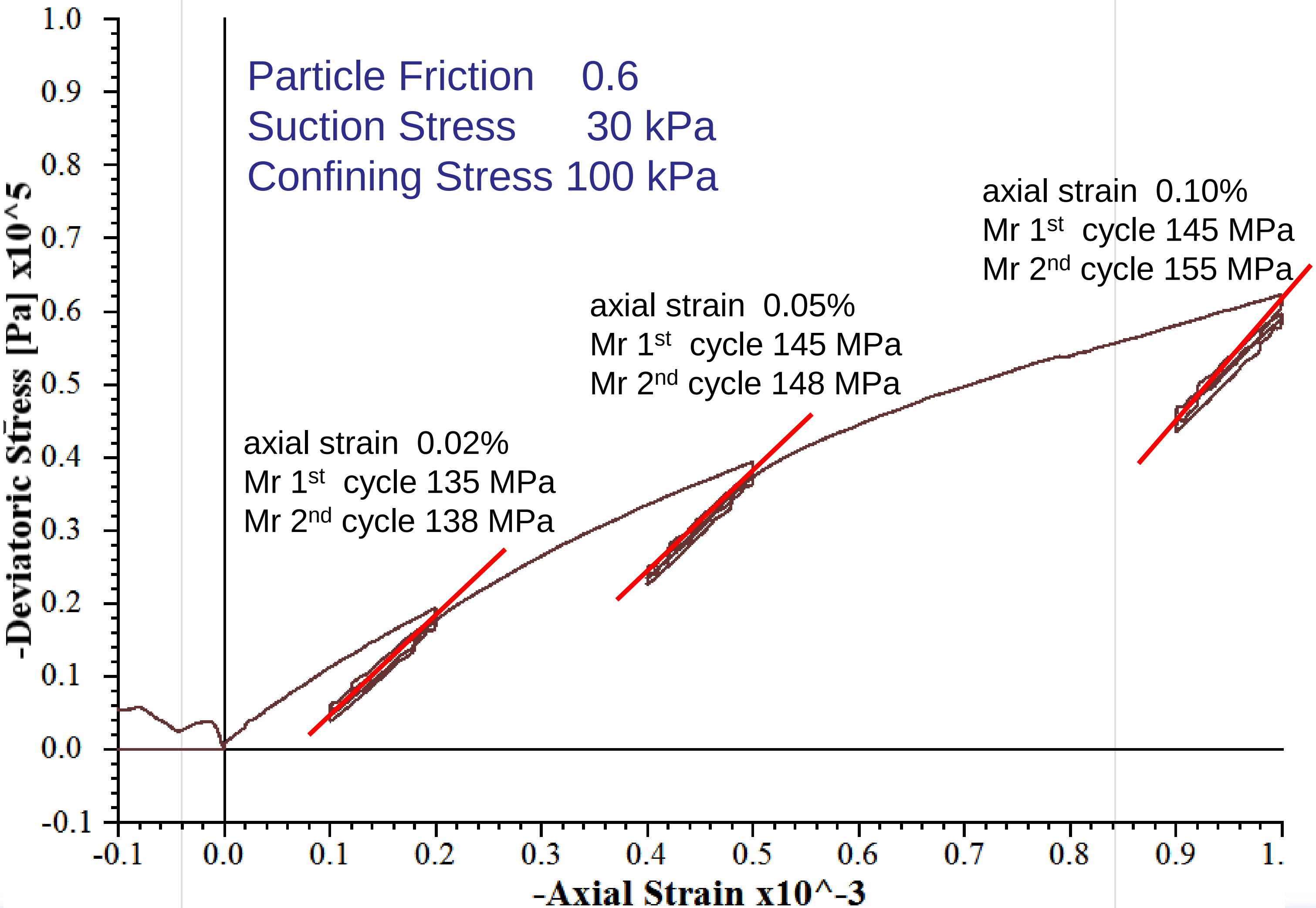


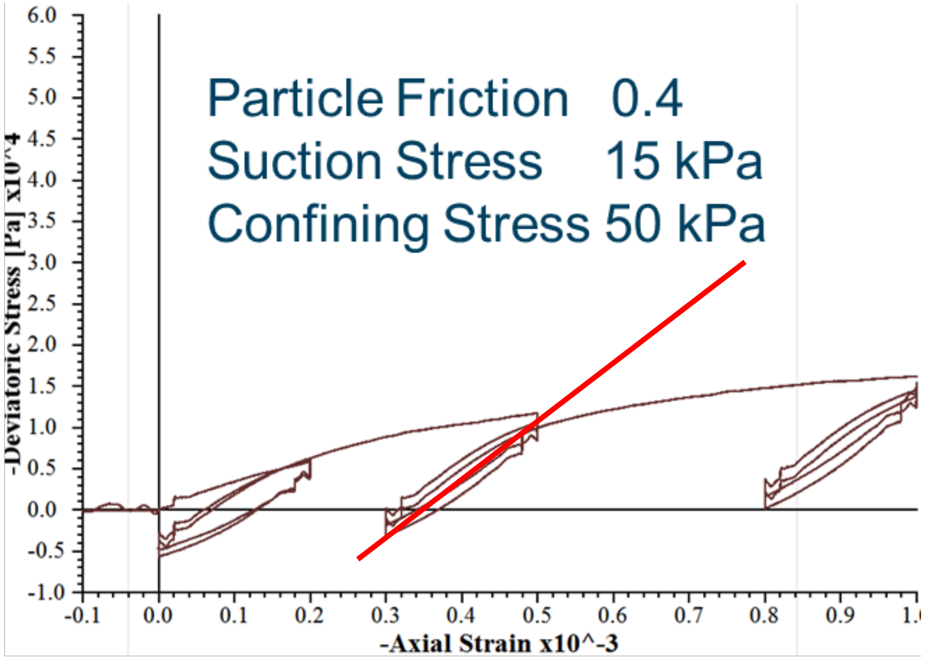
# Parameters Studied

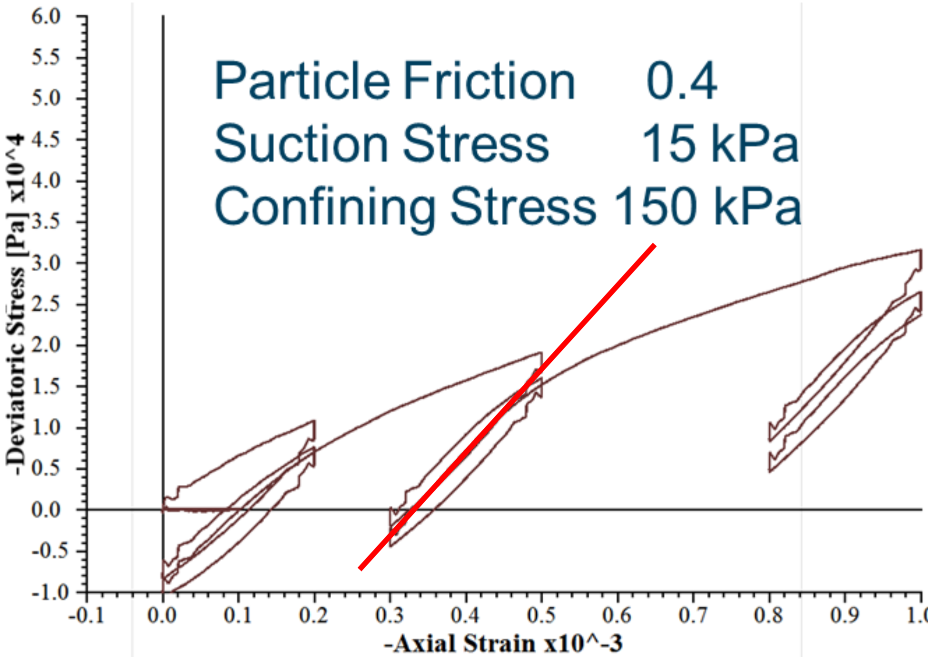
- Aggregate gradation
- Moisture content (suction/tension)
- Friction between particles (roughness)
- Confining stress

# Numerical Simulation Results



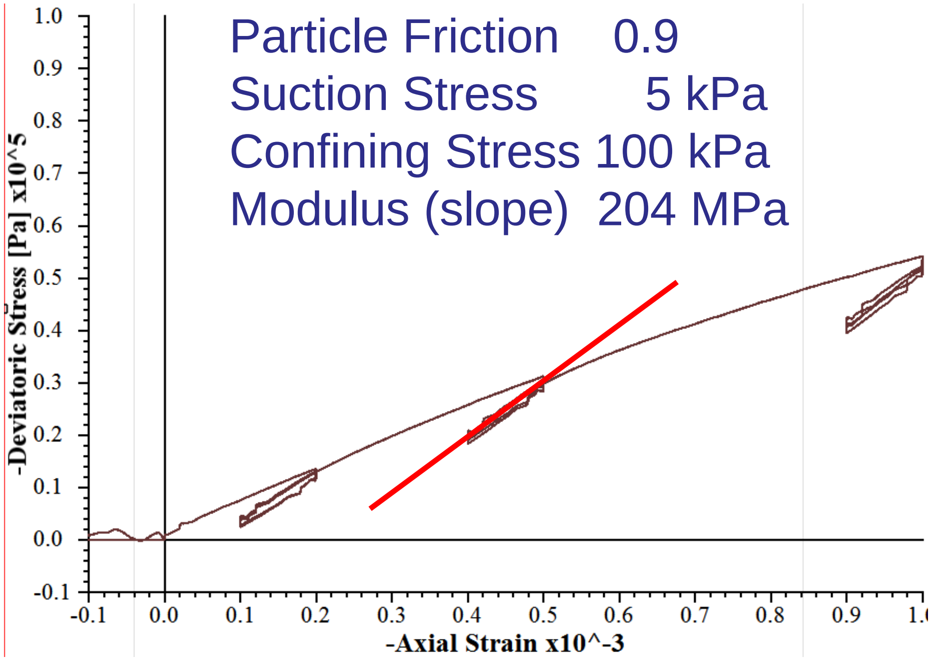
# Numerical Simulation Results

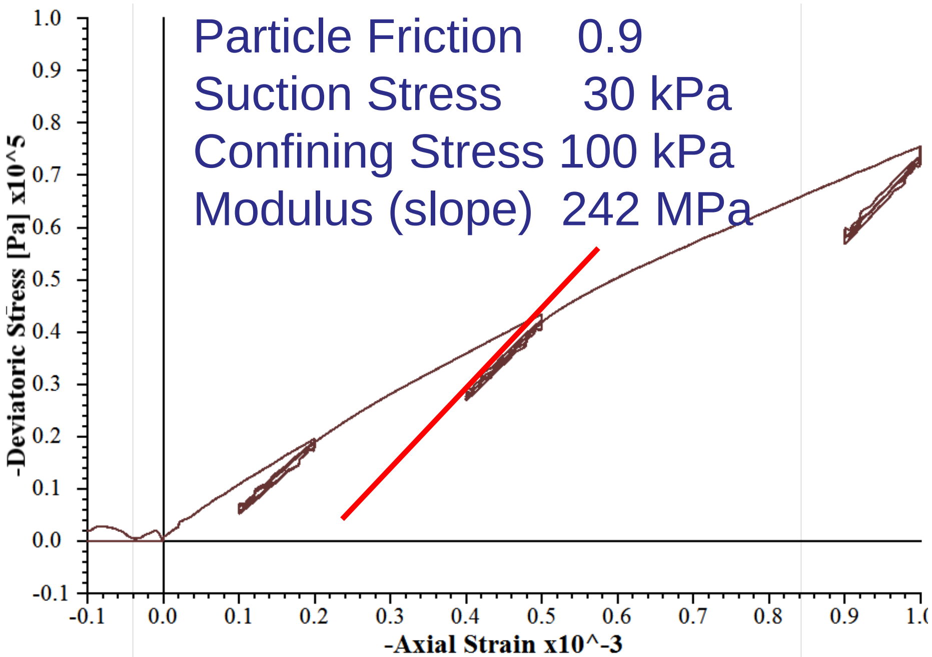



Increasing confining stress increases resilient modulus.

# Numerical Simulation Results




Increasing suction increases resilient modulus.

# Numerical Simulation Results

## Aggregate Base Unsaturated Gain Factors

particle friction 0.6 and contact bridge 1 mm (less sand and smaller particles)

| Suction (kPa) | Gain Factor @ 50 kPa and 0.05% strain | Gain Factor @ 100 kPa and 0.05% strain |
|---|---|---|
| 5 | 1.32 | 1.49 |
| 30 | 1.90 | 2.07 |
| 60 | 2.26 | 2.36 |

Gain factors are the ratio of modulus at listed suction compared to 1 kPa suction.

# Numerical Simulation Results

## Aggregate Base Unsaturated Gain Factors

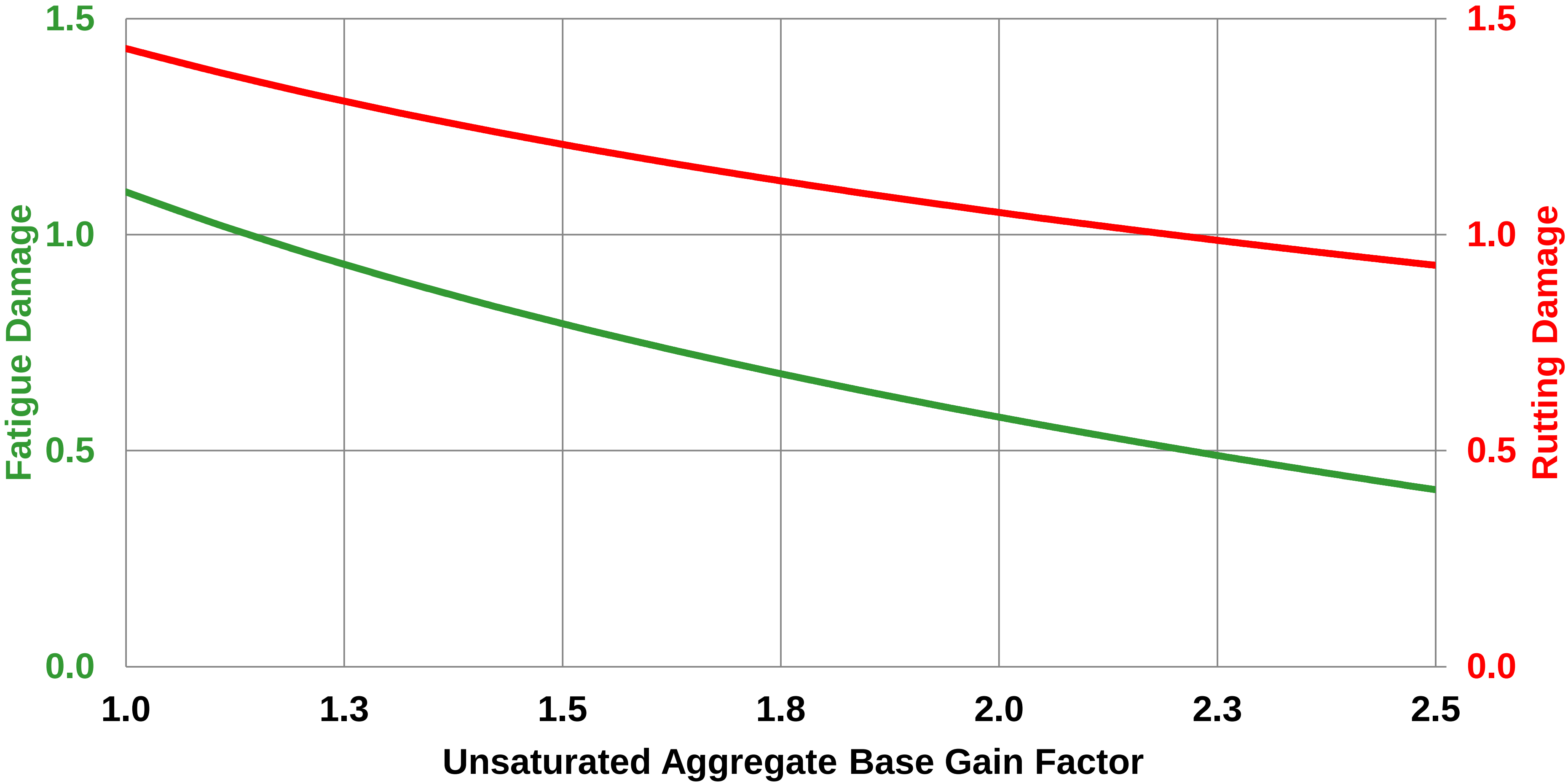
particle friction 0.6 and contact bridge 10 mm (more sand and smaller particles)

| Suction (kPa) | Gain Factor @ 50 kPa and 0.05% strain | Gain Factor @ 100 kPa and 0.05% strain |
|---|---|---|
| 5 | 1.46 | 1.30 |
| 30 | 2.26 | 1.85 |
| 60 | 2.65 | 2.14 |

Gain factors are the ratio of modulus at listed suction compared to 1 kPa suction.

# Damage vs Unsat Gain Factor

Damage must be less than of 1.0 to achieve 20 year design life.



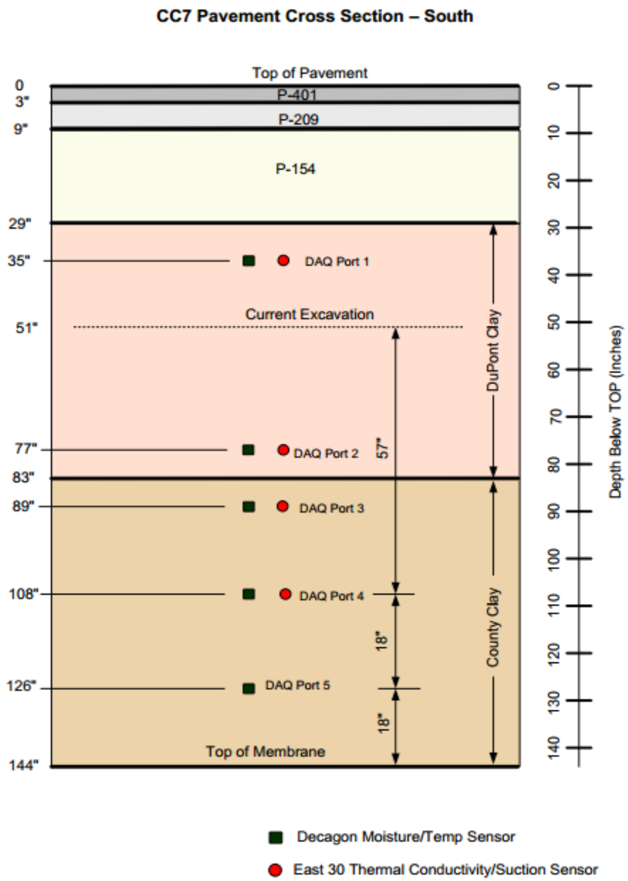
# Conclusions

- Modulus increases as suction increases and aggregate roughness increases.
- Pavement structures can be optimized by applying unsaturated geomechanics.
- Financial effectiveness can be enhanced by better utilization of limited resources.

# Suction and Moisture Collected at Field Sites and Variation Information

**Claudia Zapata**
Arizona State University

# Moisture Data Collected at FAA Test Facility

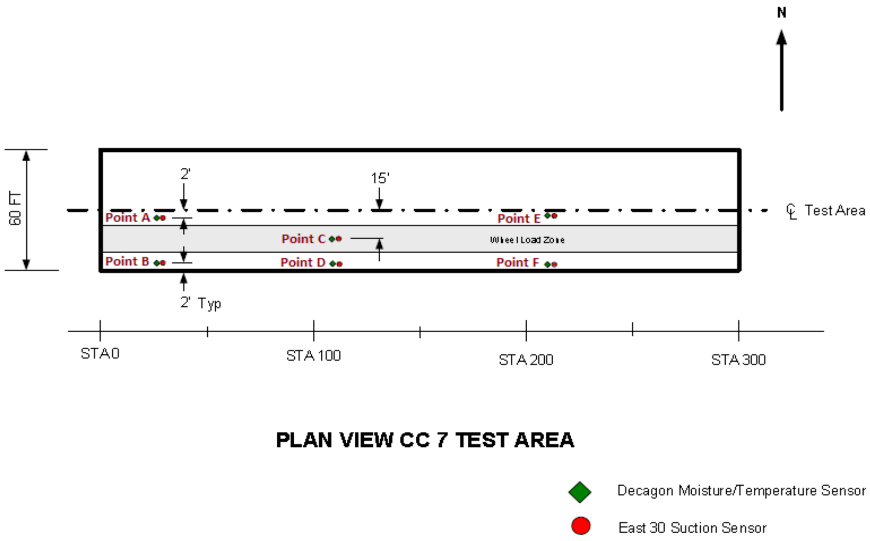


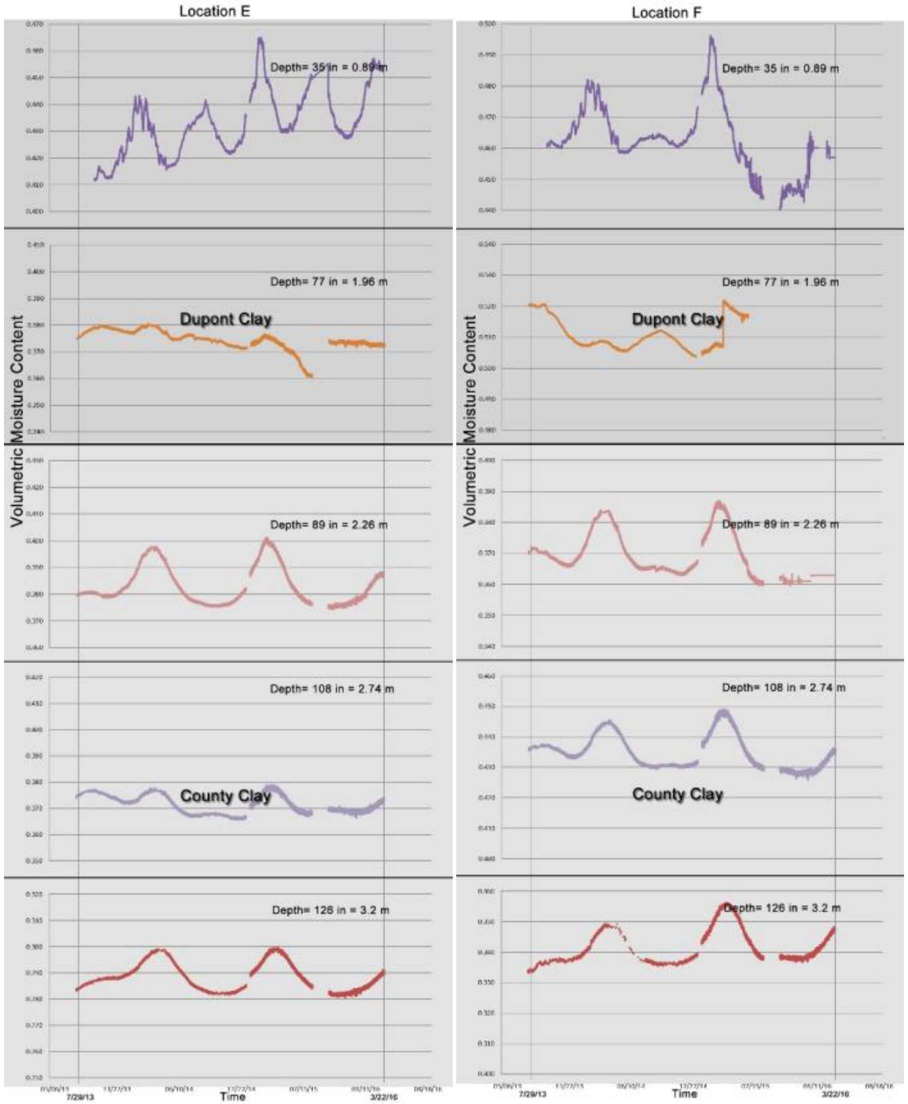

Section View of the NAPTF Test Section

# Moisture Sensors Installation

- Total of 30 sensors were installed throughout the test section
- Sensors have been collecting moisture every hour since July 2013

# Data Collected

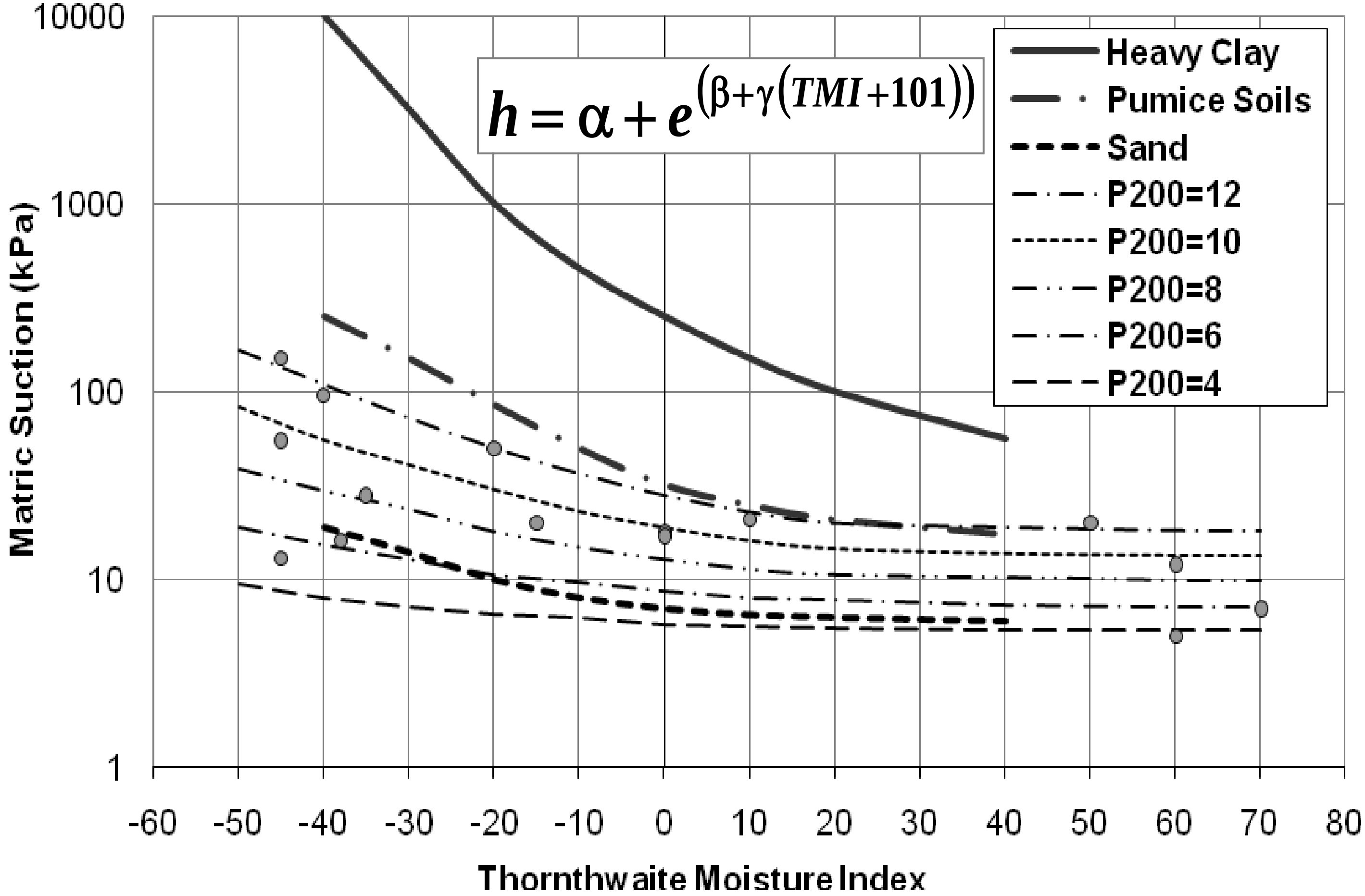


# If measuring suction in the field is not an option…

- Equilibrium suction in the field can be predicted based on climatic indexes (such as the Thornthwaite Moisture Index) and readily available soil index properties

# TMI-$P_{200}$ Model – Granular Bases

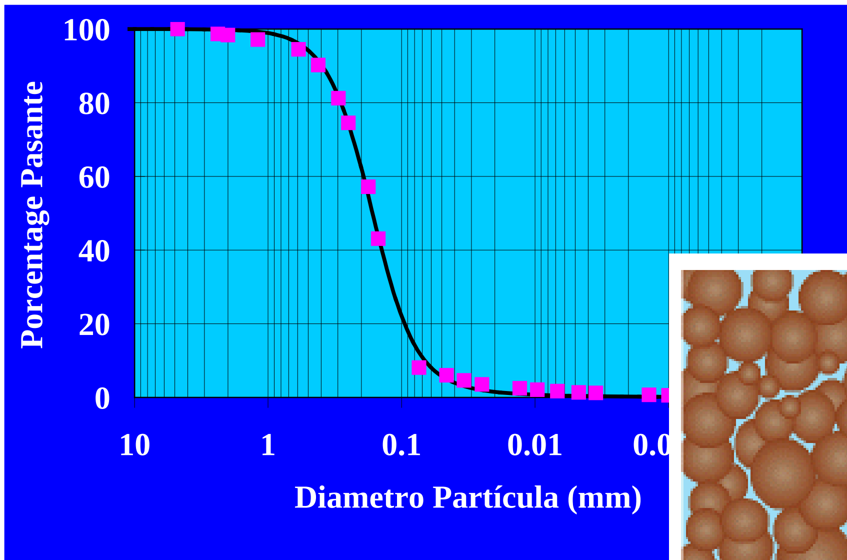


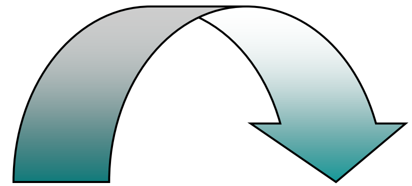

**Perera, 2003**

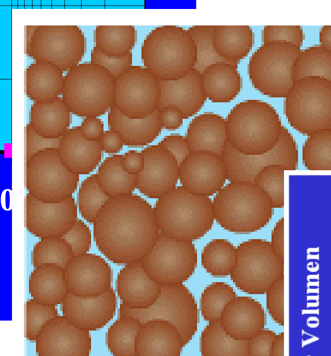
# Soil-Water Characteristic Curve Prediction

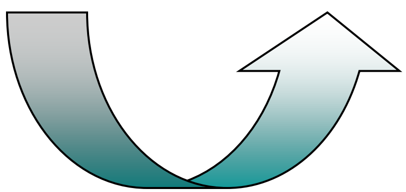
- Once the suction at equilibrium is predicted, the soil-water characteristic curve can be use to estimate the water content at equilibrium
- The SWCC can be
  - obtained in the laboratory
  - roughly estimated from grain-size distribution parameters and other soil properties

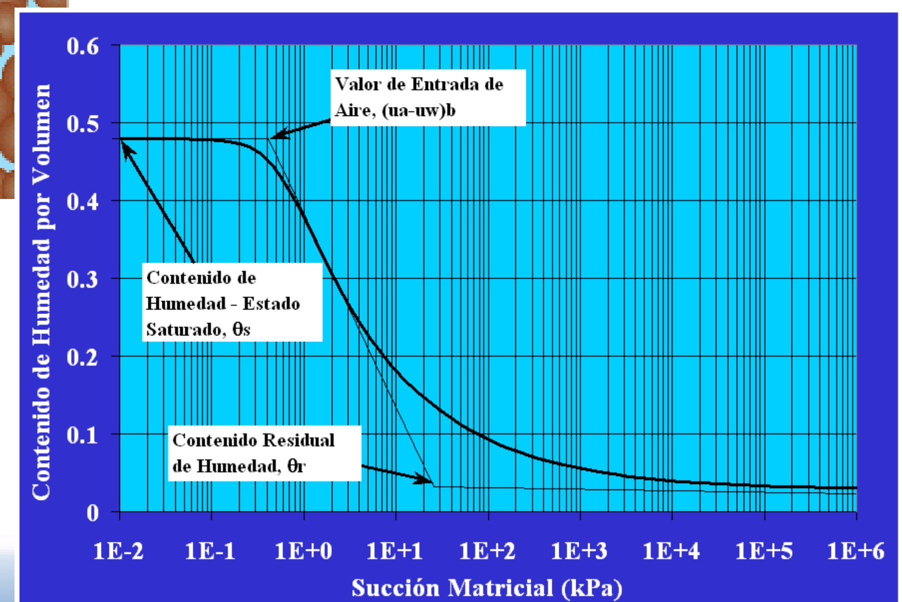
# Estimating SWCC based on Grain Size Distribution









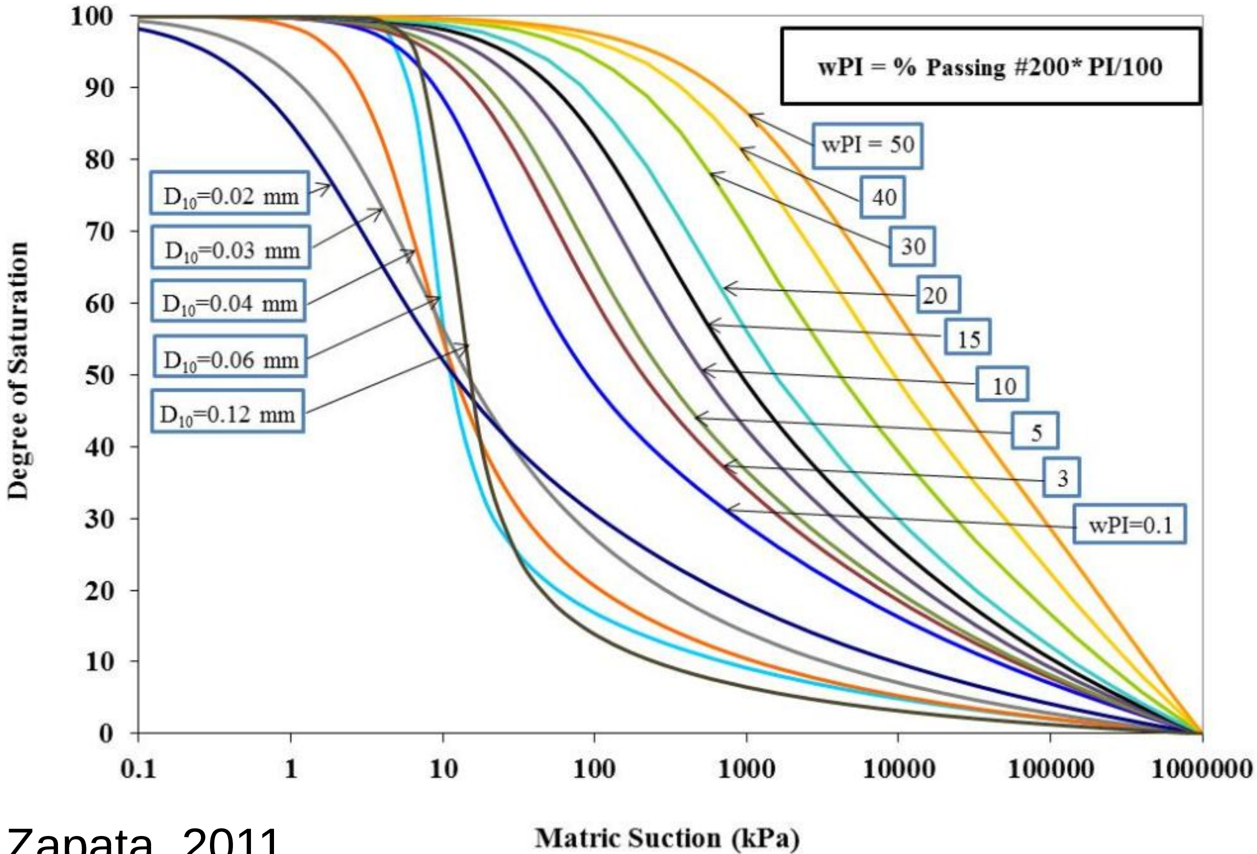

Fredlund, 1995

# Estimating SWCC for Granular Material (Torres and Zapata, 2011)

| | |
|---|---|
| SWCC Parameter af, kPa | $a_f = -967.21 D_{10}^2 + 218.37 D_{10} - 2.7$ |
| SWCC Parameter bf | $b_f = 10^{\left(-0.0075 a_f^3 + 0.1133 a_f^2 - 0.3577 a_f + 0.3061\right)}$ |
| SWCC Parameter cf | $c_f = 0.0058 a_f^3 - 0.0933 a_f^3 + 0.4069 a_f + 0.3481$ |
| SWCC Parameter hr, kPa | $h_r = 100$ |
| Correction Factor for the SWCC Equation: | $CF(\psi) = \frac{(\psi - 0.9128)}{0.017}$ |
| | Where:<br>$\theta w$ = Volumetric Water Content<br>$\theta sat$ = Saturated Volumetric Water Content<br>$\psi$ = Matric Suction, kPa<br>$GI$ = Group Index |

Once the parameters are replaced in the Fredlund and Xing equation, the family of SWCC curves can be obtained.

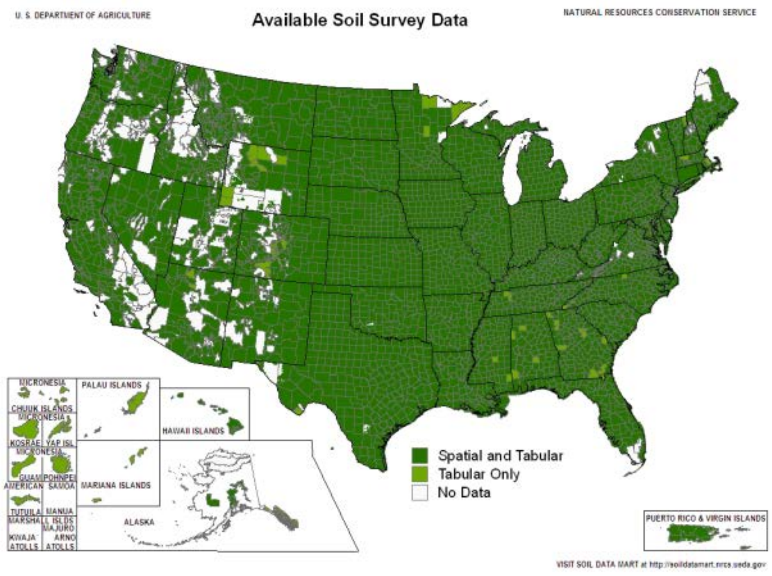
# SWCC for Granular Material based on $D_{10}$



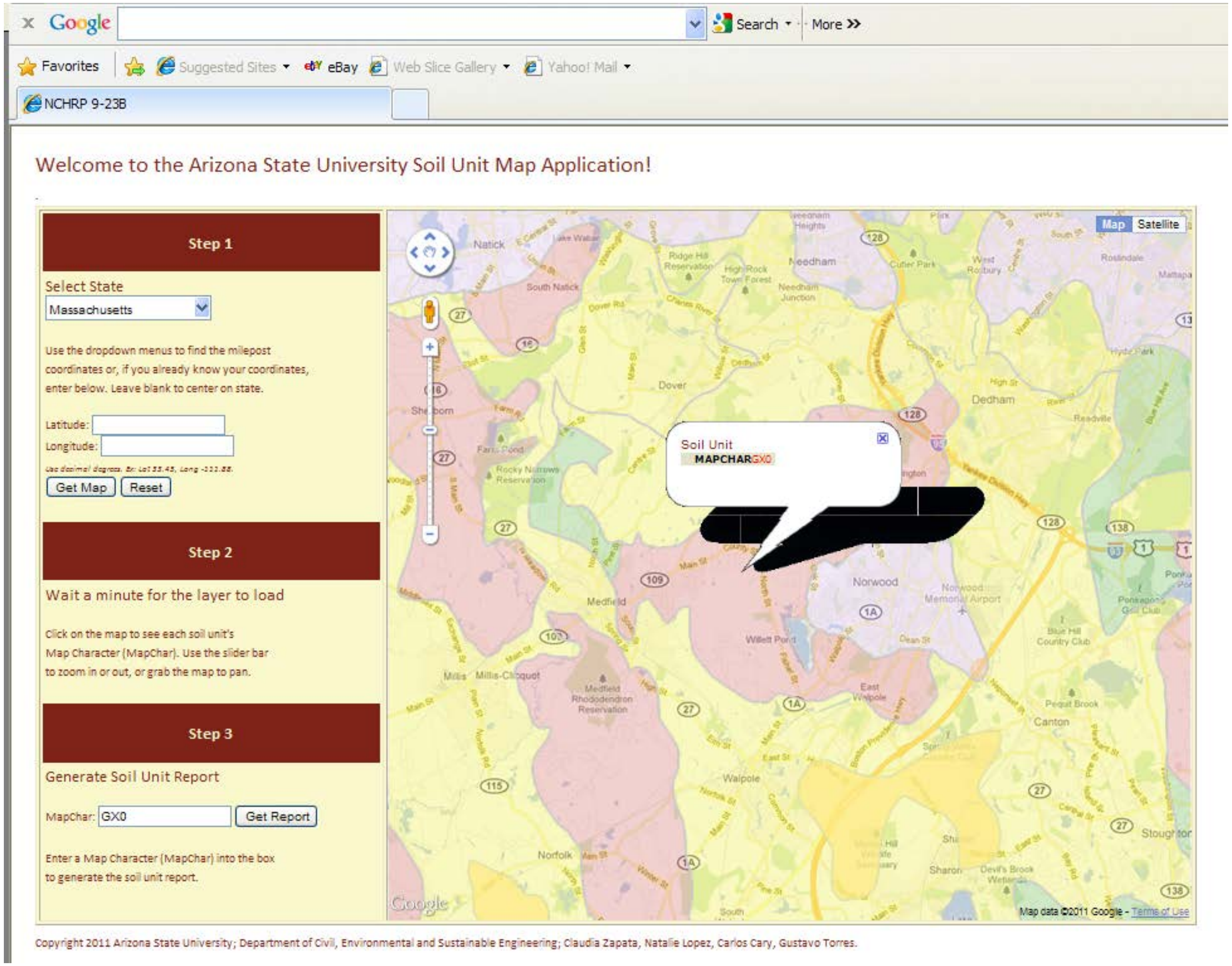

Torres and Zapata, 2011

# Suction Measurements Database

- Compiled from National Resources Conservation Service (NRCS) database
  - Initially intended for agricultural purposes
  - Key soil properties useful in highway/pavement engineering
  - Joint agreement with the then Bureau of Public Roads (BPR)



# http://nchrp923b.lab.asu.edu/



# Soil Properties Available Includes SWCC Parameters

- Grain size distribution
- Atterberg limits
- Saturated hydraulic conductivity
- AASHTO classification
- Water table depth
- Depth to bedrock
- Porosity
- Fredlund and Xing SWCC parameters

Google | Search | More

Favorites | Suggested Sites | eBay | Web Slice Gallery | Yahoo! Mail

http://nchrp923b.lab.asu.edu/SoilQuery.php?mapCh...

## Properties of Soil Unit GX0

| Map Character | Map Unit Key | Map Unit Name | Component Name |
|---|---|---|---|
| GX0 | 668403 | Scituate-Montauk-Canton (s3123) | Montauk |

| AASHTO Classification | AASHTO Group Index | Top Depth (in) | Bottom Depth (in) | Thickness (in) | % Component | Water Table Depth Annual Min (ft) | Depth to Bedrock (ft) |
|---|---|---|---|---|---|---|---|
| A-4 | 0 | 0 | 2 | 2 | 11 | N/A | N/A |
| A-4 | 0 | 2 | 27.2 | 25.2 | 11 | N/A | N/A |
| A-2-4 | 0 | 27.2 | 72 | 44.9 | 11 | N/A | N/A |

| CBR from Index Properties | Resilient Modulus from Index Properties (psi) | Passing #4 (%) | Passing #10 (%) | Passing #40 (%) | Passing #200 (%) | Passing 0.002 mm (%) | Liquid Limit (%) |
|---|---|---|---|---|---|---|---|
| 46.3 | 29754 | 72.5 | 65 | 52.5 | 42.5 | 12 | 17.5 |
| 44.3 | 28928 | 80 | 75 | 62.5 | 47.5 | 12 | 17.5 |
| 61.6 | 35688 | 80 | 75 | 50 | 30 | 9.5 | 15 |

| Plasticity Index (%) | Saturated Volumetric Water Content (%) | Saturated Hydraulic Conductivity (ft/hr) | Parameter af (psi) | Parameter bf | Parameter cf | Parameter hr (psi) |
|---|---|---|---|---|---|---|
| 2 | 37 | 0.27506 | 1.1231 | 1.0687 | 0.7417 | 3000.03 |
| 2 | 36 | 0.27506 | 2.0655 | 1.0066 | 0.7998 | 3000.03 |
| 1 | 24 | 0.02751 | 6.706 | 1.1387 | 0.6662 | 3000.01 |

1 record found matching your criteria

Print Report | Close

# Laboratory Measurement of Suction & Relating it to Resilient Modulus

**Claudia Zapata**
Arizona State University

# How to Obtain Soil Suction?

Hierarchical Levels

- DIRECT MEASUREMENTS
  - Laboratory Measurements
    Field Measurements
- INDIRECT MEASUREMENTS
  - Prediction based on
    Grain-Size Dtstribution
  - Prediction based on
    Simple Index Properties

Most accurate

Sophisticated equipment

High cost

Higher uncertainty

Very low cost

Easier to implement

# How to Obtain Matric Suction?

- Laboratory measurements
  - Pressure plates, pressure membranes
  - Filter paper method
- Field measurements
  - Thermal conductivity sensor
  - Tensiometers
  - Gypsum blocks

# Measuring Matric Suction

- One way to measure matric suction is to directly measure or control **$-u_w$** and **$u_a$**.
- Because **$u_w$** is commonly highly negative, measuring or controlling **$u_w$** in the lab often requires increasing **$u_a$** to avoid cavitation of water in the measurement device.
- The **axis-translation technique** is a common method used for the direct measurement of soil matric suction.

# Axis-Translation in the Lab

- This procedure changes the atmospheric pressure in the chamber to move the origin of reference for the pore-water pressure from the standard level to the final air pressure in the chamber.
- This is why the procedure is called "axis-translation.”
- **Cavitation is prevented** because water pressure in the measuring system **does not** become highly negative.

# Methods Available to Measure Matric Suction

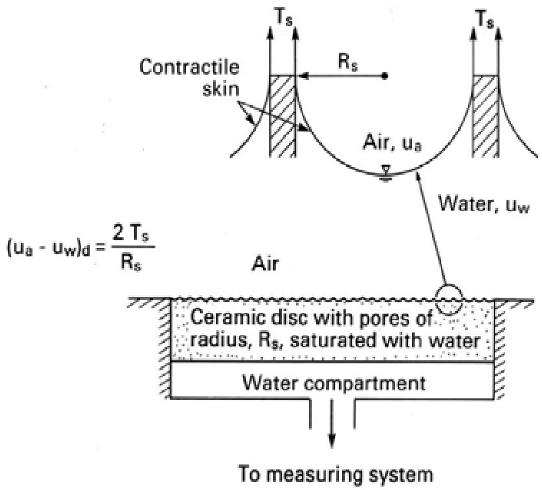
- Direct methods:
  - o Tempe cells
  - o Pressure cells
  - o Tensiometers

Mounted and Unmounted Ceramic Disks

# Measuring Matric Suction

- High air-entry ceramic disks, which are uniformly porous and separate air and water, are used.
- If the disk is saturated with water, air cannot pass through it since the air-water interface resists the flow of free air.

Mounted and Unmounted Ceramic Disks




Modified from Fredlund and Rahardjo, 1993

# Air-Entry Value

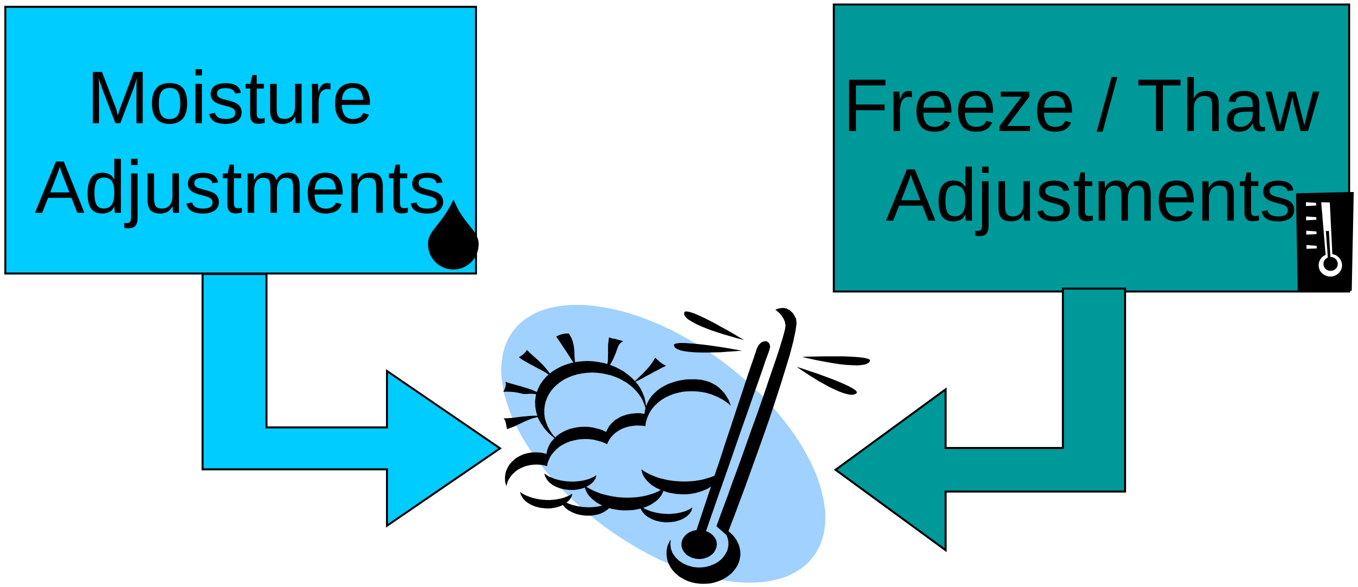
**Table 4.3 Properties of High Air-Entry Disks Manufactured by Soilmoisture Equipment Corporation[1] (Manufacturer's Results)**

| Type of Disks | Approximate Pore Diameter (x $10^{-3}$ *mm*) | Measured Air-Entry Value, $(u_a - u_w)_d$, *kPa* |
|---|---|---|
| ½ bar High flow | 6.0 | 48-62 |
| 1 bar | 2.1 | 138-207 |
| 1 bar High flow | 2.5 | 131-193 |
| 2 bar | 1.2 | 241-310 |
| 3 bar | 0.8 | 317-483 |
| 5 bar | 0.5 | > 550 |
| 15 bar | 0.16 | > 1520 |

[1] Soilmoisture Equipment Corporation, Santa Barbara, CA, USA

# Relating Suction and Resilient Modulus

# How can the resilient modulus be adjusted for environmental conditions?




**Environmental Factor, $F_{env}$**

$$M_r = F_{env} \times M_{r_{opt}}$$

# Models by Andrei and Witczak (2003)

$$M_R = \underbrace{10^{a+\frac{b-a}{1+EXP\left(\beta+k_m\cdot\left(S-S_{opt}\right)\right)}}}_{\textbf{MOISTURE ADJUSTMENT FACTOR } (F_{env})} \cdot M_{Ropt}$$

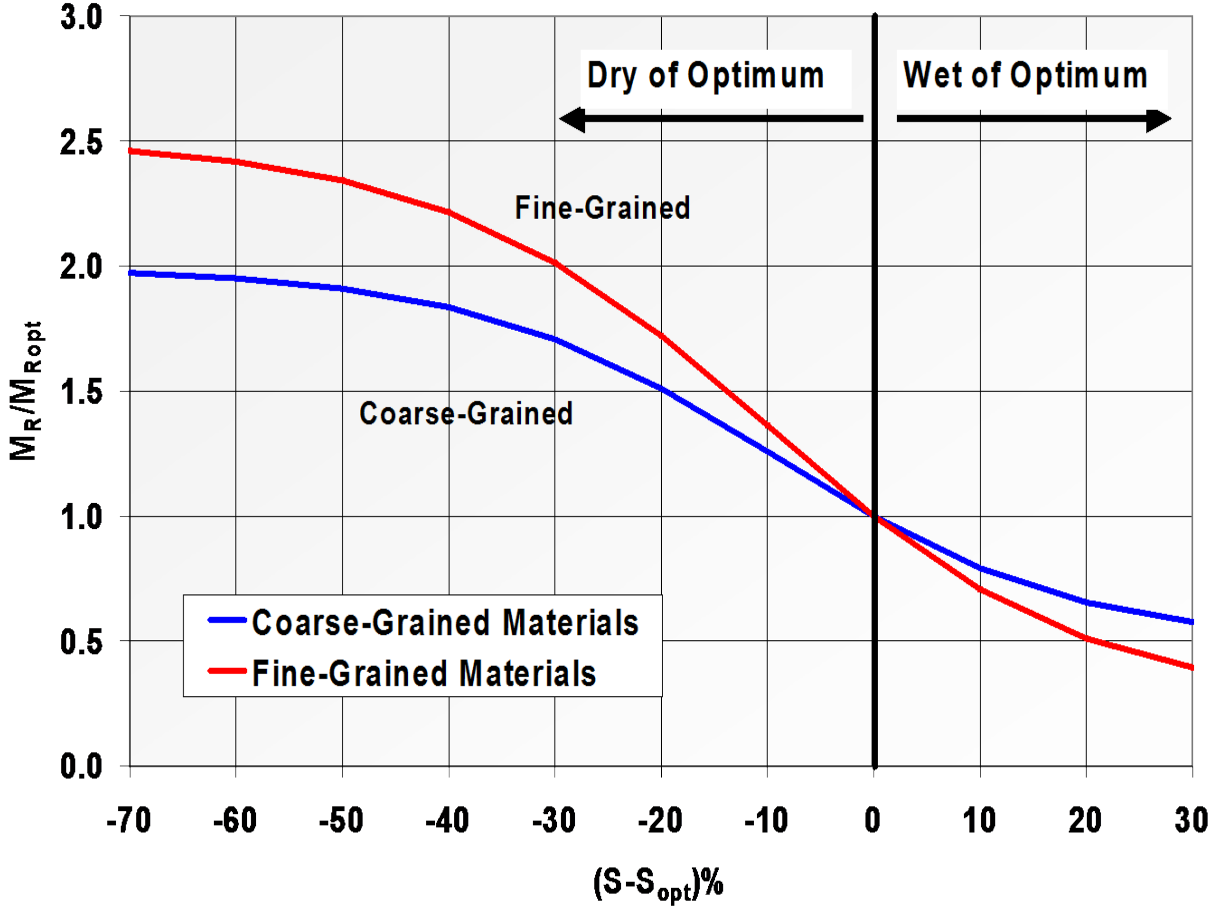
$M_R$ = Resilient Modulus at any degree of saturation (S)

$M_{Ropt}$ = Resilient modulus at optimum degree of saturation ($S_{opt}$) or initial compaction conditions

$F_{env}$ = Environmental adjustment factor

a, b, $k_m$, $\beta$ = Regression parameters

# Models by Andrei and Witczak (2003)

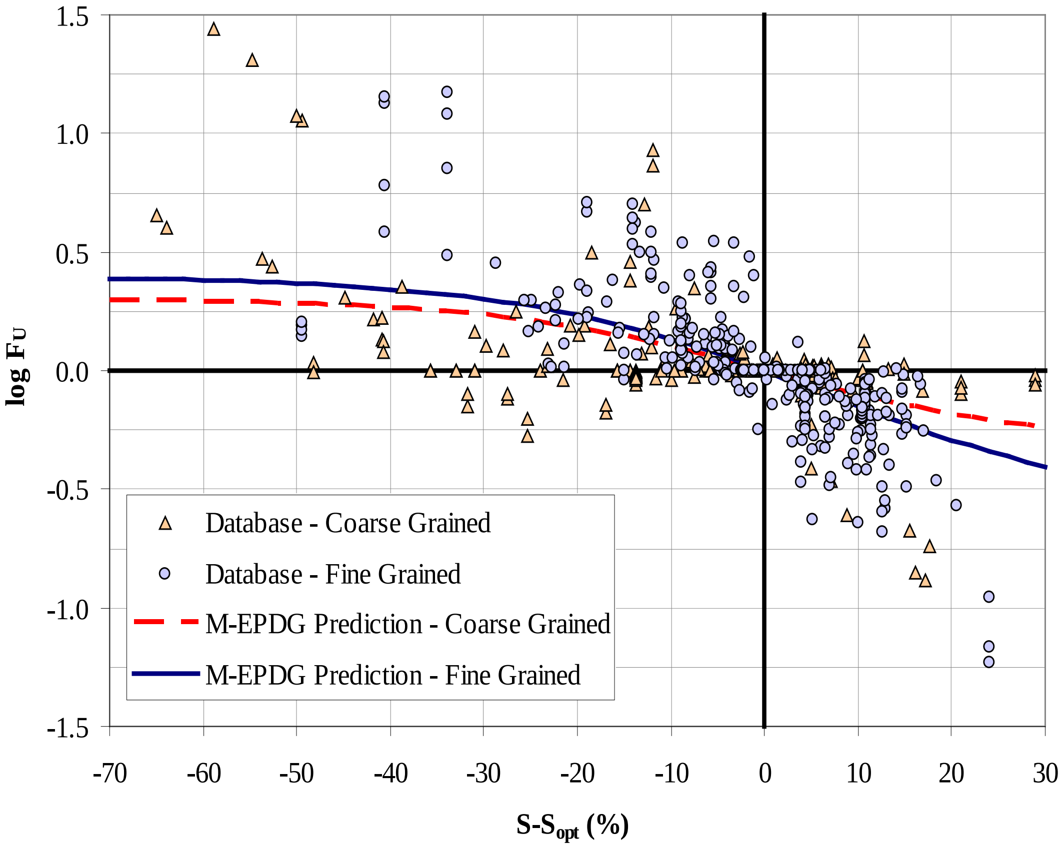


# Resilient Modulus at Optimum

$$M_{Ropt} = k_1 \cdot p_a \cdot \left( \frac{\theta}{p_a} \right)^{k_2} \cdot \left( \frac{\tau_{oct}}{p_a} + 1 \right)^{k_3}$$

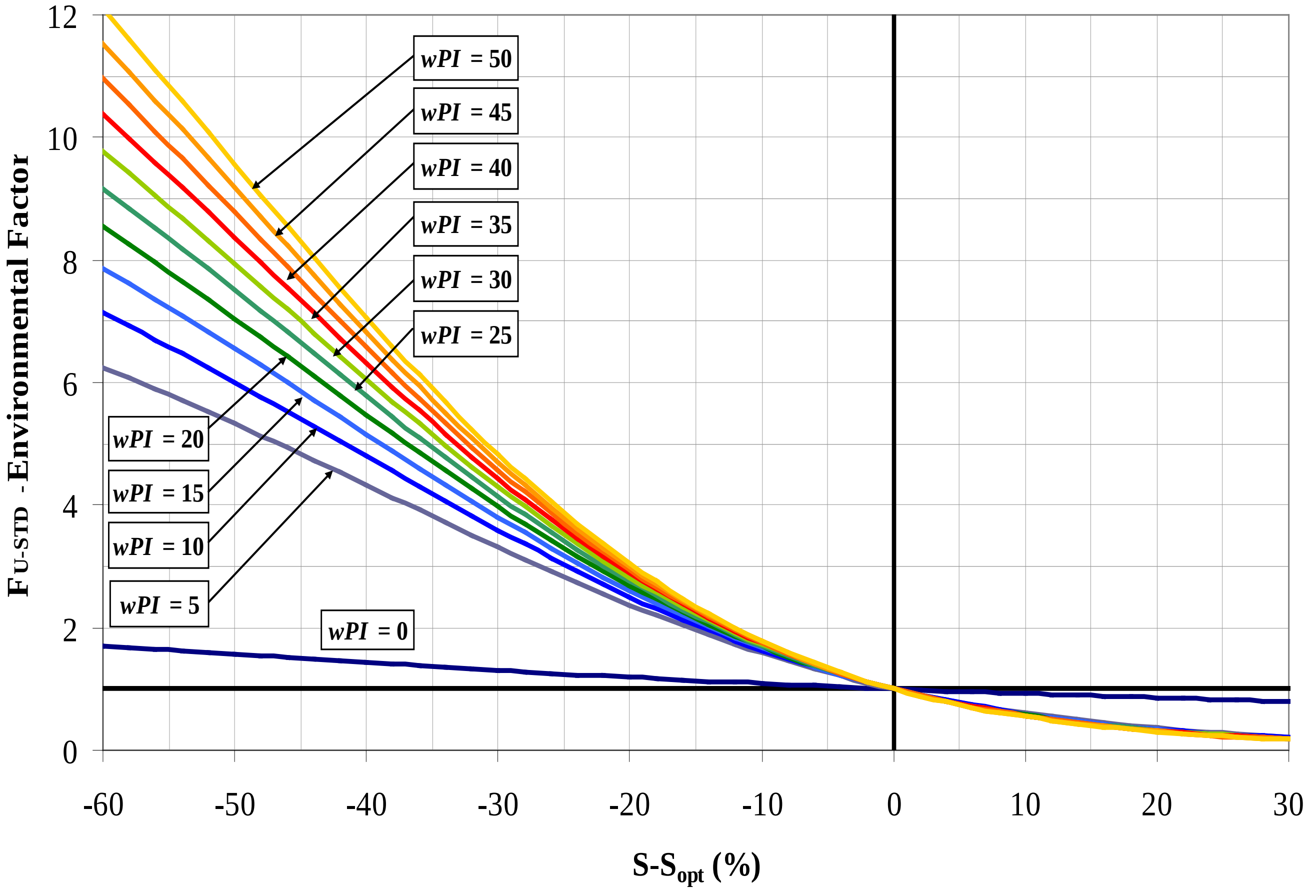
- Universal model
  - Implemented in the ME-PDG for “unfrozen” unbound materials
  - Stress dependent model

# More data collected indicated…




- $F_{env}$ conservatively predicted
- $F_{env}$ for fine grained materials underestimated at dry conditions

# Environmental Factor as a Function of Soil Type




Cary and Zapata (2010)

# Moisture and Compaction Measurement and Field Performance

**Erol Tutumluer**
University of Illinois
at Urbana-Champaign

# Rutting is the Main Performance Indicator

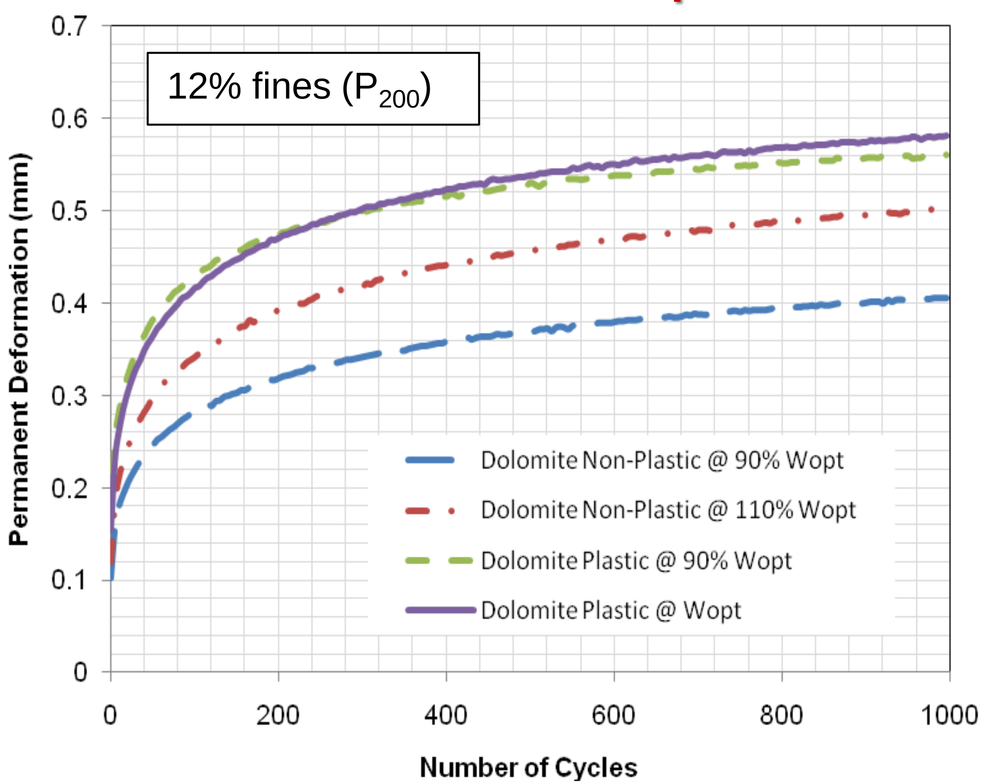
*UIUC ATLAS APT Device*

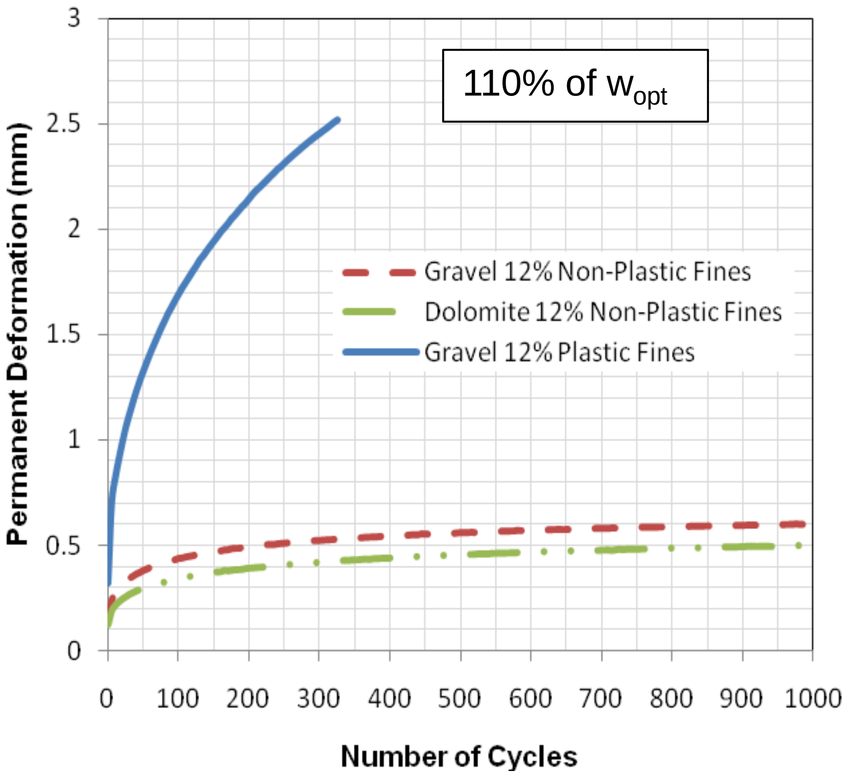
**ICT R27-81 Research Project**

(Mishra & Tutumluer et al. 2013; ict.illinois.edu)

# Moisture Content and Aggregate Quality Influencing Permanent Deformation Behavior

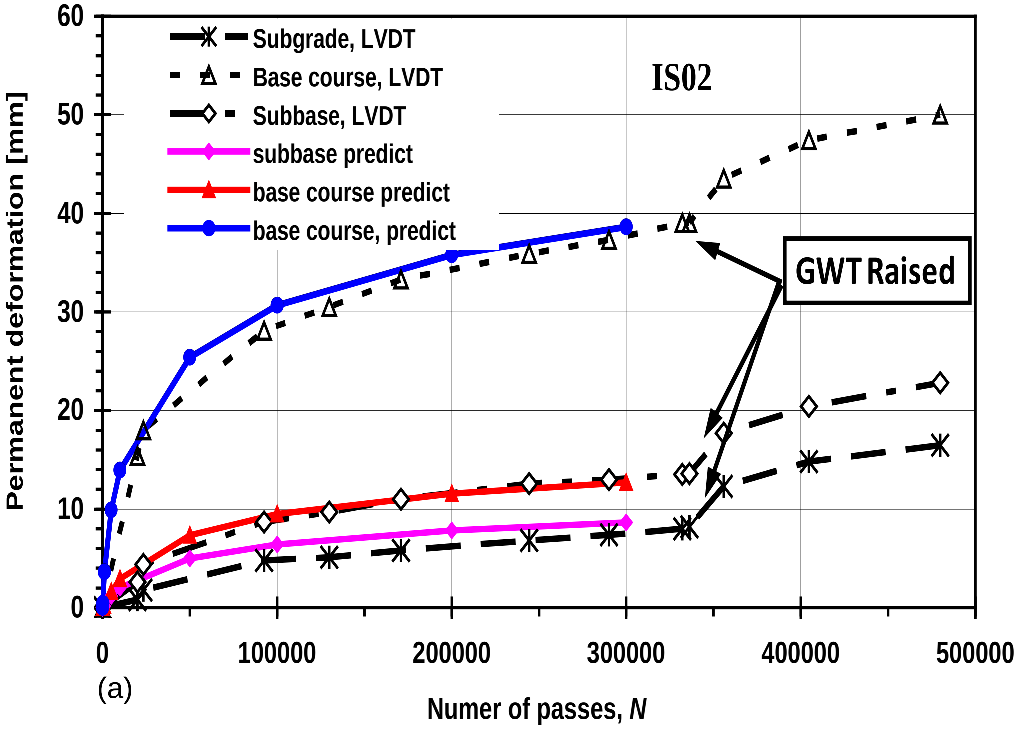
## Repeated Load Triaxial Test Results

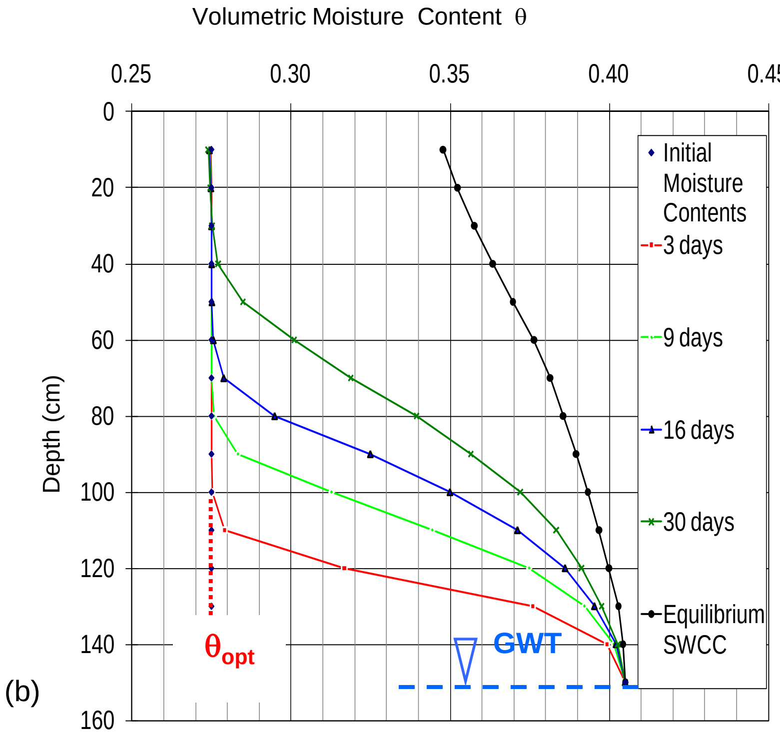



(Tutumluer et al., 2009; R27-1 Project; ict.illinois.edu)

# Effect of Shallow Ground Water Table on Permanent Deformation Accumulation



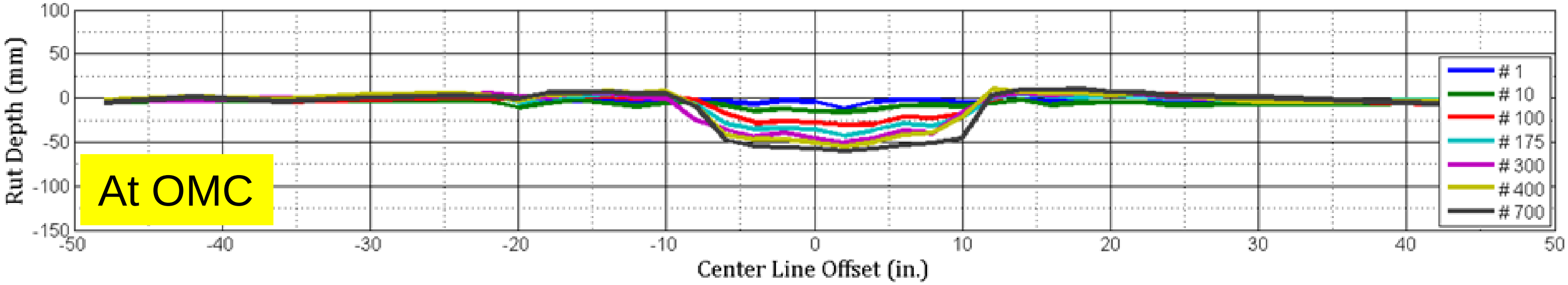

(Erlingsson and Ingason, 2004)

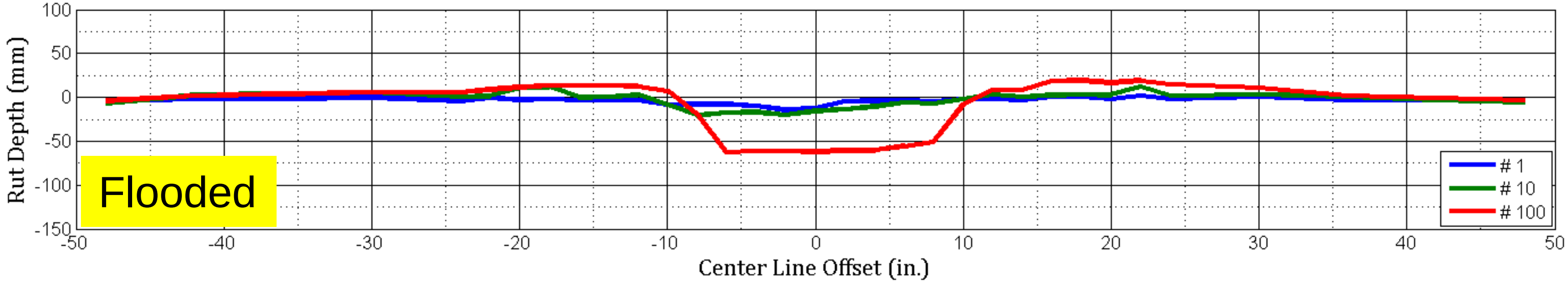
# Dolomite (14-in. thick) over CBR=3 Subgrade

ICT R27-124 Project; (Kazmee & Tutumluer, 2015)

100% crushed, 11% passing No. 200 sieve, PI=0

| Cell | OMC (%) (Std Proctor) | | MDD (pcf) (Std Proctor) | |
|---|---|---|---|---|
| | Quarry Reported | UIUC | Quarry Reported | UIUC |
| 3 | 8.1 | 7.7 | 141.5 | 142.5 |



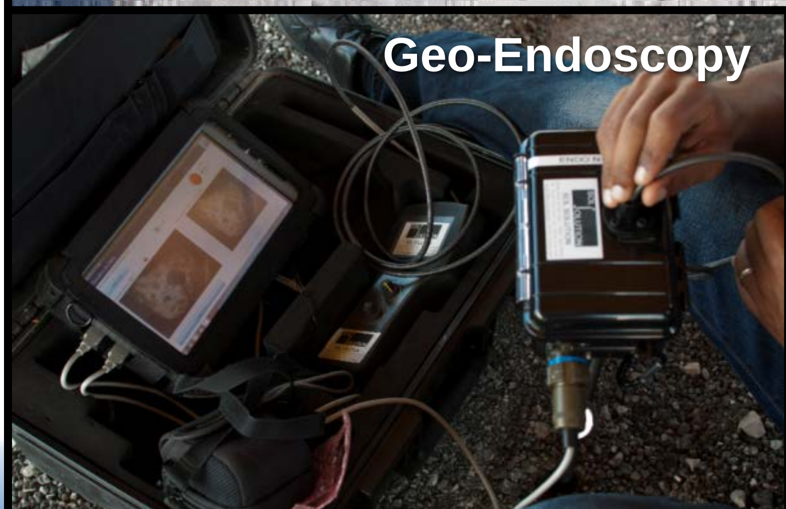



# Sustainability in Aggregate Layer Construction

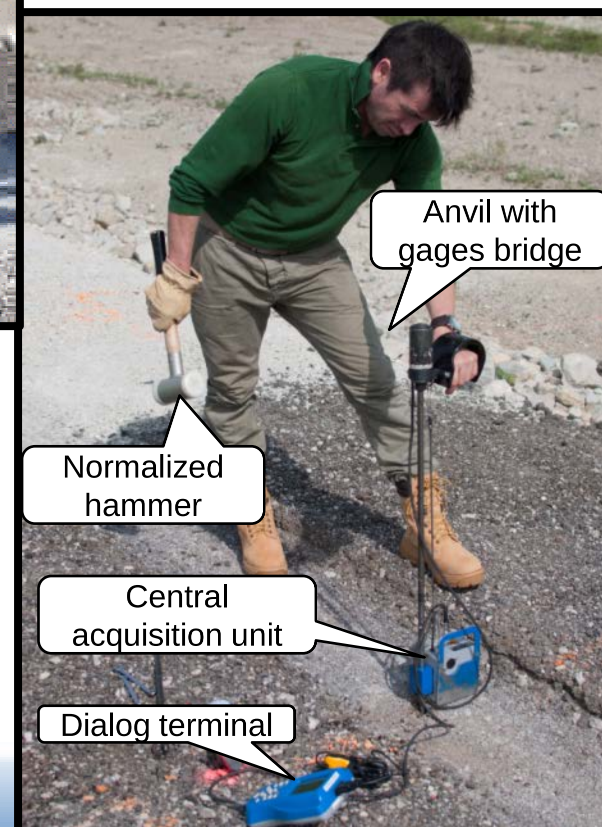
**ICT R27-81 Research Project**
(Mishra & Tutumluer 2013; ict.illinois.edu)

# Pavement Forensics – PANDA & Geo-Endoscopy

**Strength** assessment using **DCP** and **PANDA** penetrometer

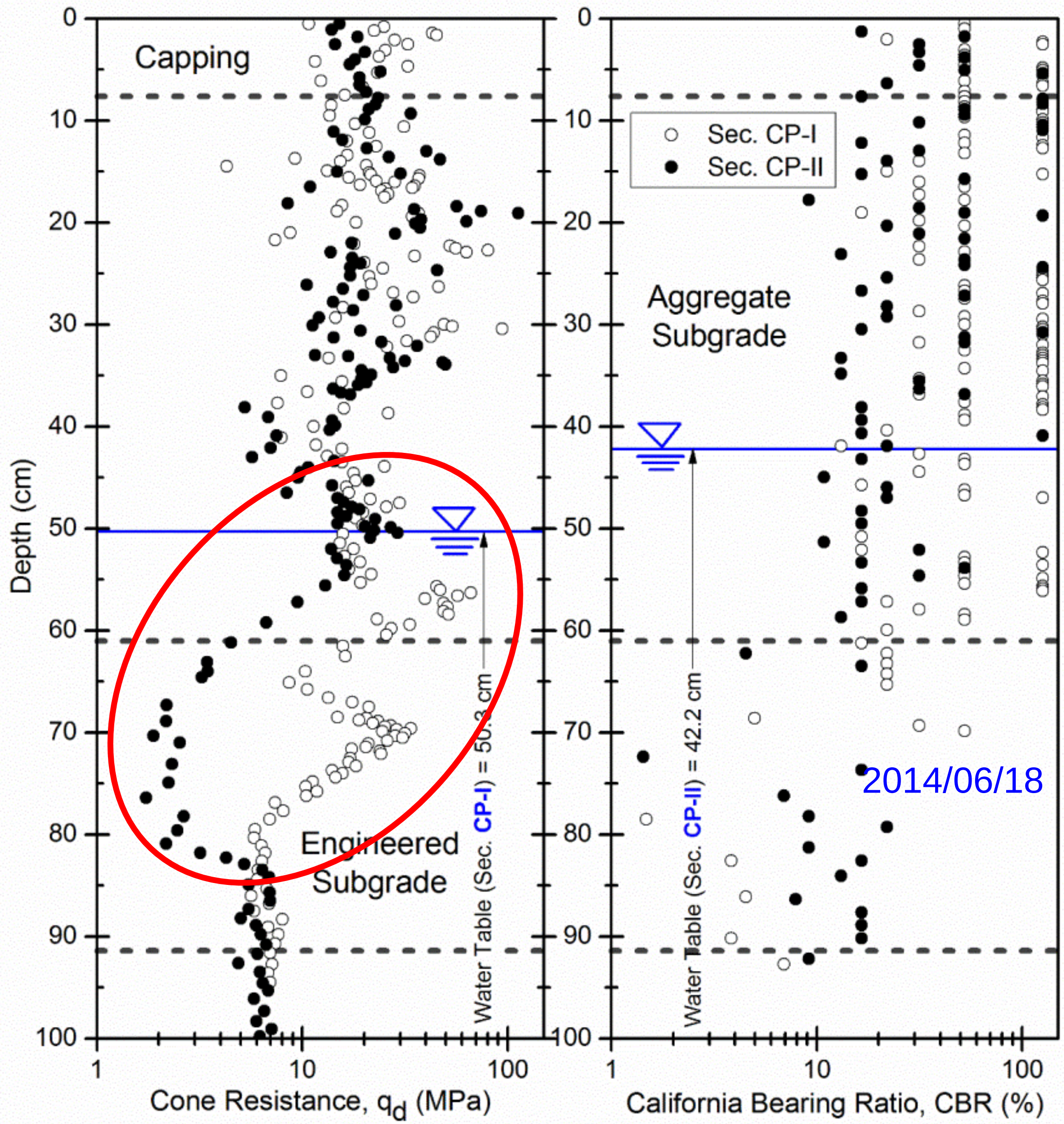



Detection of **water table** and **layer interface**



# Depth of Water Table & Pavement Layer Strength

1.9 cm
12.4 cm
38.0 cm
50.3 cm
68.4 cm




1.0 cm
15.5 cm
25.6 cm
42.2 cm
50.9 cm

**Sec. CP-I**

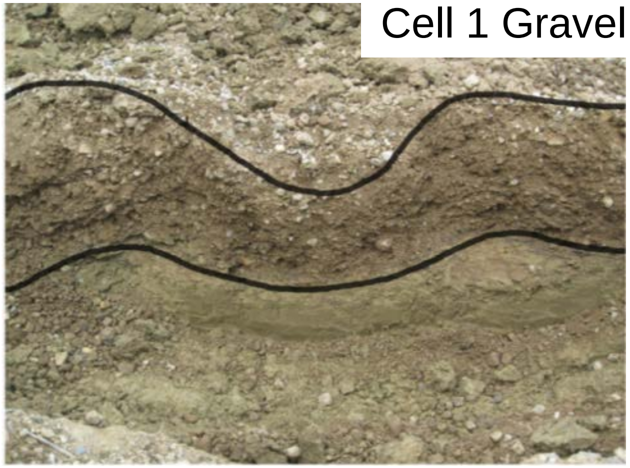
**Sec. CP-II**

ICT R27-124 Project; (Kazmee & Tutumluer, 2015)

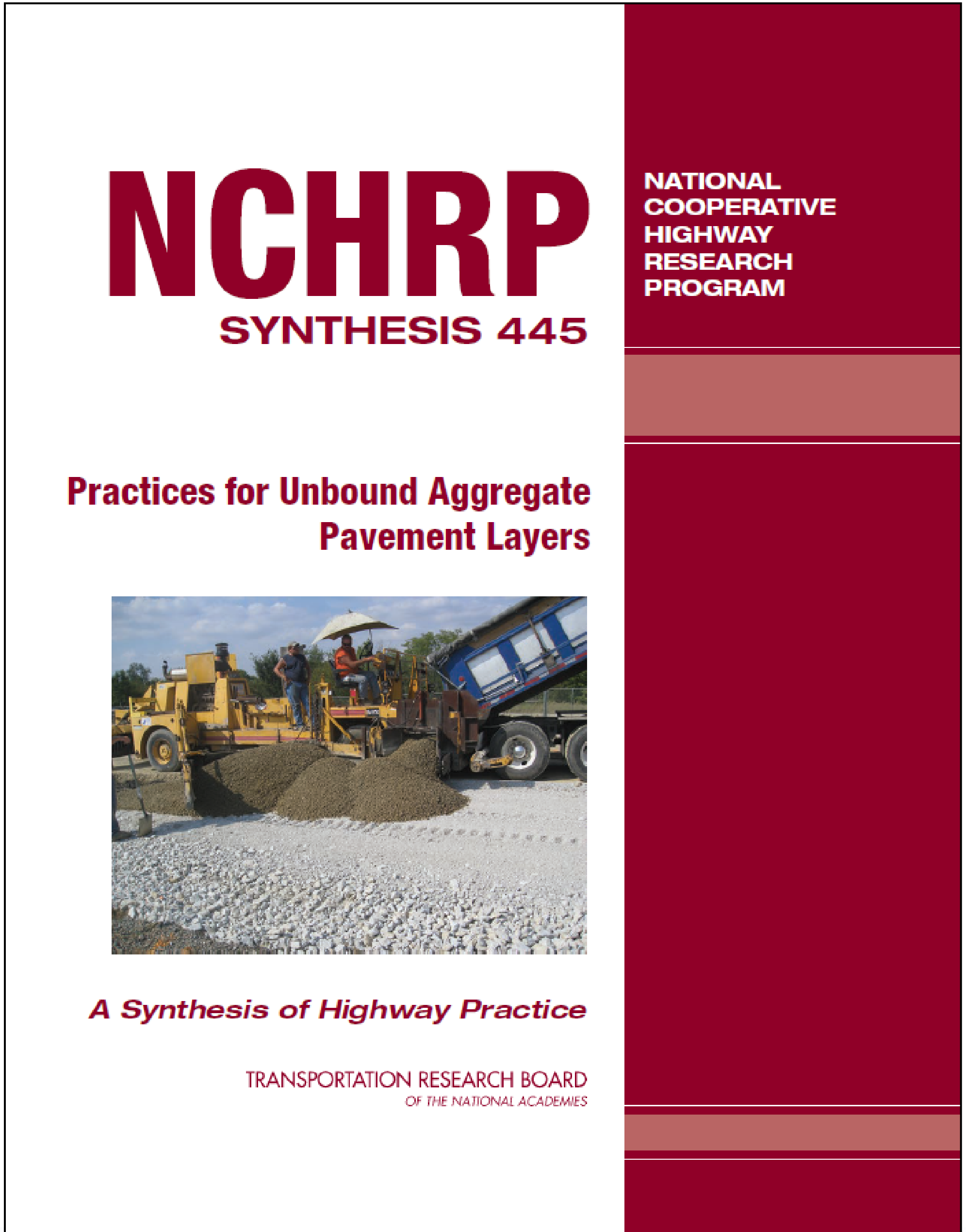
# Minimize Rutting Due to Shearing in Base


- **Resist shear deformation** within the aggregate base
  - Crushed, high quality angular stone for higher stability
  - **Proper compaction!!!**

**(Density, Density, Density…)**




**ICT R27-81 Research Project**
(Mishra & Tutumluer, 2013; ict.illinois.edu)

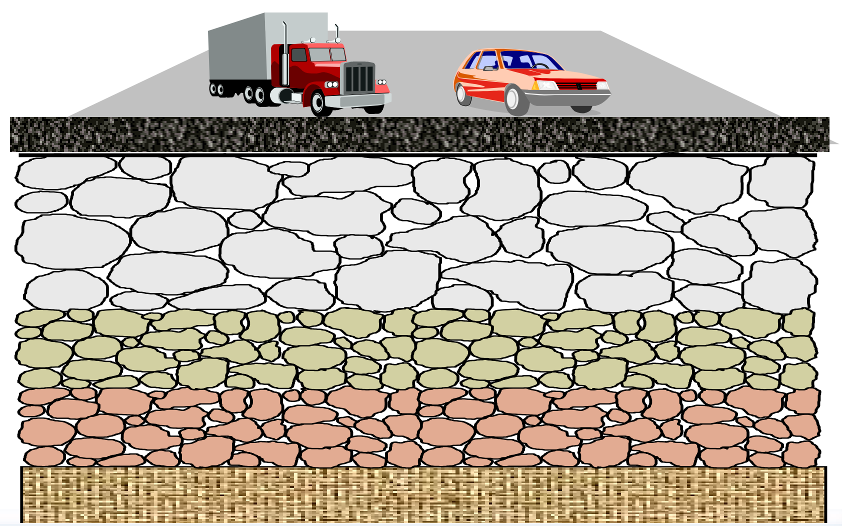



# NCHRP
# Synthesis 445

**(Tutumluer, 2013)**

Download from the TRB Website:

http://onlinepubs.trb.org/onlinepubs/
nchrp/nchrp_syn_445.pdf

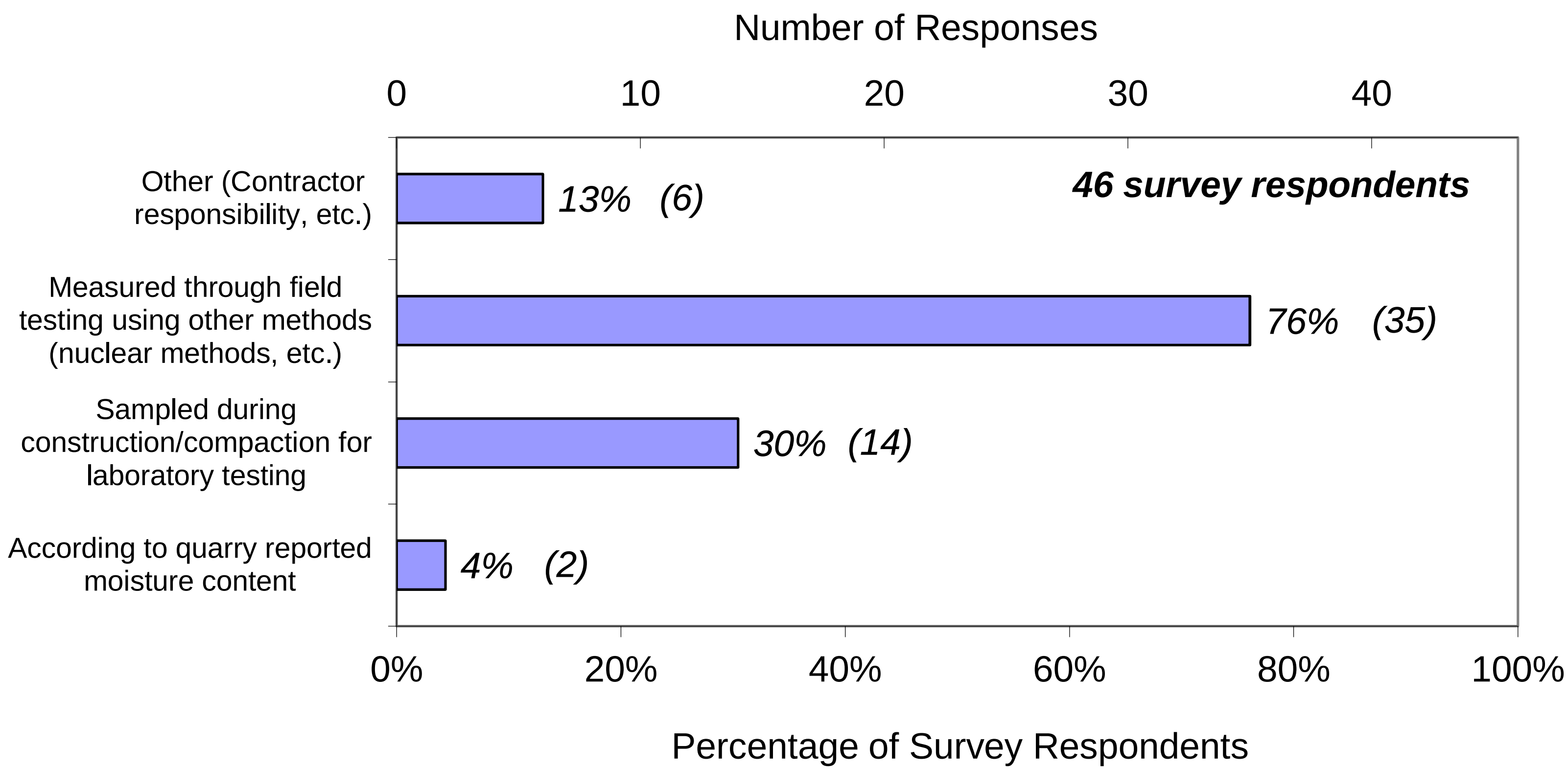


# **Best Practices:** Aggregate Layers

- **Equipment:**
  - Mixing by stationary plant e.g. pugmill / rotary mixer.
  - Use mechanical spreaders to avoid segregation & achieve grade control.
  - Suitable vibratory compaction equipment.
- **Mixing and Transporting:**
  - Plant mix aggregates and water to OMC +1% / -2%
  - Transport to site avoiding segregation and loss of moisture.
- **Spreading:**
  - Place at correct moisture & thickness by mechanical spreader.
  - When thickness >13 inches, consider 500-ft long test section to demonstrate adequate compaction without particle degradation.

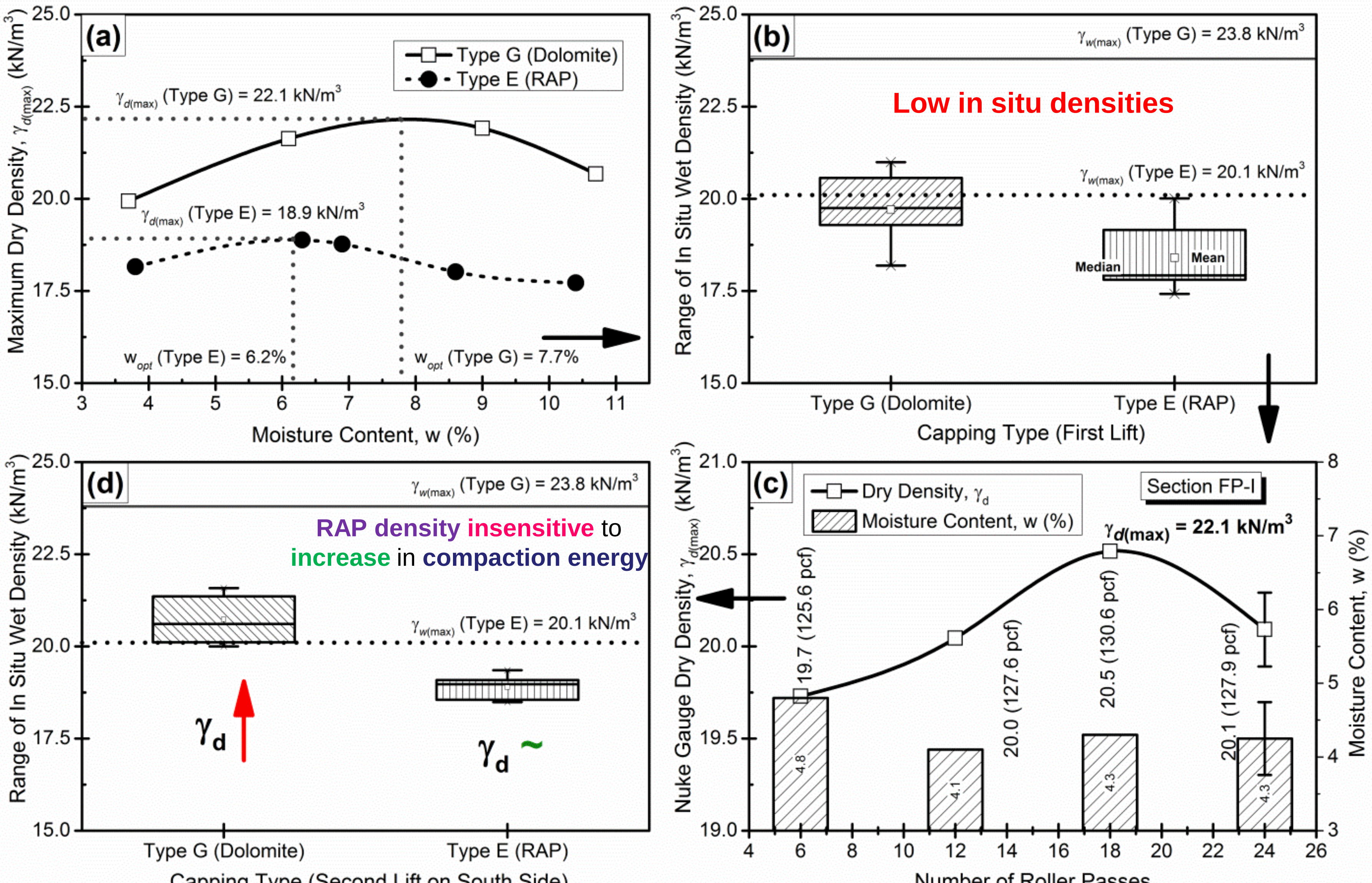
# Aggregate Placement & Compaction

# Methods to Control the Moisture Content of Unbound Aggregate Base/Subbase Layers




*(NCHRP Synthesis 445 - 2013)*

# Laboratory & In Situ Compaction (soft subgrade)



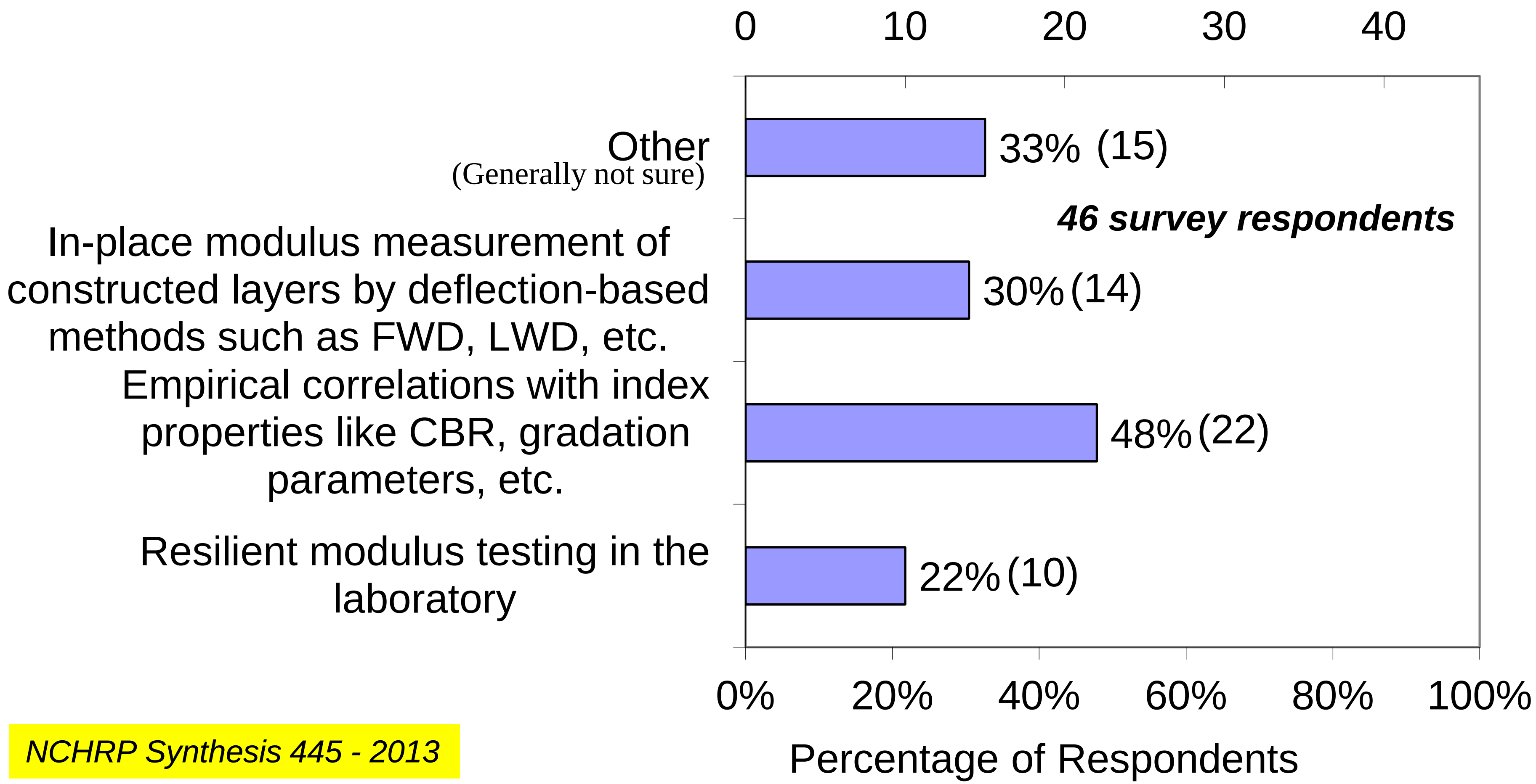

(Kazmee & Tutumluer, 2015)

# In-Place Modulus Measurement of Constructed Aggregate Layers

- ✓ Density **is not a required input** for Mechanistic-Empirical pavement design methods

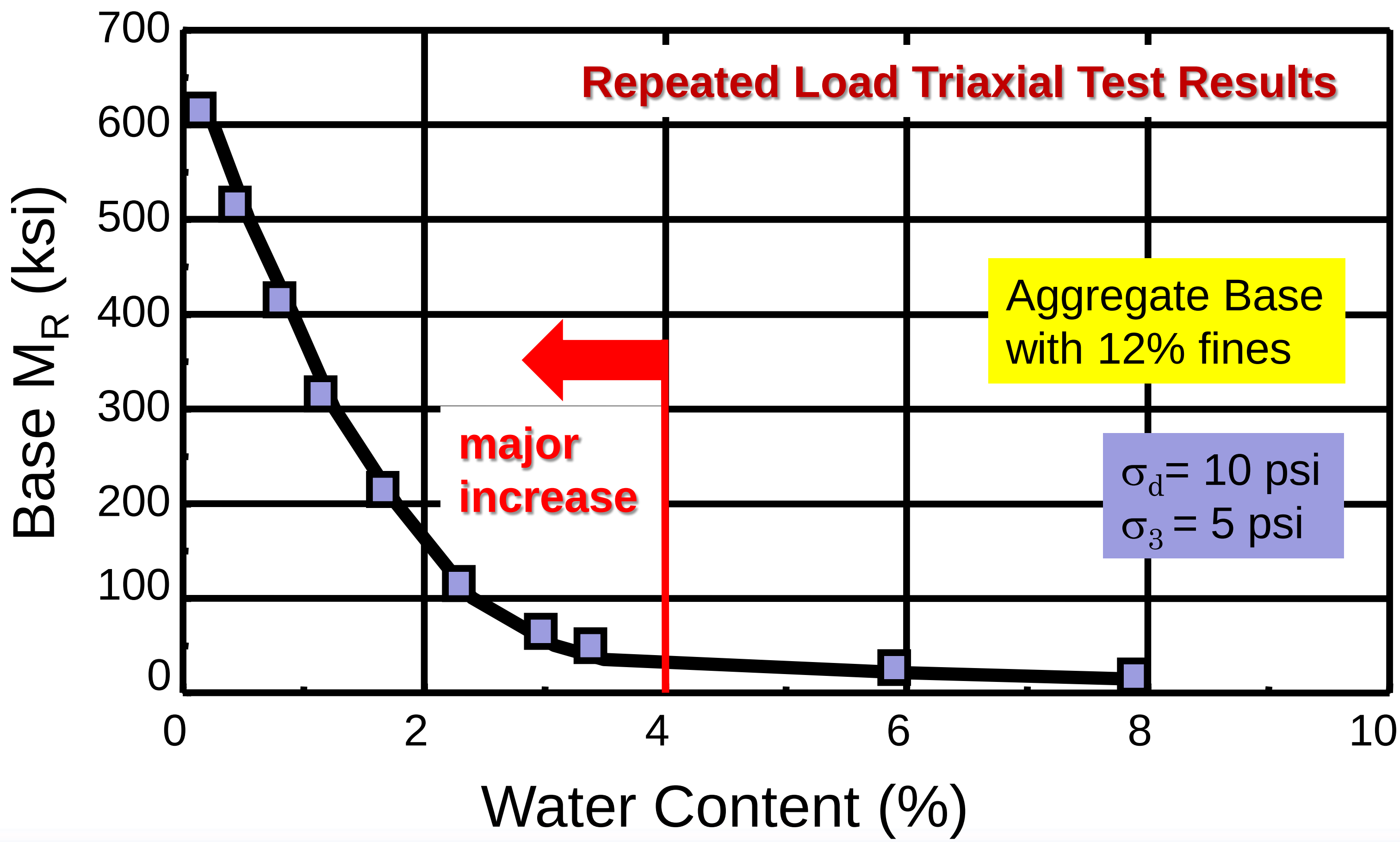
- ✓ Resilient modulus ($M_R$) is used as a key input
  - ✓ Using $M_R$ for construction quality control may facilitate linkage with design methods

# Methods to Determine the Resilient Modulus of Unbound Aggregate Materials for Use in Granular Base and Subbase Layers



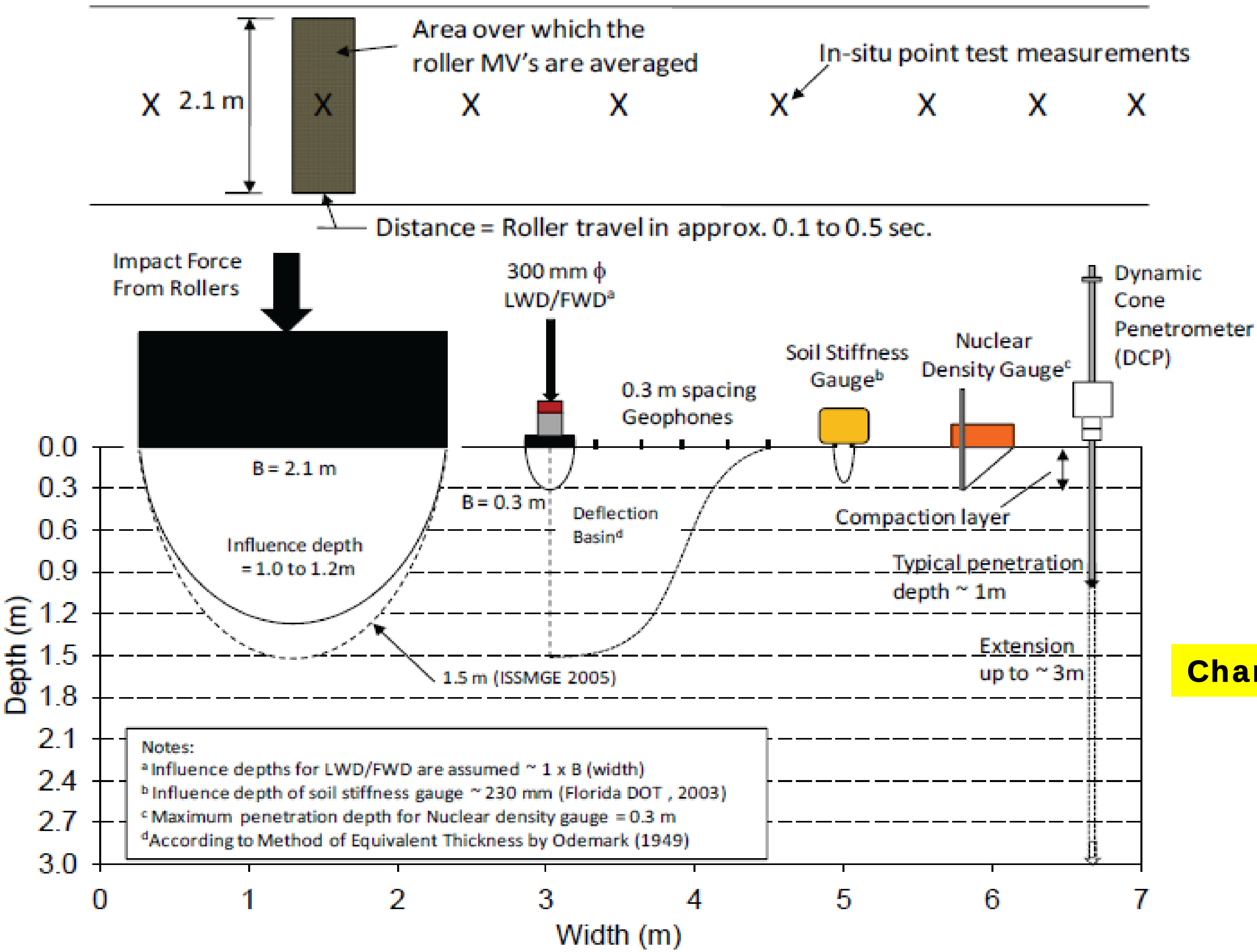

*NCHRP Synthesis 445 - 2013*

# Moisture (Suction) Effects on Aggregate Base Course Resilient Modulus ($M_R$)



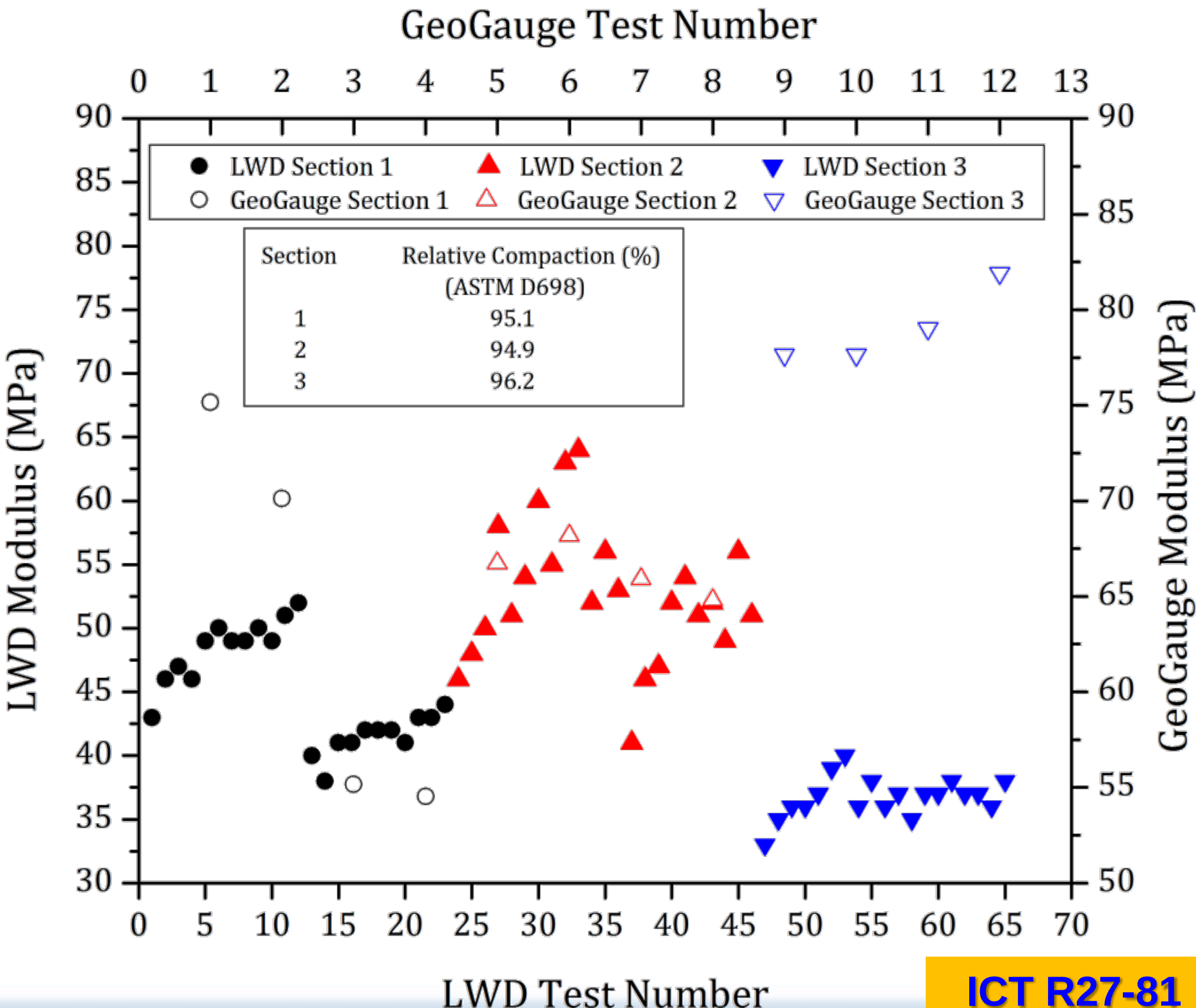
# Different Methods for In-Situ Modulus Measurement


# Need to Know What We Are Measuring !!




**Chang et al. (2011)**

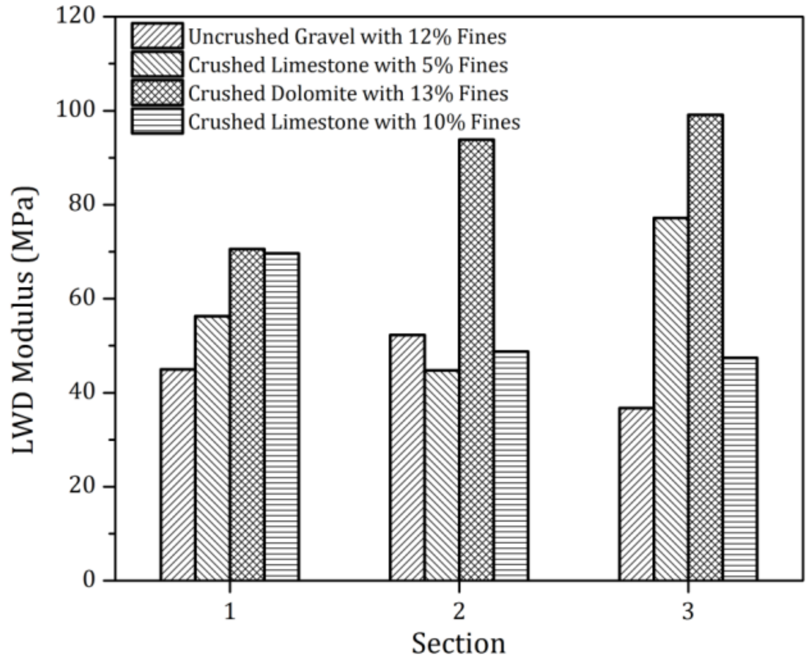
# Need to Know What We Are Measuring !!

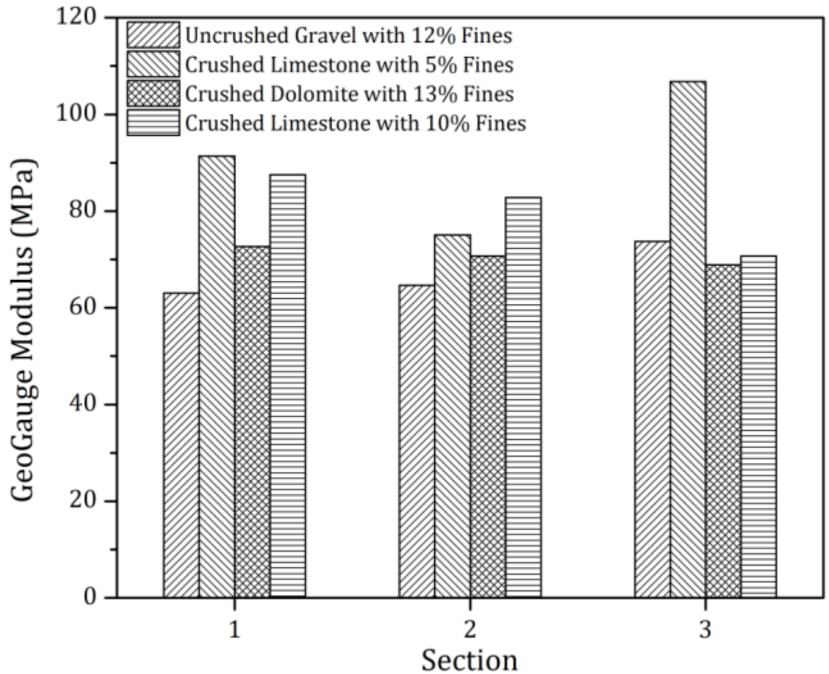


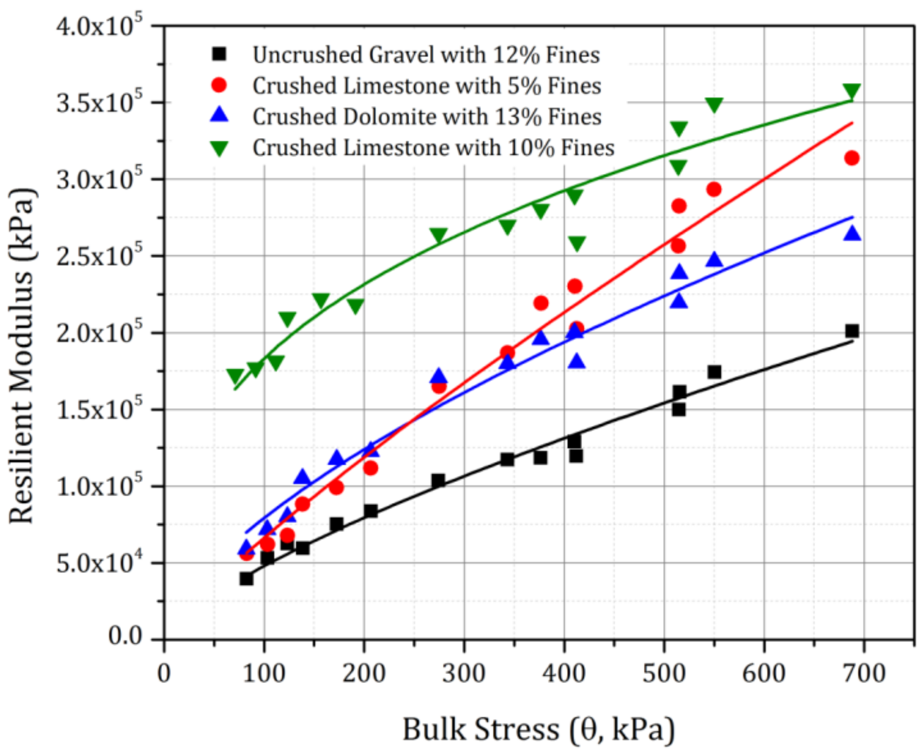

**Constructed Aggregate Layer Modulus Measure-ment**

**ICT R27-81 Research Project**
(Mishra & Tutumluer, 2013; ict.illinois.edu)

# Comparing Field Moduli with Lab $M_R$




**Field moduli do not always relate to material quality as good as Lab $M_R$**

# Modulus-Based Compaction Control

- ✓ Combine the aspects of in-place modulus measurement and construction quality control

- ✓ Key issues to consider
  - ✓ Measurement Depth
  - ✓ Induced Stress State (In relation to Strength)
  - ✓ Proper Algorithms for Layer Modulus Estimation

*NCHRP Synthesis 445 (2013)*

- ✓ Ideal approach (Do not rely on any one measurement!)
  - ✓ Density: Target Value ± Tolerance
  - ✓ Moisture Content: Target Value ± Tolerance
  - ✓ ***Layer Modulus:*** Target Value ± Tolerance

# Development of Modulus-Based Compaction Control Specifications

## Requirements:

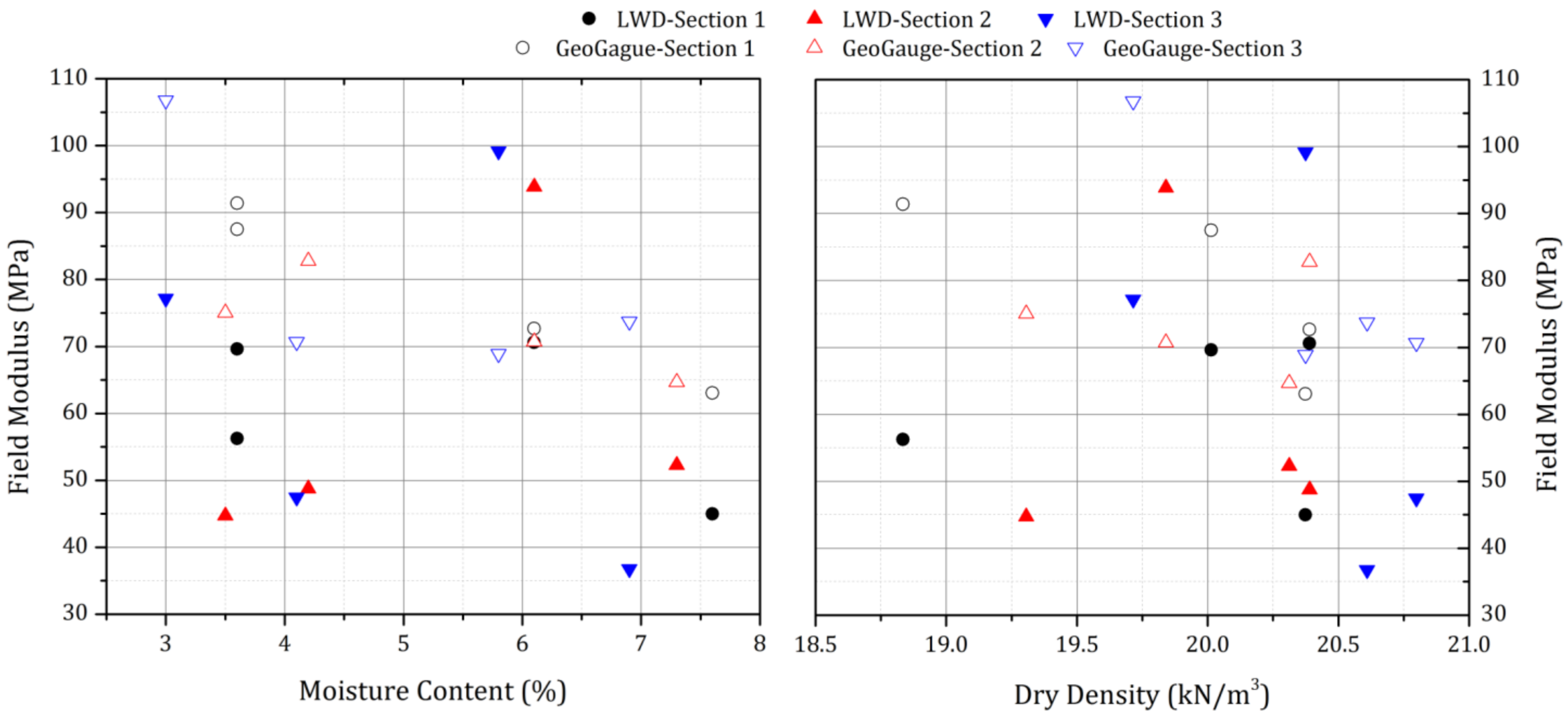
*NCHRP Project 10-84*

- Should be based on field measures of the **stiffness or modulus** and **moisture content**
- Should directly account for the **seasonal variation of the modulus** of the compacted unbound aggregate
- Should be founded on a comprehensive review of the current literature on the **long-term behavior of various soils and unbound aggregates** in terms of the principles of **unsaturated soil mechanics**

Indiana and Georgia implement modulus-based compaction control for demonstration projects only

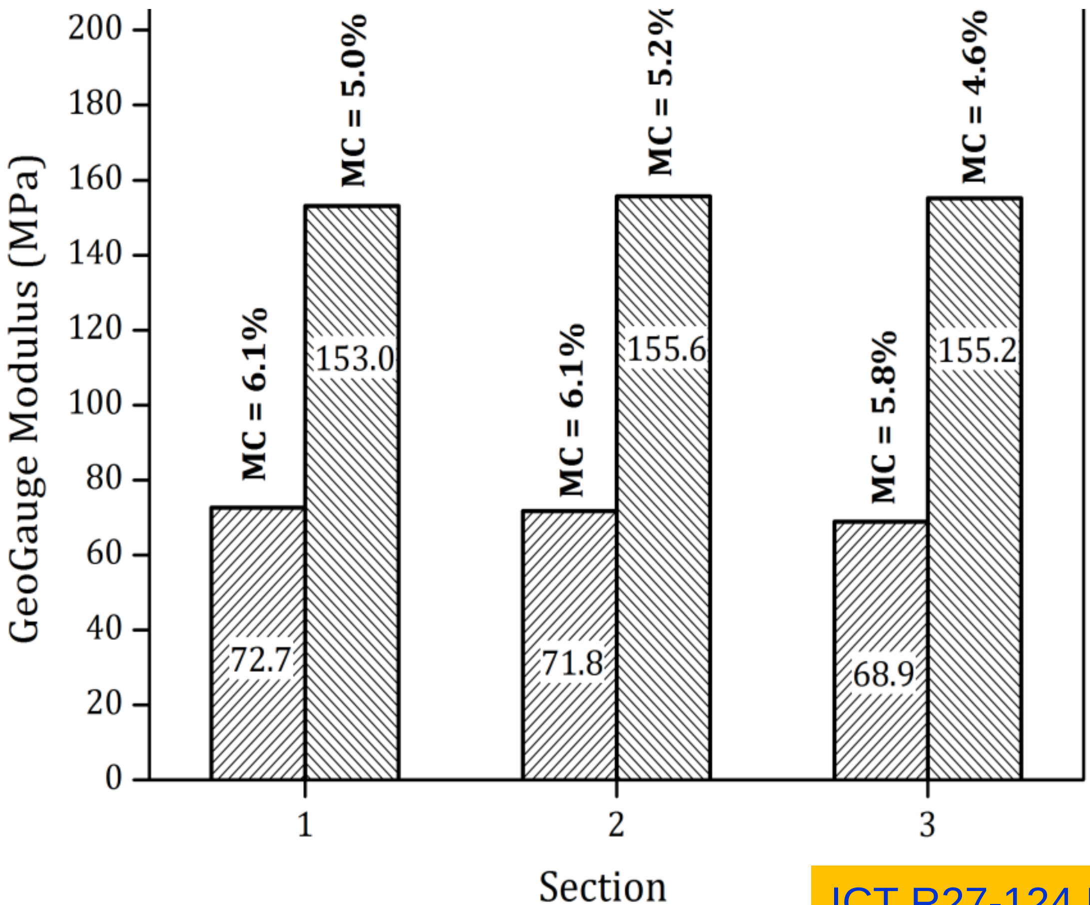
# Effect of Moisture Conditions in the Field

**ICT R27-81** (Mishra & Tutumluer, 2013)




- **Increase in Moisture → Decrease in Field Modulus**
- **No clear trend in effect of dry density**

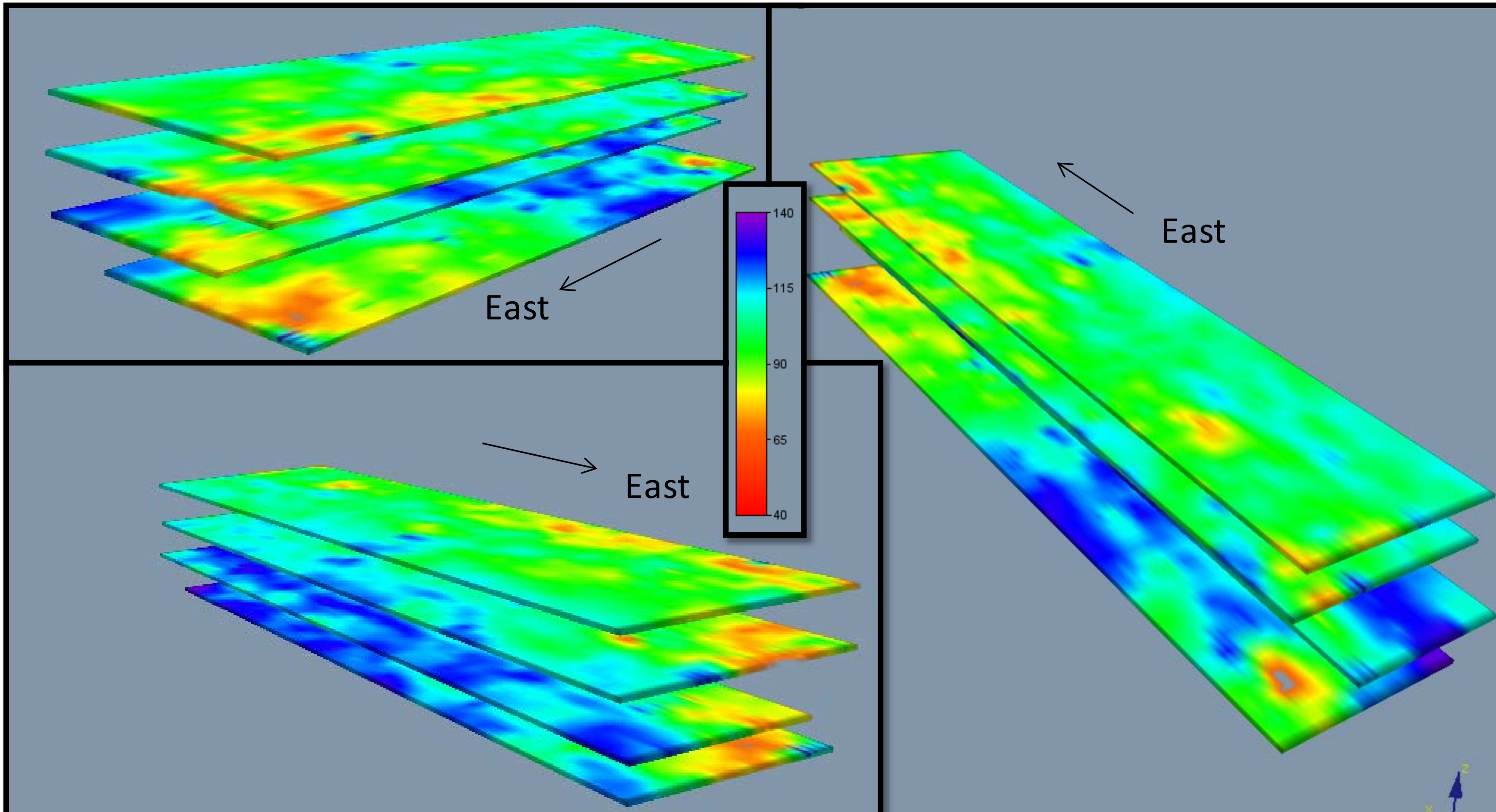
# Moisture (Suction) Effects on Field Modulus Increase




- Crushed dolomite
- 11% passing No. 200 sieve
- Nonplastic fines

ICT R27-124 Project; (Kazmee & Tutumluer, 2015)

# Variation of response as detected by sensors in a roller compactor



# Webinar Conclusions

- Moisture changes suction
- Suction changes resilient modulus & rutting resistance
  - Therefore granular layers in pavements are sensitive to moisture and other factors that change suction
- Tools available to measure suction and suction effects
- Better compaction occurs when suction low (near OMC)
- Density has value in providing basic mineral skeleton, but modulus is fundamentally important and is sensitive to suction/moisture effects.
- Assessing in-situ density or modulus by indirect methods must acknowledge moisture/suction effects

# Question Time