DESIGNING BASES AND SUBGRADES FOR BETTER PAVEMENT PERFORMANCE

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Houston Foundation Performance Association

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Better Models for Base Course and Subgrade for Pavement Design and Performance Prediction

NCHRP 1-53 Project

AASHTO Pavement ME Design Product Task Force

Hilton Savannah Desoto Hotel
Savannah, Georgia
April 4-5, 2017

Introduction and Objectives

- Problem: performance of flexible and rigid pavements shows low sensitivity to subgrade/unbound layer properties

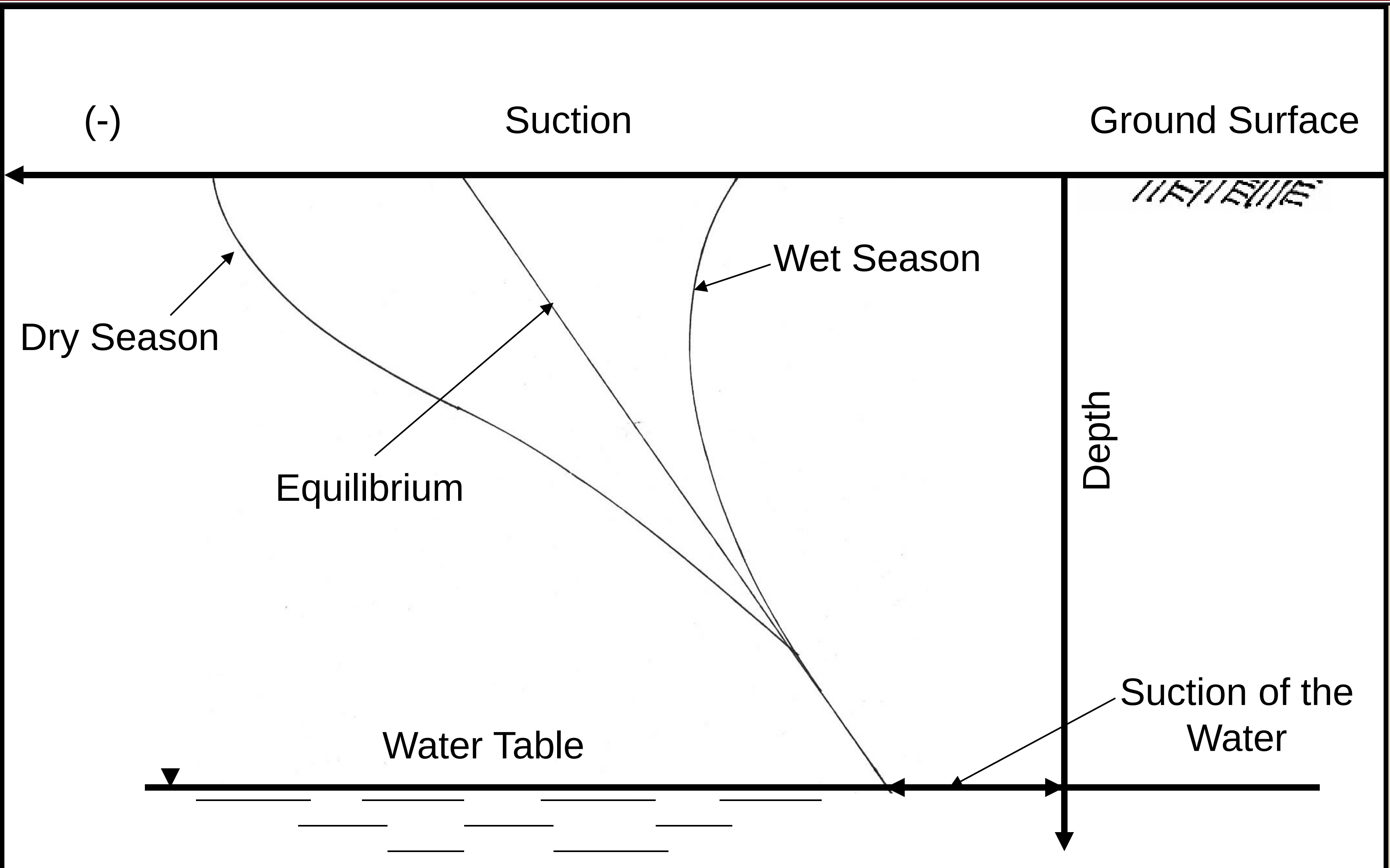
- Objective: propose enhancements needed to better reflect the influence of subgrade/unbound layers (properties and thickness)

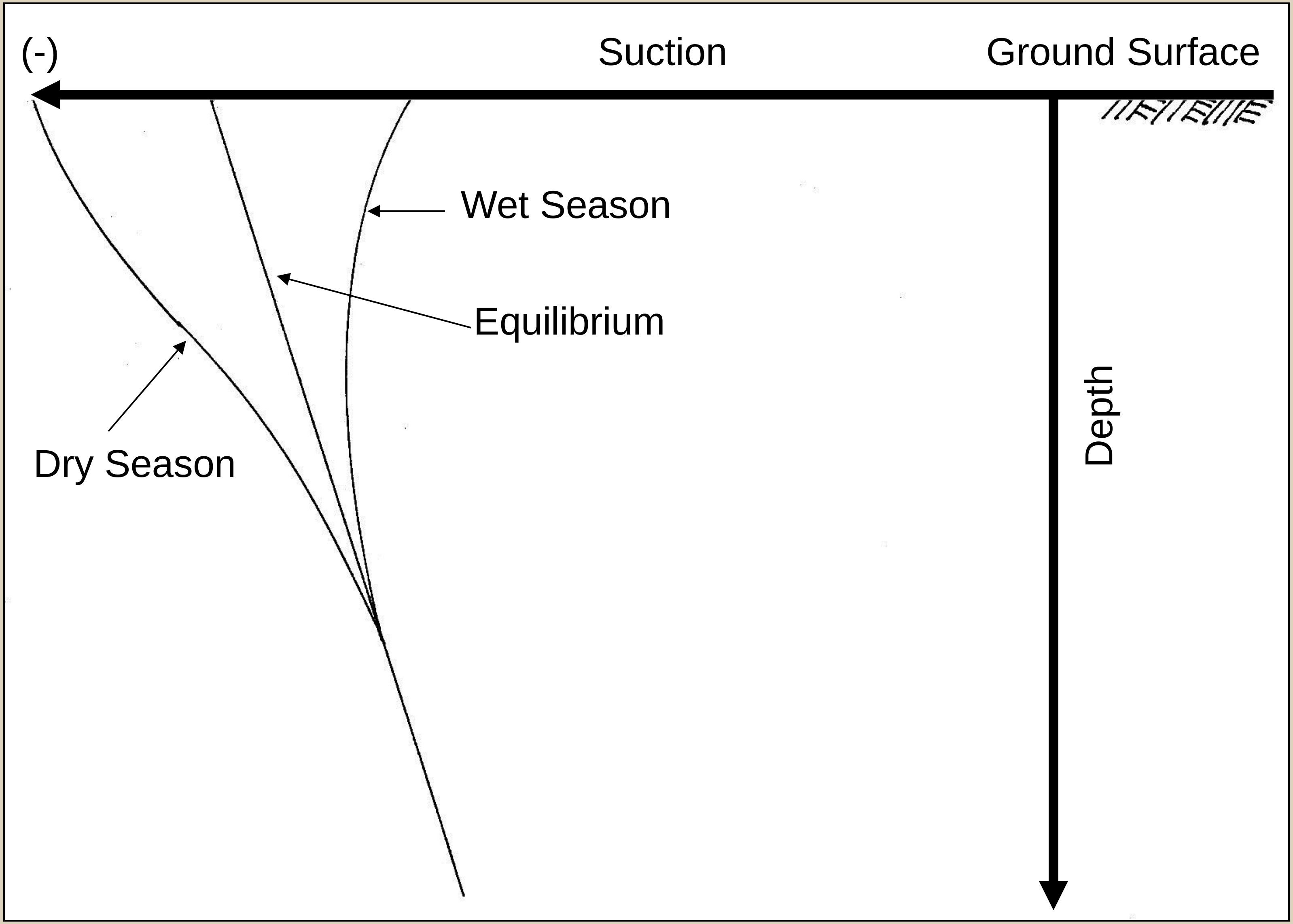
What do we need to emphasize? (1/2)

- Unbound layers
  - Modulus: moisture-sensitive, stress-dependent, cross-anisotropic
  - Permanent deformation: moisture-sensitive, stress-dependent
  - Shear strength: moisture-sensitive
  - Erosion
  - Thickness

What do we need to emphasize? (2/2)

- Subgrade
  - Modulus: moisture-sensitive, stress-dependent
  - Permanent deformation: moisture-sensitive, stress-dependent
  - Shear strength: moisture-sensitive
  - Foundation

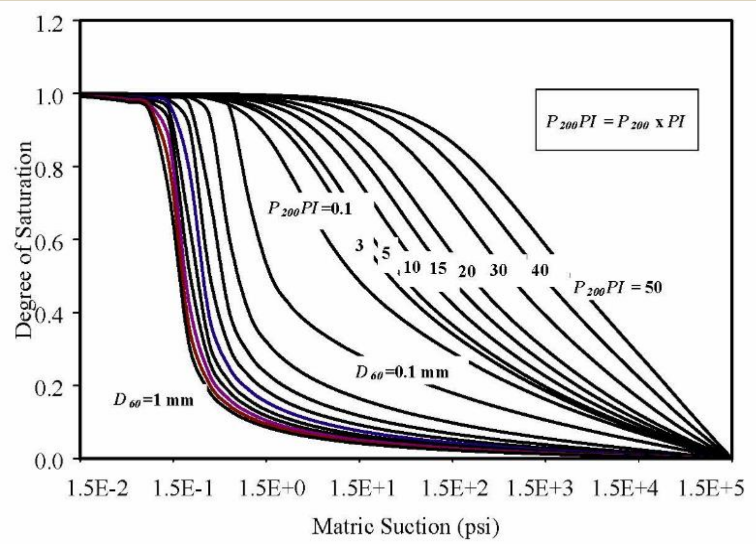

(-)
Suction
Ground Surface
Wet Season
Dry Season
Equilibrium
Depth
Suction of the Water
Water Table


(-)
Suction
Ground Surface
Wet Season
Equilibrium
Dry Season
Depth

Hierarchical Input Level

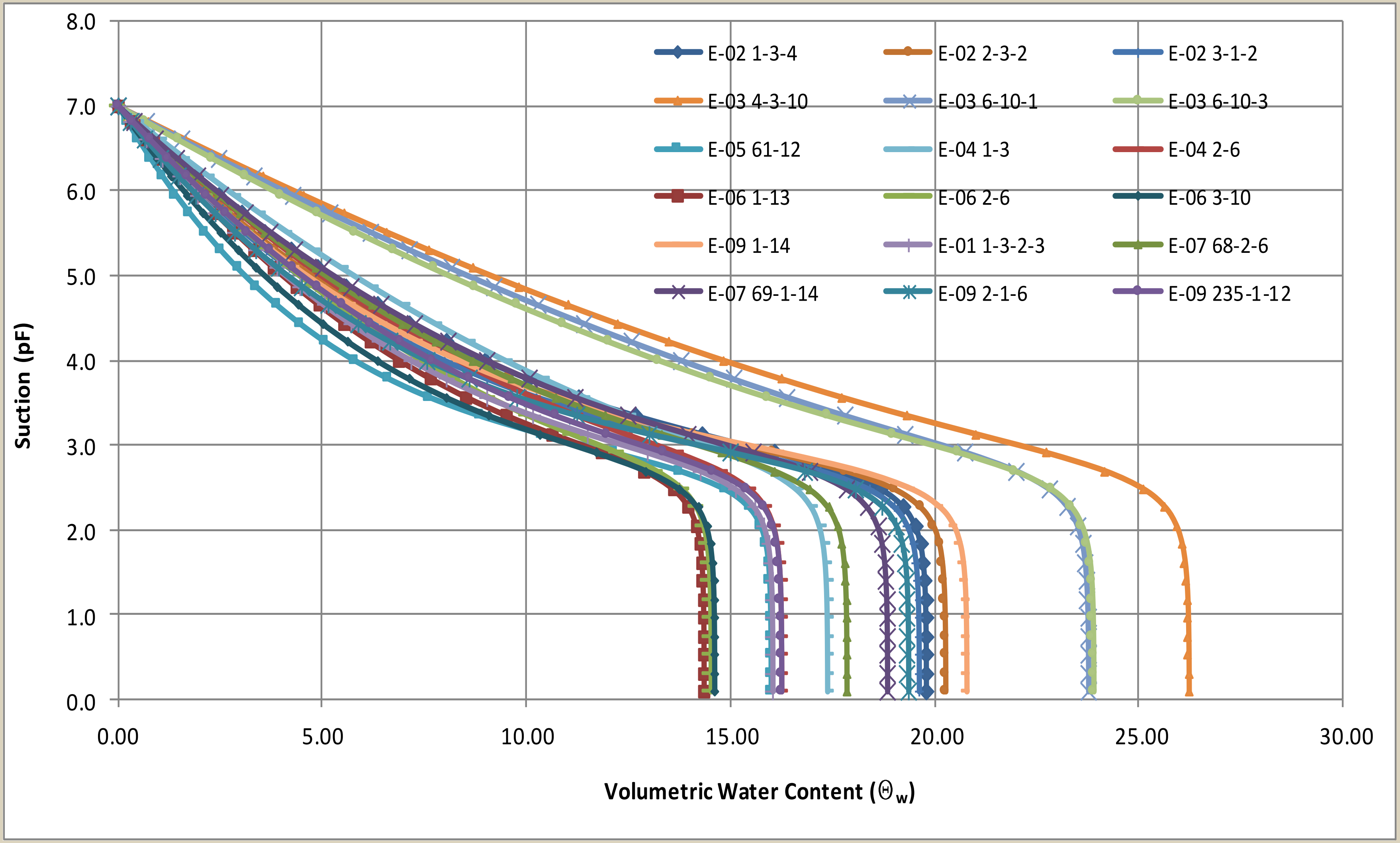
Level 1:

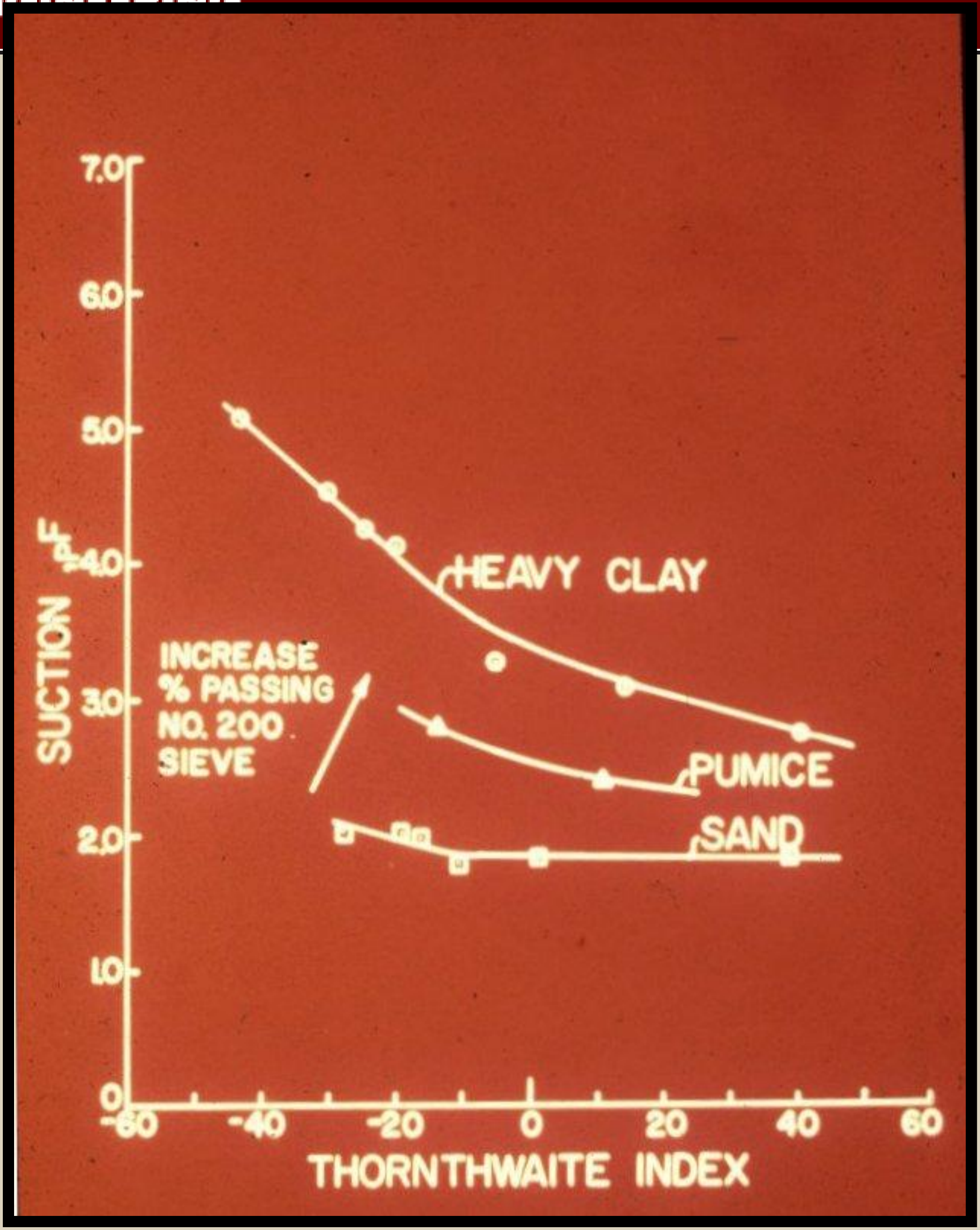
- Laboratory-measured k_1, k_2, k_3
- SWCC
- Equilibrium suction and its depth

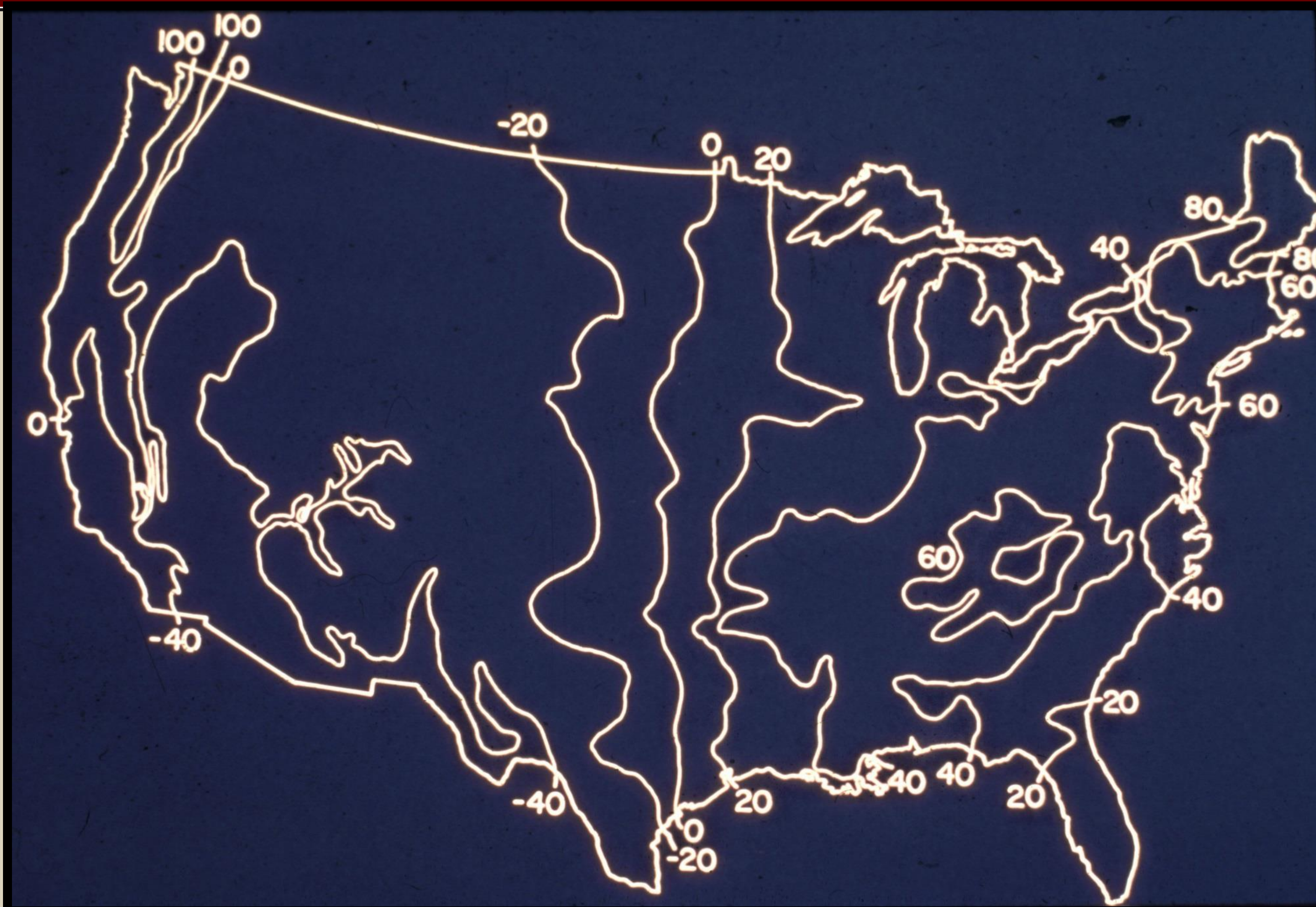


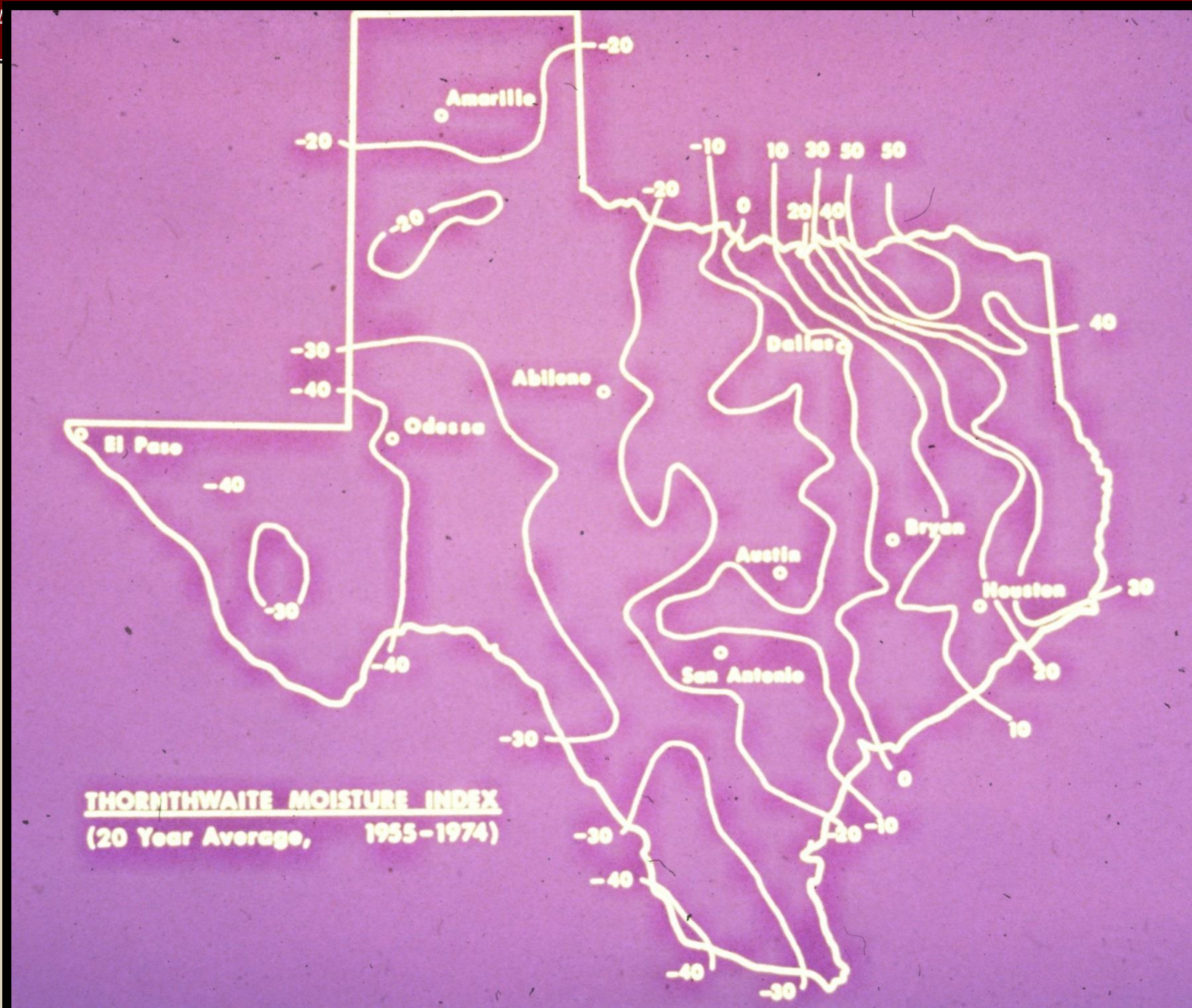
SWCC in Pavement ME Design

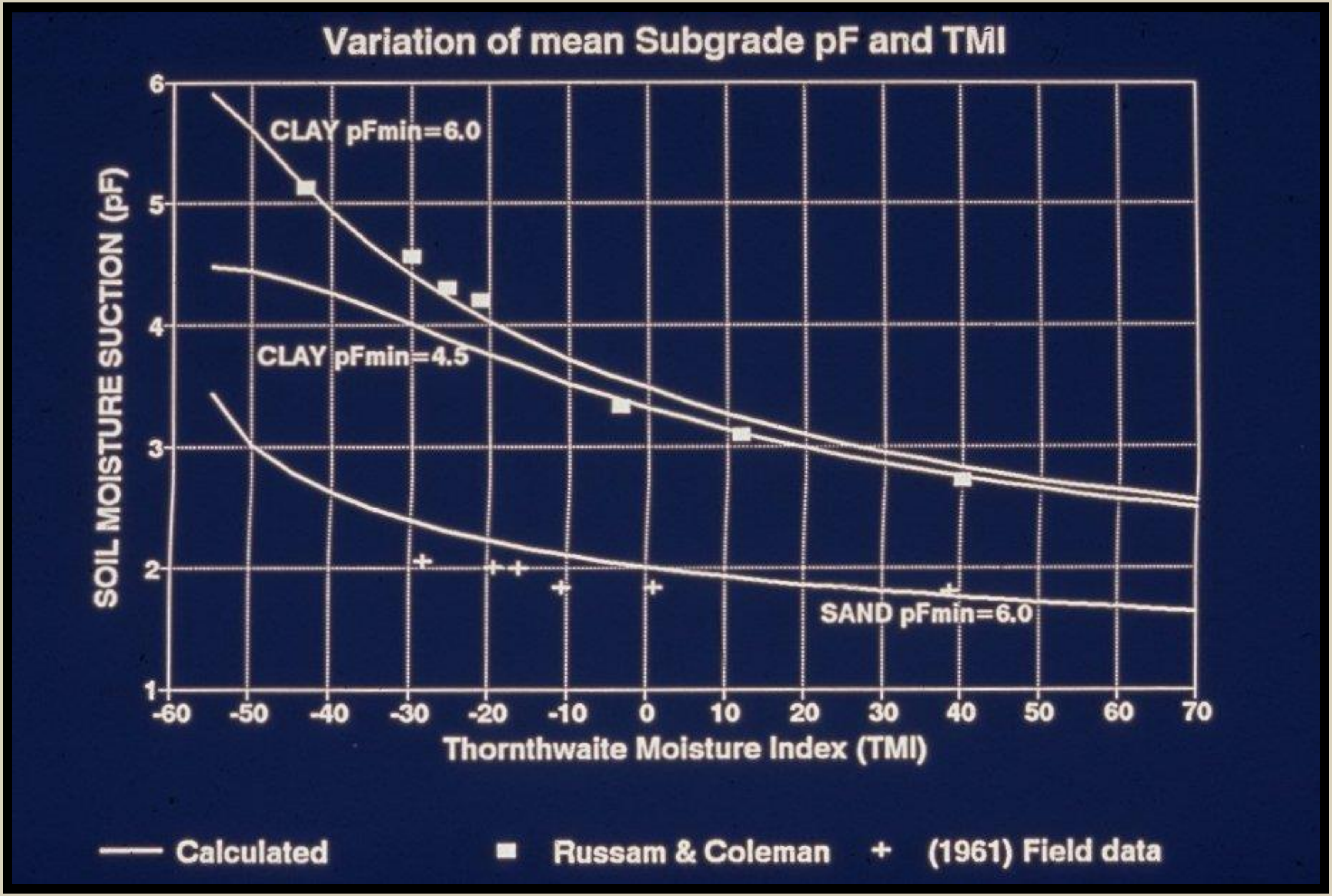
A Family of Generated SWCCs

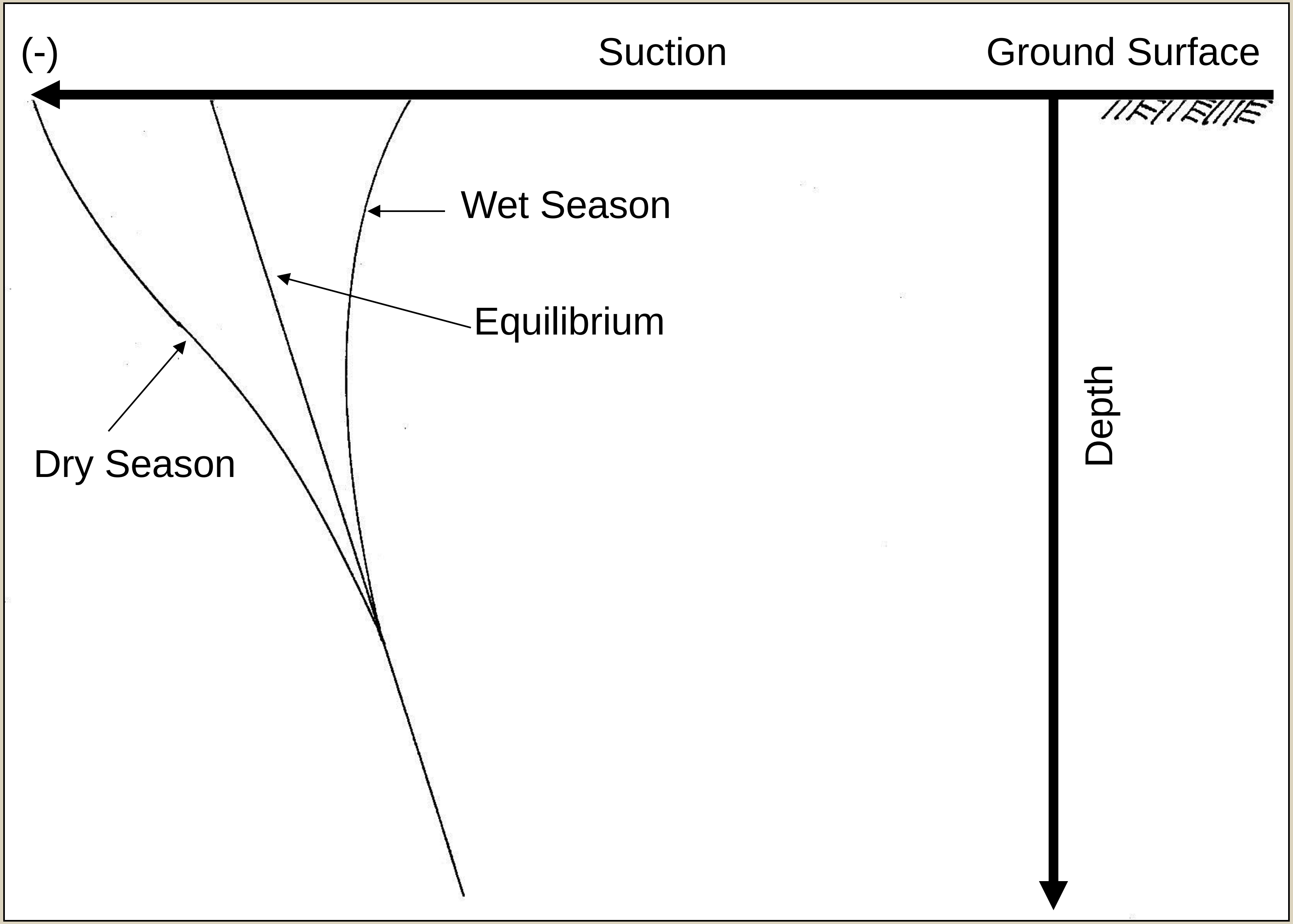



7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
SUCTION pF
HEAVY CLAY
INCREASE
% PASSING
NO. 200
SIEVE
PUMICE
SAND
-60
-40
-20
0
20
40
60
THORNTHWAITE INDEX


100
100
0
-20
0
20
80
40
80
60
0
60
60
40
-40
20
40
40
-40
20
0
-20
20


Amarillo
-20
-20
-20
-10
10 30 50 50
-20
0
20 40
Dallas
40
-30
Abilene
-40
Odessa
El Paso
-40
-30
Bryan
Austin
Houston
30
-40
San Antonio
20
10
-30
0
THORNTHWAITE MOISTURE INDEX
(20 Year Average, 1955-1974)
-30
-20 -10
-40
-40
-30


Variation of mean Subgrade pF and TMI
SOIL MOISTURE SUCTION (pF)
6
5
4
3
2
1
CLAY pFmin=6.0
CLAY pFmin=4.5
SAND pFmin=6.0
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70
Thornthwaite Moisture Index (TMI)
Calculated
Russam & Coleman
(1961) Field data

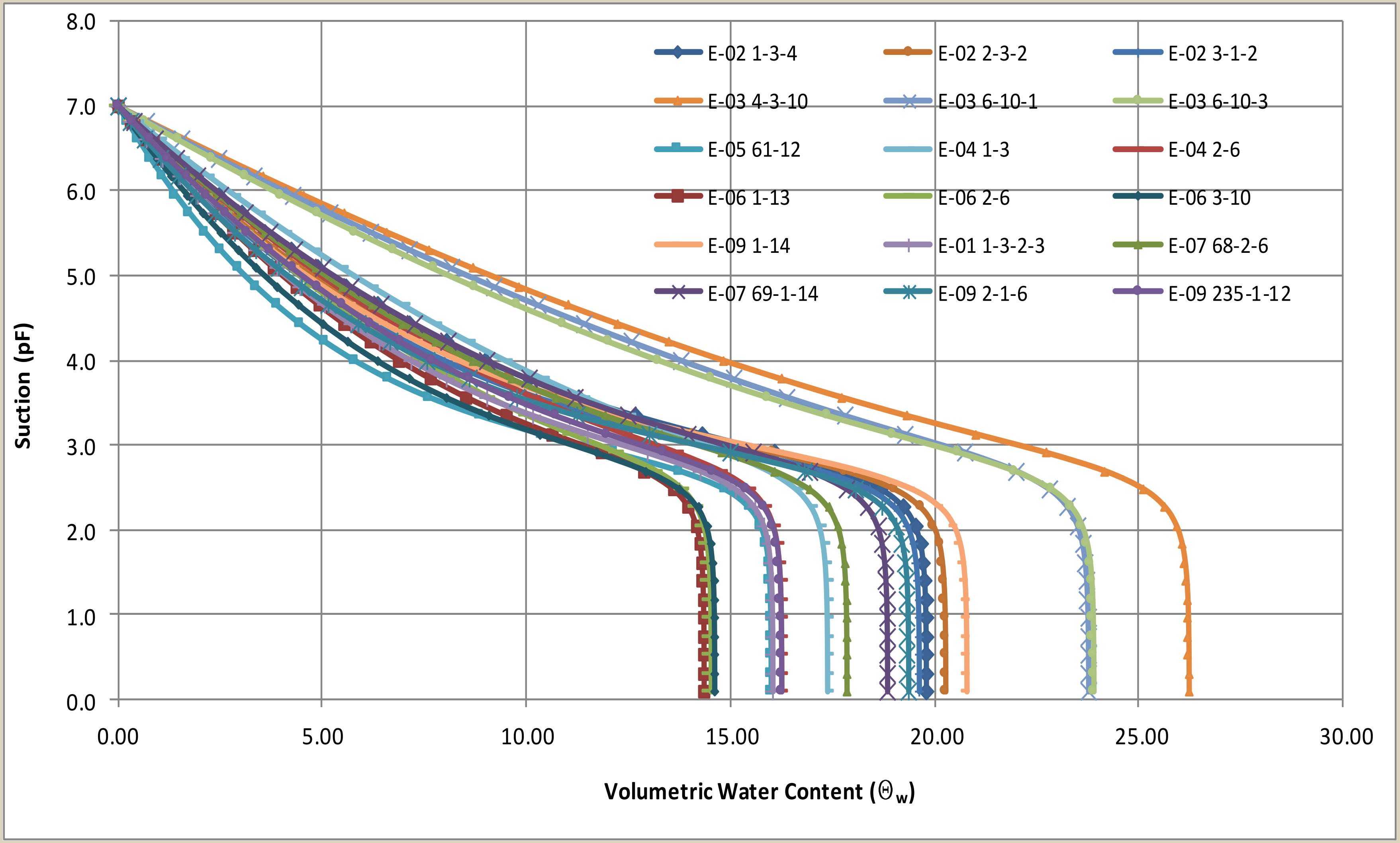

(-)
Suction
Ground Surface
Wet Season
Equilibrium
Dry Season
Depth

Some Characteristic Curves

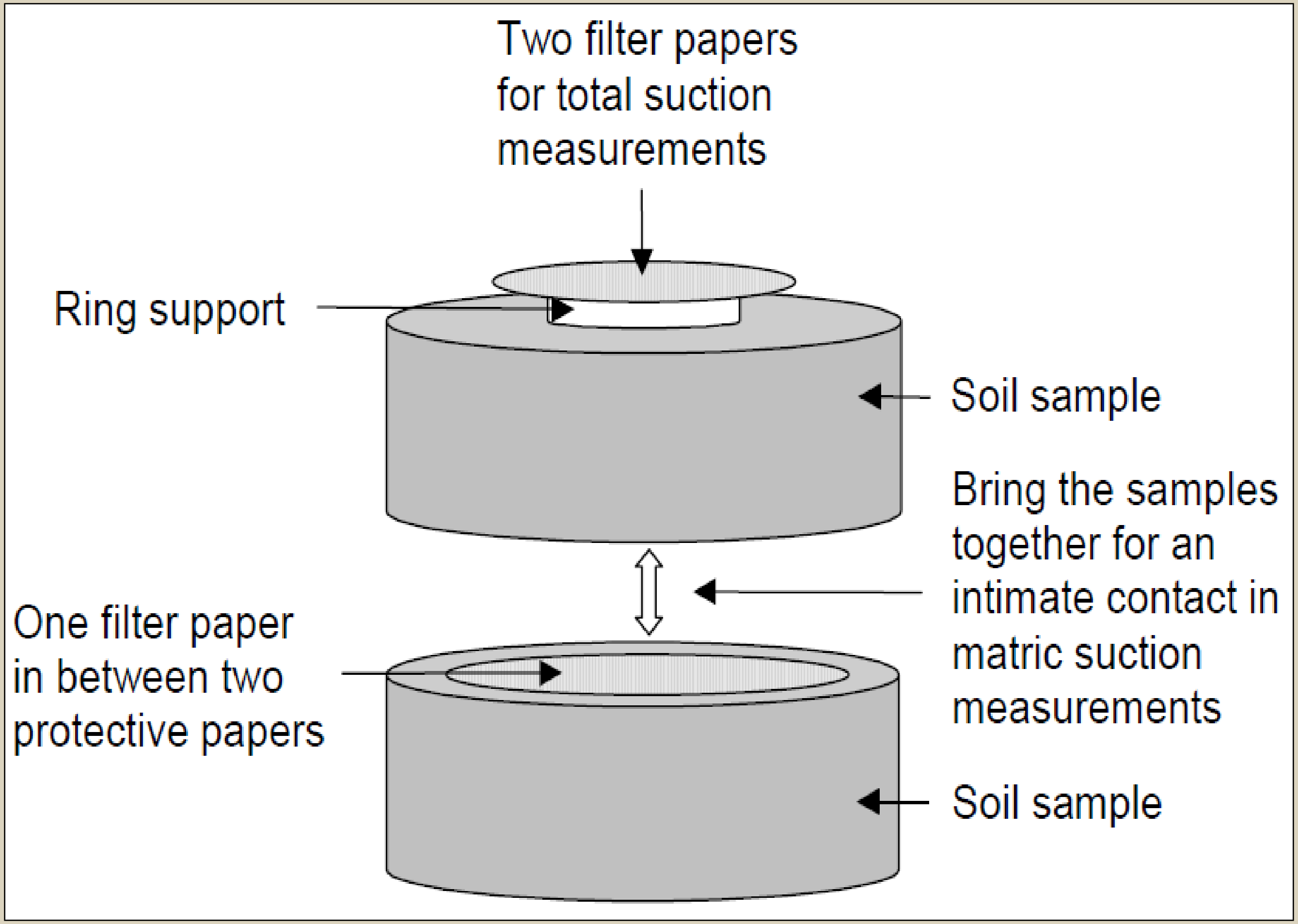
- Soil water characteristic curve
- Soil dielectric characteristic curve
- Soil conductivity characteristic curve
- Soil osmotic suction – evaporable water content curve
- Soil osmotic suction – electrical conductivity curve

Soil Water Characteristics Curve (SWCC)

A Family of Generated SWCCs



Filter Paper Suction Test Setup



Soil Water Characteristics Curve (SWCC)

Fredlund and Xing Equation (1994)

Saturated volumetric water content

$$\theta_w = C(h) \times \left[\frac{\theta_s}{\left[\ln\left[\exp(1) + \left(\frac{h}{a} \right)^b \right] \right]^c} \right]$$

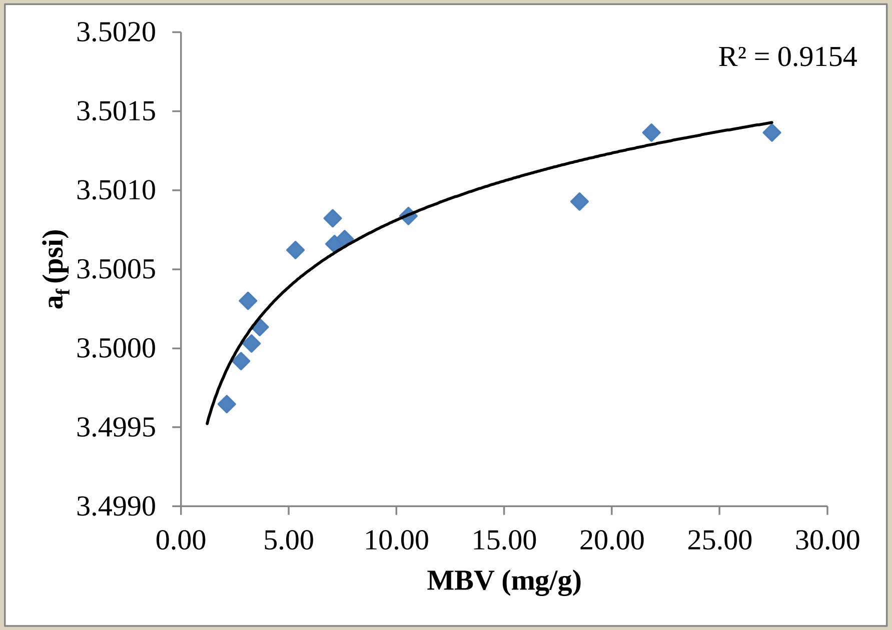
Volumetric water content

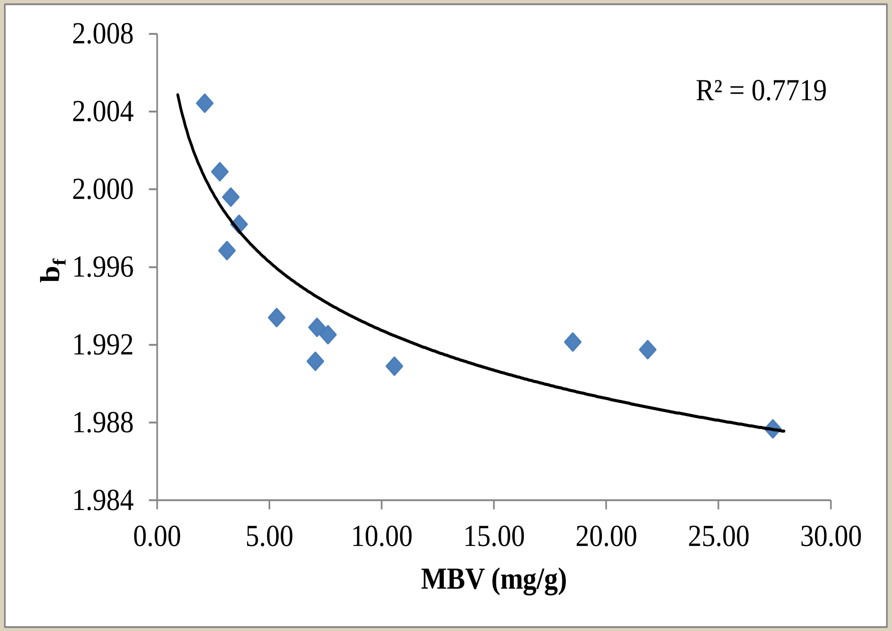
Four soil parameters

$$C(h) = \left[1 - \frac{\ln\left(1 + \frac{h}{h_r} \right)}{\ln\left(1 + \frac{10^6}{h_r} \right)} \right]$$

Four Parameters

Correlations for parameters a_f and b_f :



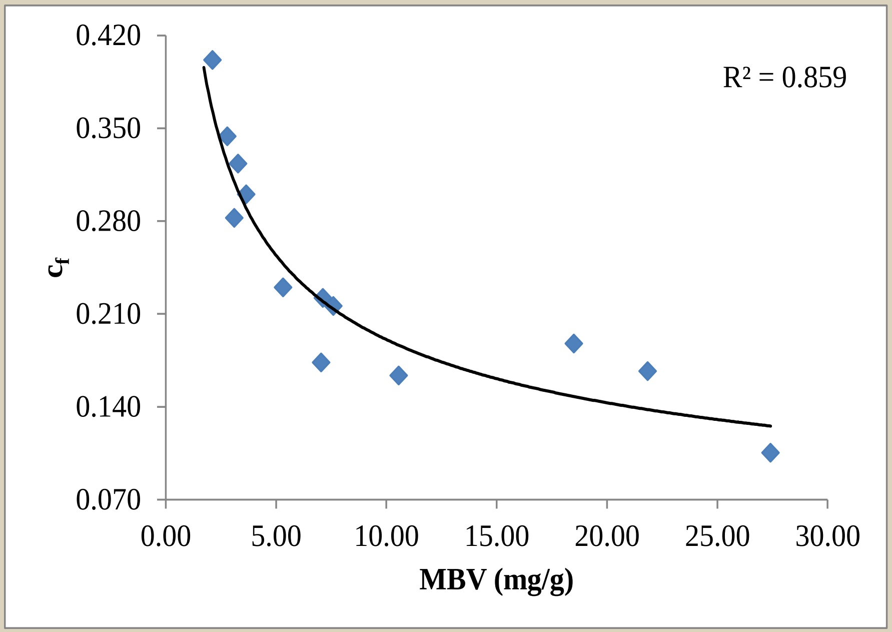


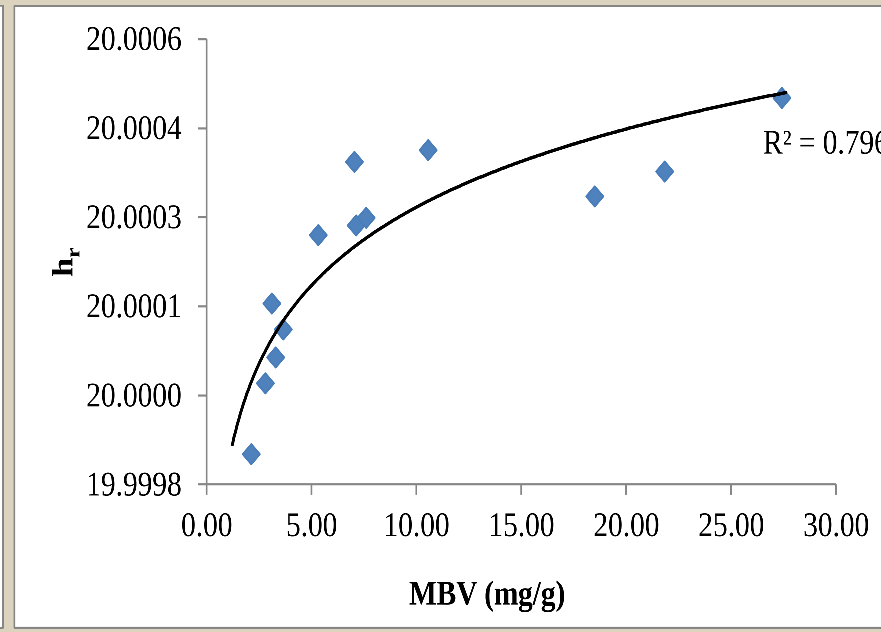
$$a_f = 3.4994 MBV^{0.0002}$$

$$b_f = 2.0044 MBV^{-0.003}$$

Four Parameters

Correlations for parameters c_f and h_r:





$$c_f = 0.4956 MBV^{-0.415}$$

$$h_r = 20.00 x MBV^{9.5E-06}$$

Soil Dielectric Characteristics Curve (SDCC)

Soil Dielectric Characteristics Curve (SDCC)

Curve fitting parameters

Saturated dielectric constant

$$\varepsilon_r = \left[\frac{\varepsilon_{sat} + \varepsilon_{\min} \alpha \left[\frac{h}{\left(1.45x10^5 - h\right)} \right]^{\gamma}}{1 + \alpha \left(\frac{h}{h_m - h} \right)^{\gamma}} \right]$$

Suction

Maximum Suction

Minimum dielectric constant

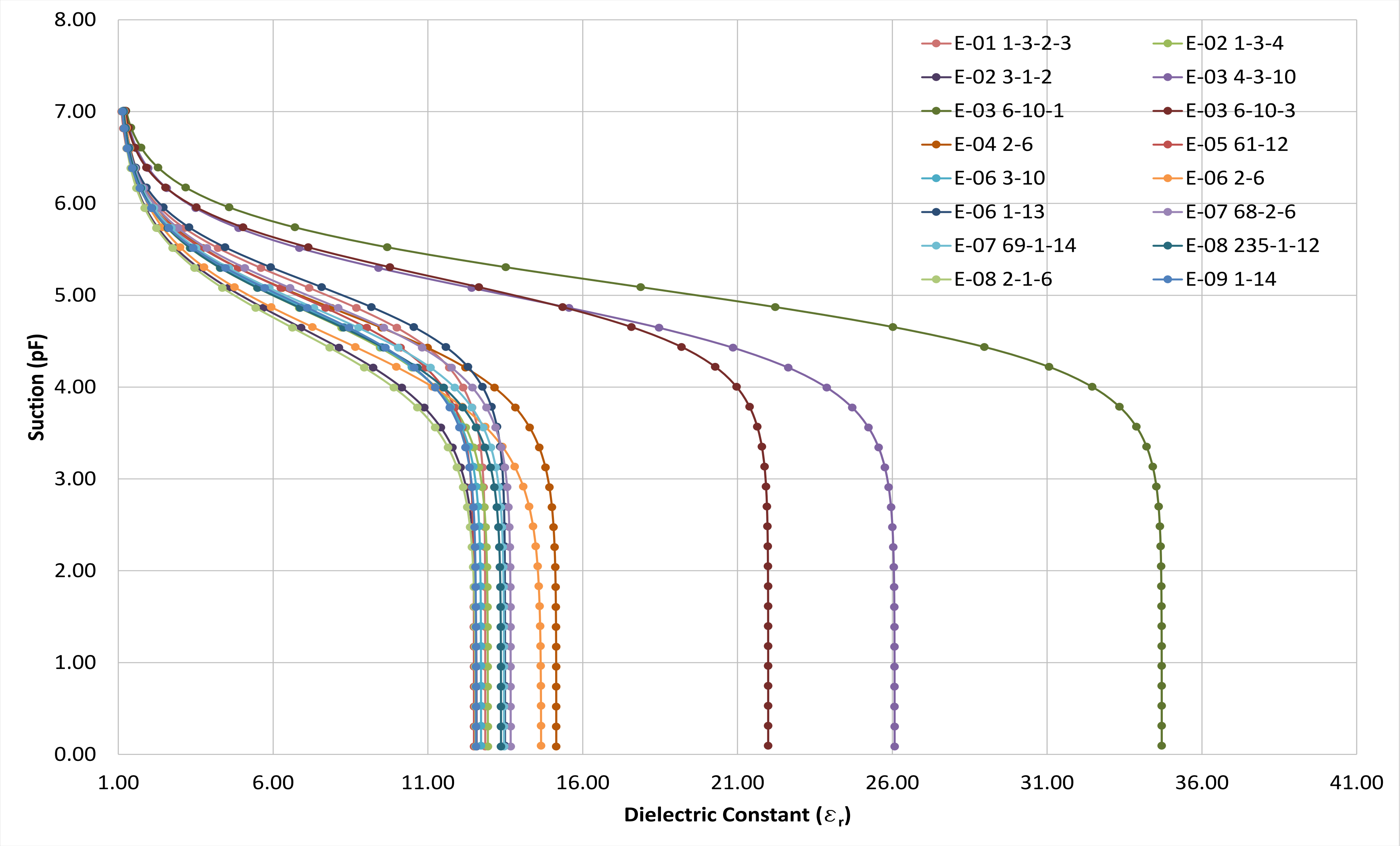
Dielectric constant

A Standard Percometer Device with Surface Probe

Dielectric Constant Measurements Process with a Percometer

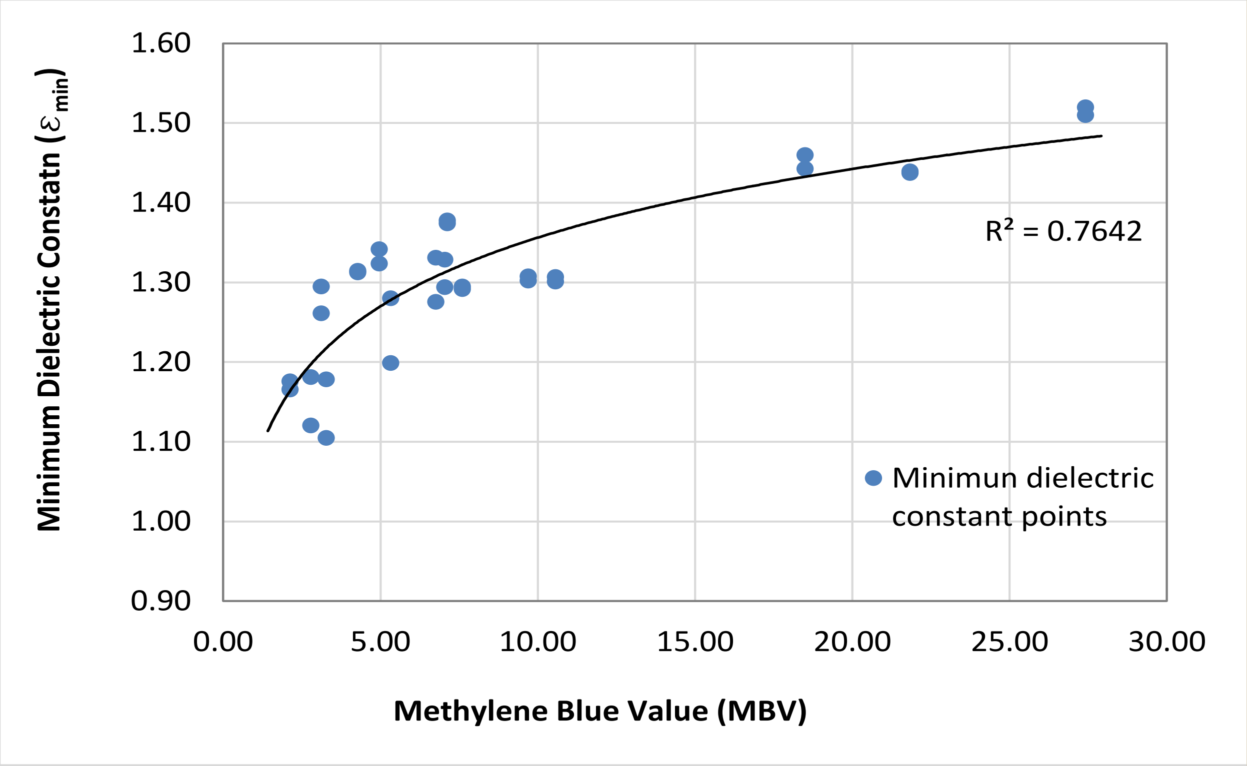
Material	Dielectric Constant
Air	1.0
Water	81.0
Asphalt	4.0-6.0
Concrete	8.0-12.0
Clay	4.0-40.0

A Family of Generated SDCCs



Minimum Dielectric Value

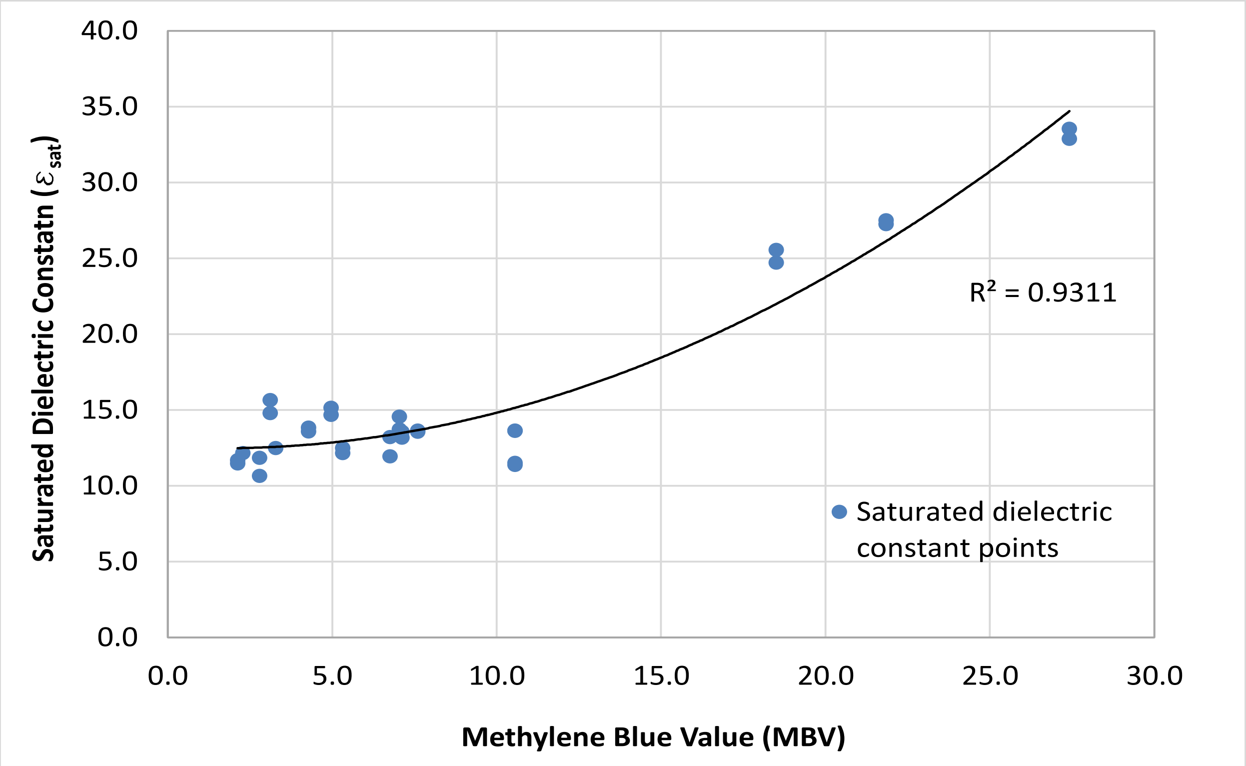
Correlation for minimum dielectric vs MBV



$$\varepsilon_{min} = 0.1243\log(MBV) + 1.0668$$

Saturated Dielectric Value

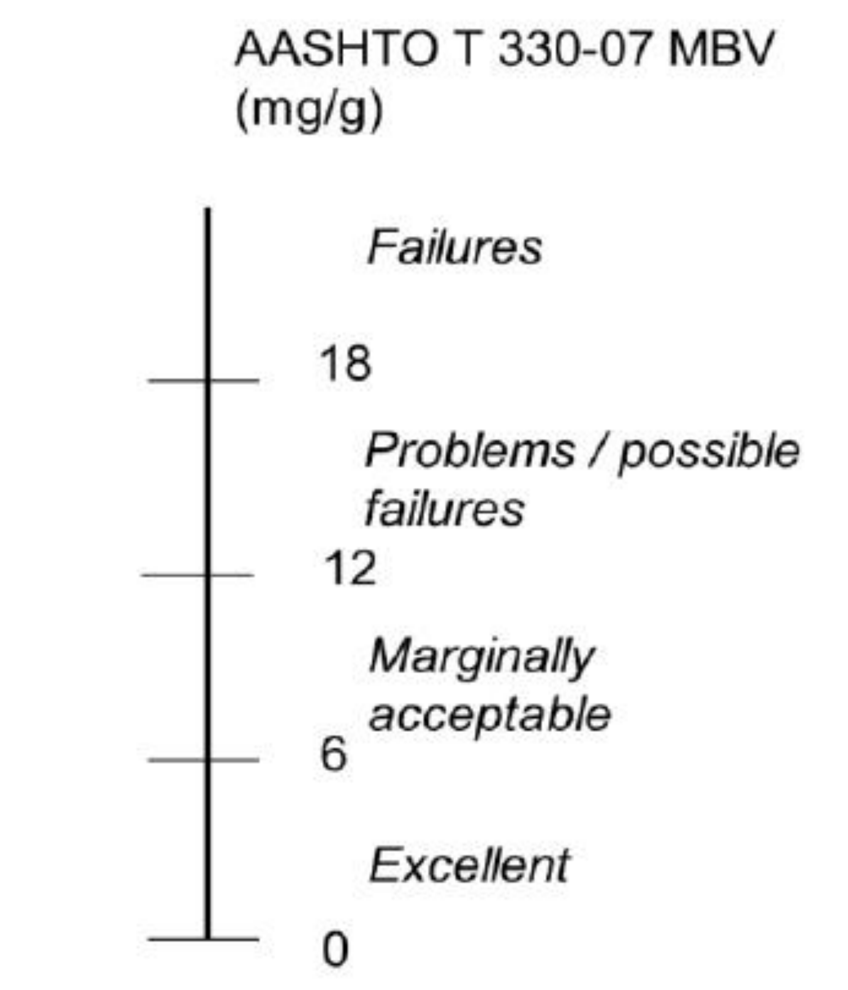
Correlation for saturated dielectric vs MBV



$$\varepsilon_{sat} = 0.0334(MBV^2) - 0.1086(MBV) + 12.569$$

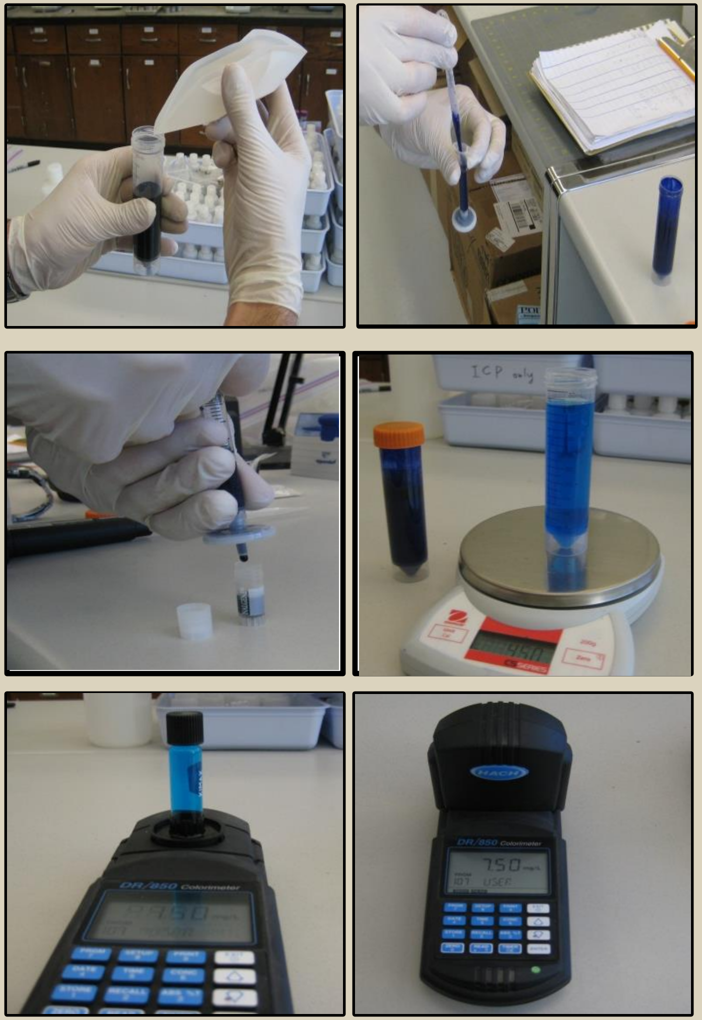
Base Course Aggregate

AASHTO T 330-07 Methylene Blue Scale



Methylene Blue Equipment

Grace Methylene Blue Test



Weigh 20g of sample***and 30g MB. Mix them and shake for 5 min.

Take solution into syringe that has 2 micrometer filter.

Replace the plunger and push solution to filter into a 1 mL plastic tube.

Dilute the 130 mL aliquot with distilled water to accurately total 45 g.

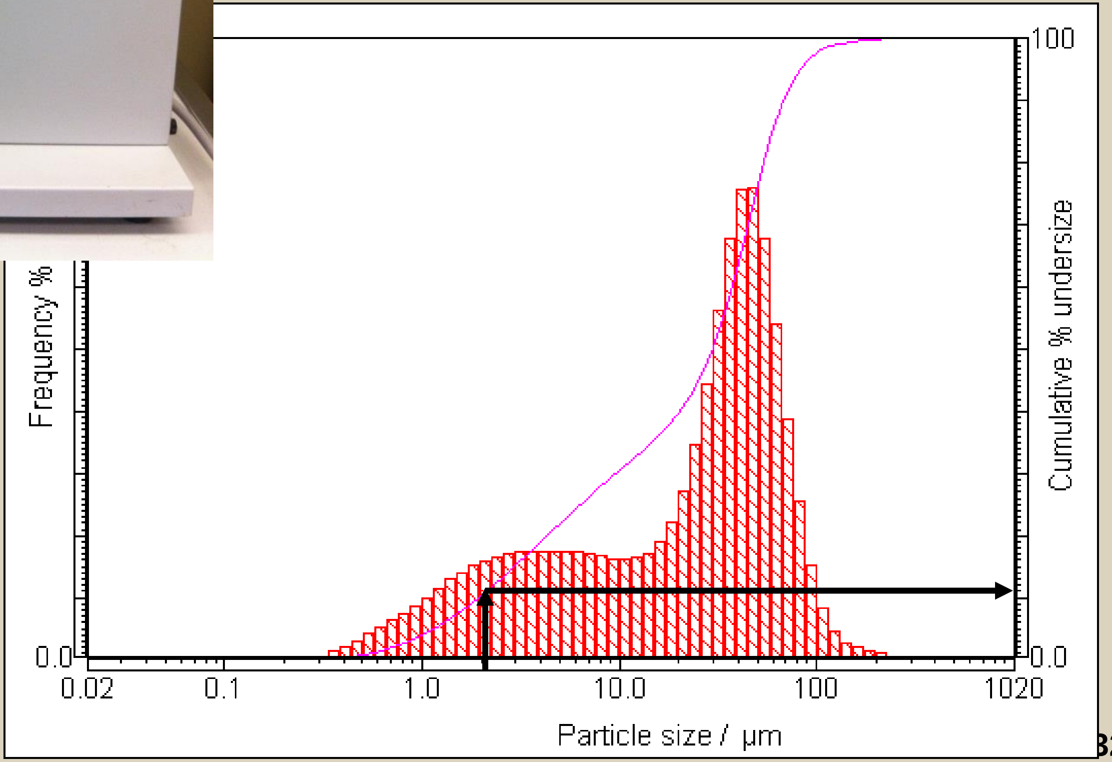
Fill the glass tube with the diluted solution and place in the colorimeter.

Place cover over the glass tube and take a reading. MB Reading will display in couple seconds.

Determine the percent clay based on MB from the chart.

HORIBA Particle Size Distribution Analyzer

- Particle size distribution curve of passing No 200 sieve
- Total measurement time is less than 10 min



- Typical test result of a soil sample
- Determine size of 2 µm particle

What is pfc?

Percent passing
2 micrometer

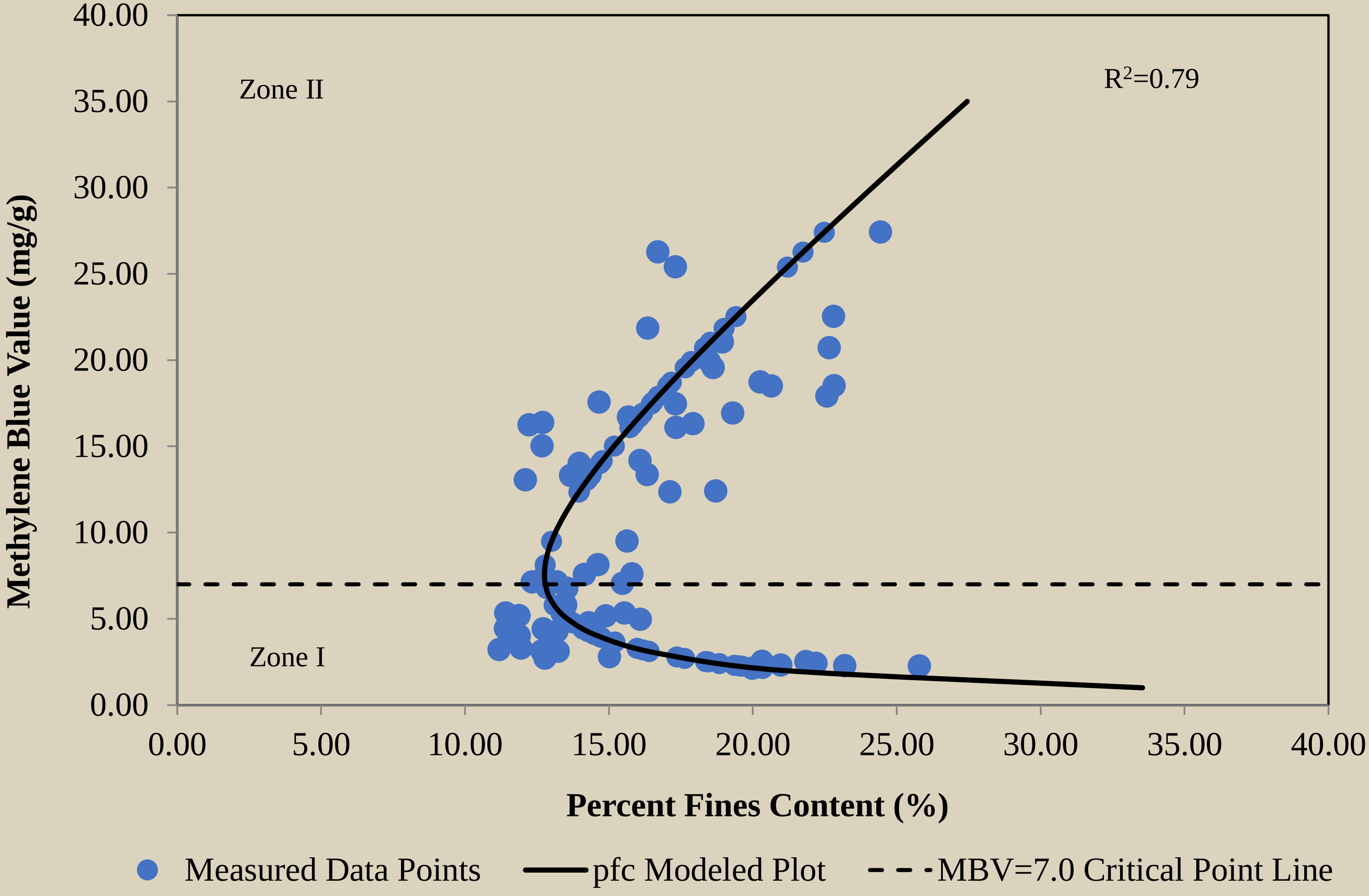
percent
fines
content

$$pfc = \frac{-2\,\mu m}{-\#200} \times 100$$

Percent passing
No.200 sieve

Percent Fines Content

The Relationship Between MBV and pfc



"C" Shaped Curve Equation

Coefficient parameters depend on soil type

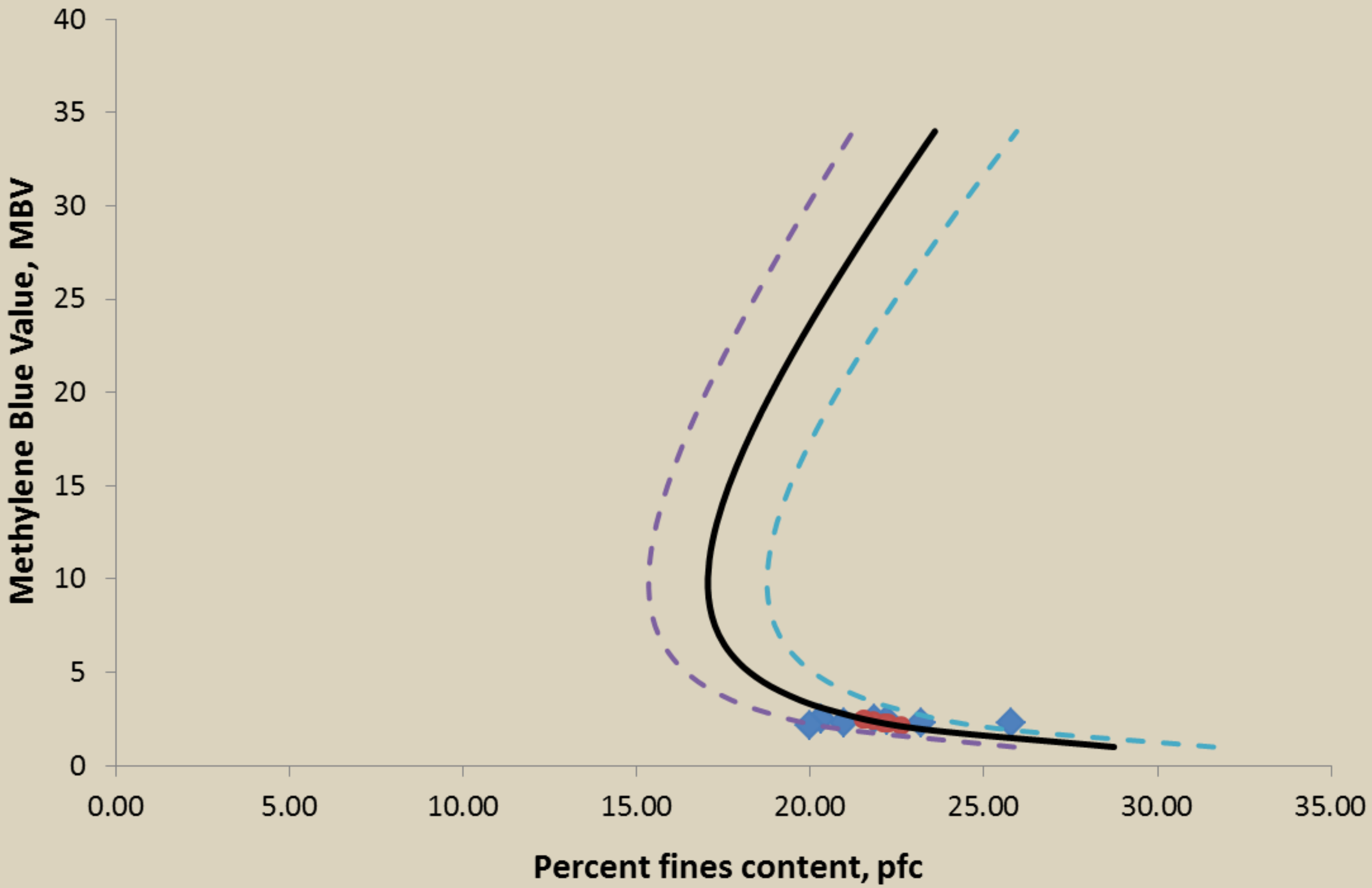
$$pfc = \frac{a}{(MBV)^n} + b(MBV)$$

Percent fines content

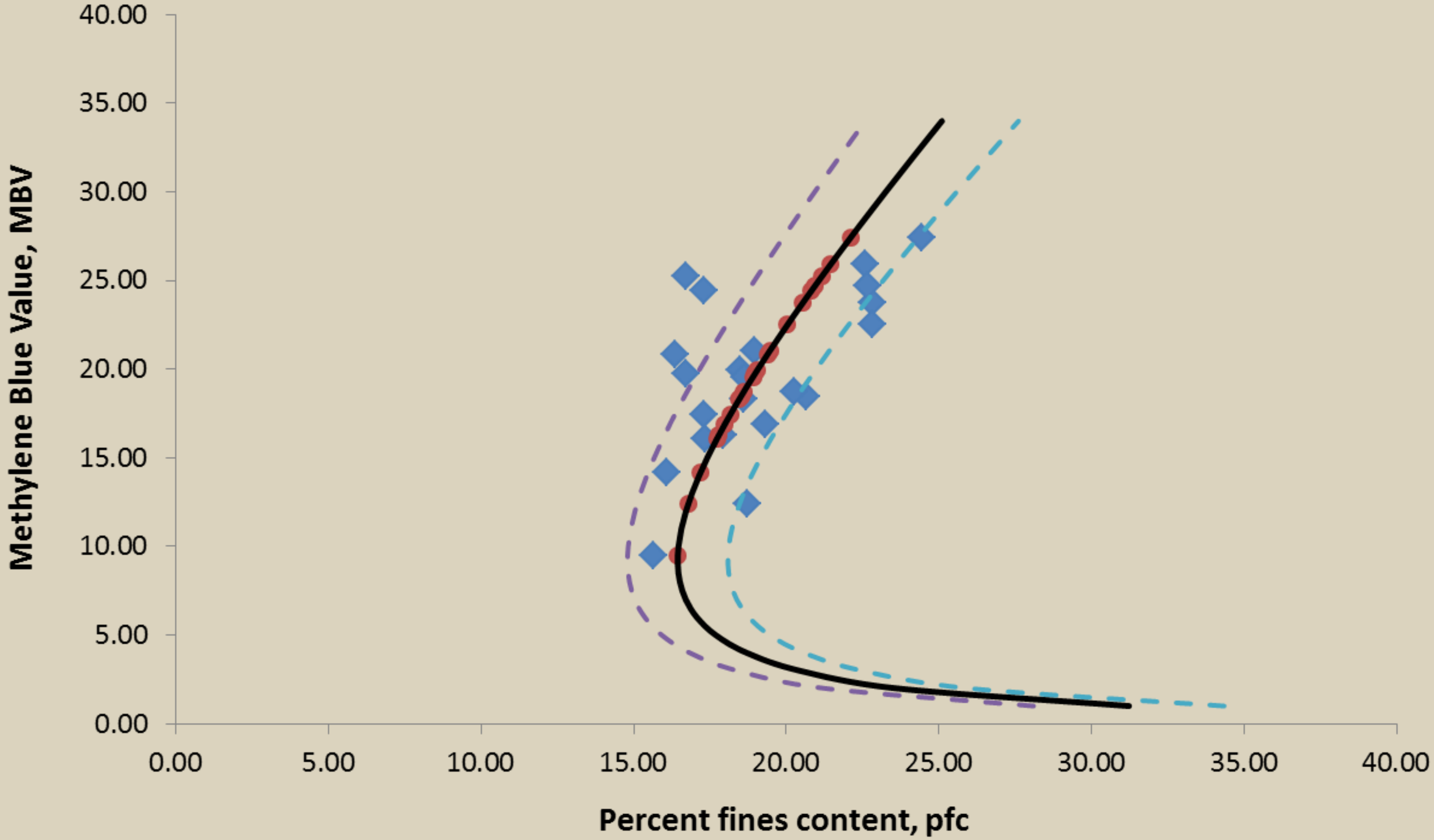
Methylene Blue Value

Typical Values	
a	28.014
b	0.8131
n	0.6288

A Good Quality Base Course

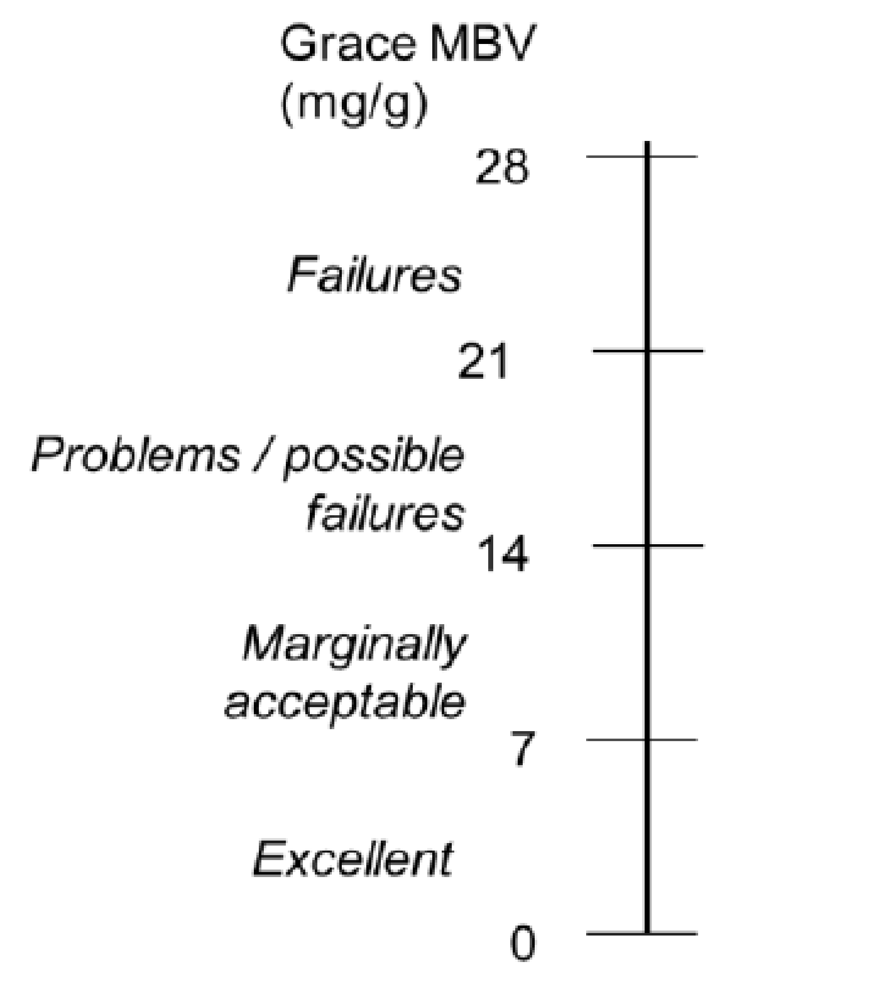


A Poor Quality Base Course

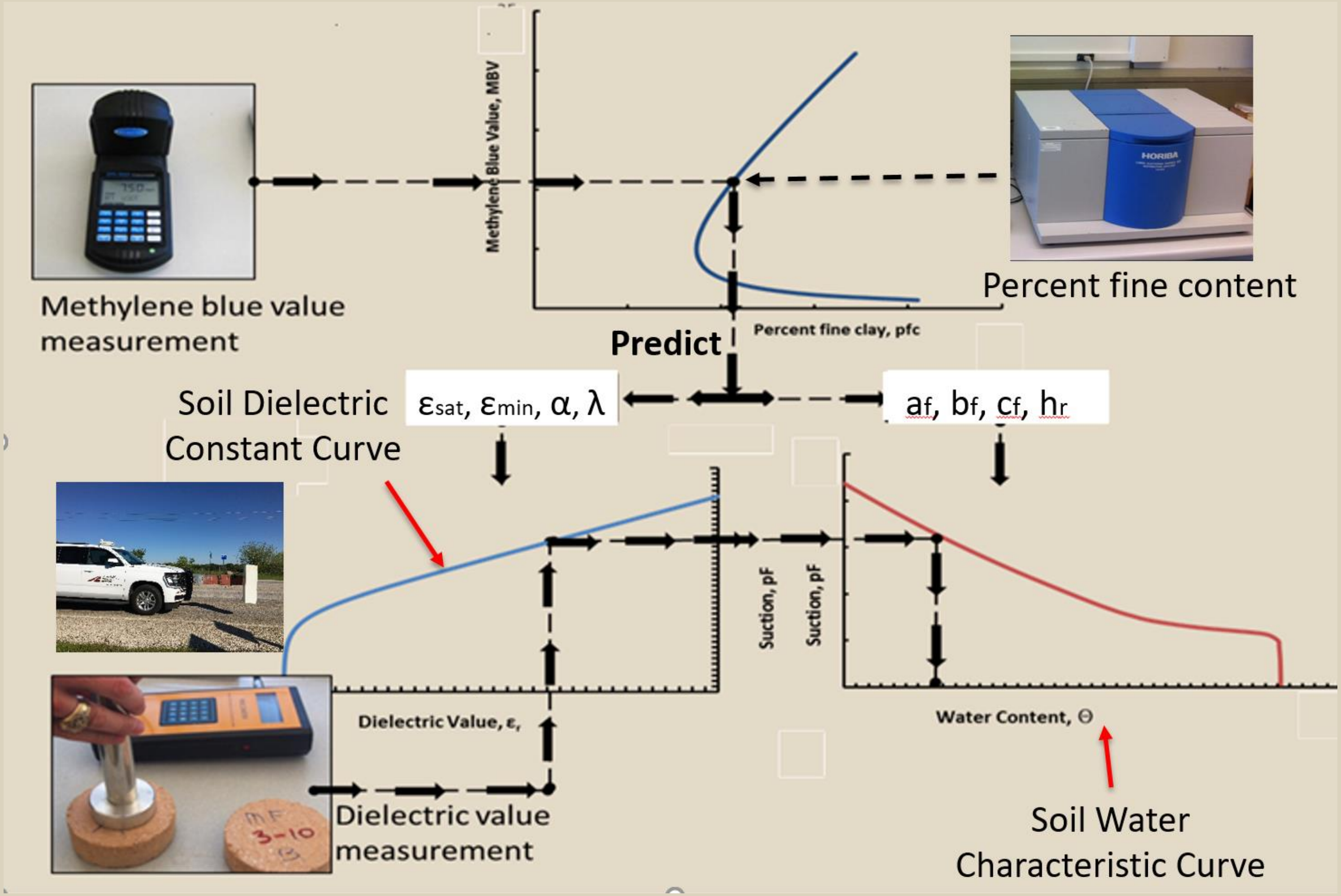


Base Course Aggregate

Grace Methylene Blue Value Scale



Matric Suction and Water Content Measurements



Resilient Modulus

$$E_y = k_1 P_a \left(\frac{I_1 - 3\theta f h_m}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}\right)^{k_3}$$

Volumetric water content

Saturation factor $1 \le f \le \frac{1}{\theta}$

Octahedral shear stress

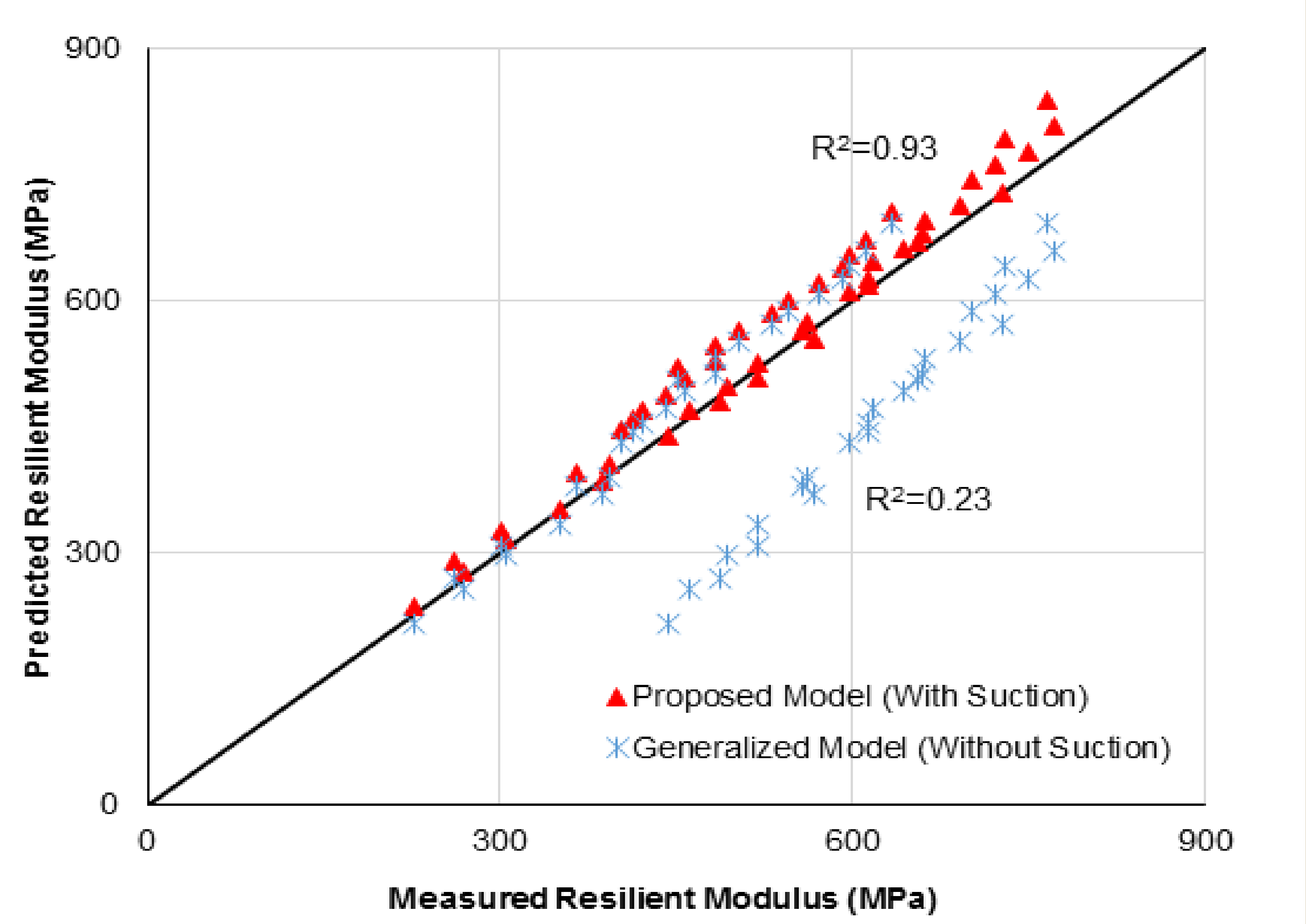
First invariant of the stress tensor

Matric Suction

Atmospheric pressure

k_1, k_2, k_3 – Coefficients of resilient modulus model

Aggregate Properties and k Values



Aggregate Properties and k Values

Aggregate Property		k Values		
		k_1	k_2	k_3
γ_d (Dry Density)		✓		
ω (Water Content)			✓	
MBV		✓	✓	✓
pfc				
Gradation	a_G			✓
	λ_G			
Angularity	a_A		✓	✓
	λ_A		✓	✓
Shape	a_S	✓	✓	
	λ_S		✓	✓
Texture	a_T	✓		
	λ_T			

Compaction Curve Equation

Three fitting parameters change with soil type

Dry unit weight

$$\left(\frac{\gamma_d}{\gamma_w}\right) = a_d\left[\operatorname{csch}\left(\frac{\theta_w\theta_{sat}}{G_s\left(\theta_{sat}-\theta_w\right)}\right)\right]^{n_d} - b_d\left[\operatorname{csch}\left(\frac{\theta_w\theta_{sat}}{G_s\left(\theta_{sat}-\theta_w\right)}\right)\right]$$

Unit weight of water

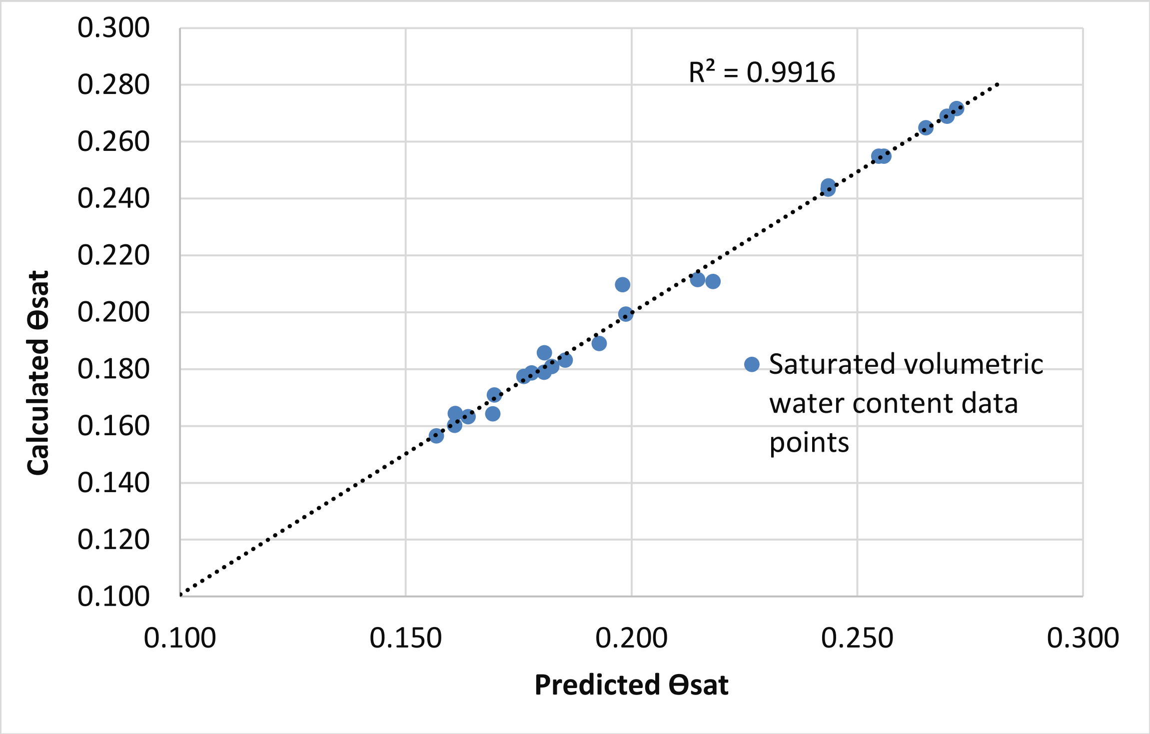
Specific gravity

Volumetric water content

Saturated volumetric water content

Saturated Volumetric Water Content

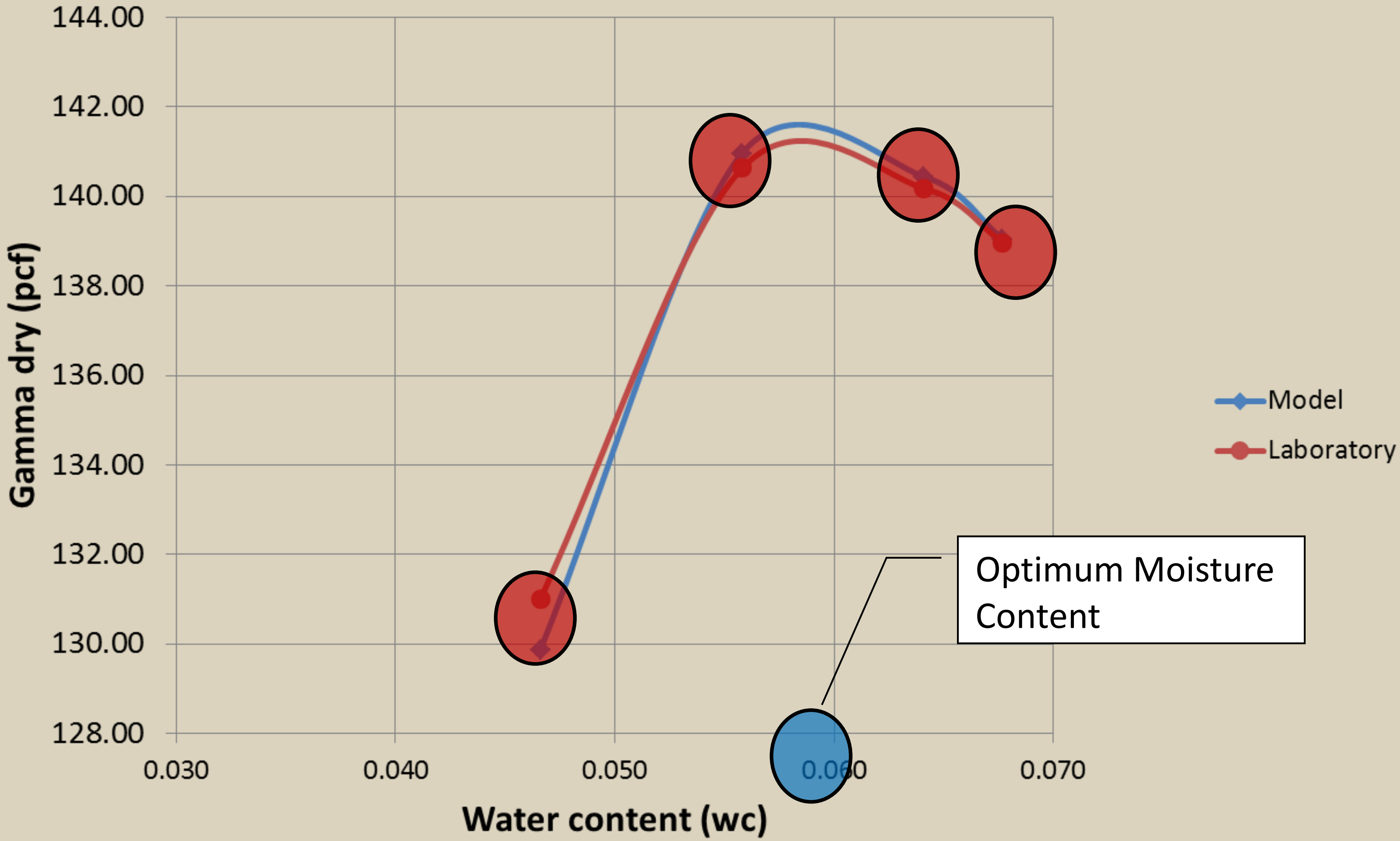
Predicted and calculated saturated volumetric water contents



$$\theta_{sat} = 0.214926485 H_{1\theta_{sat}} + 0.27640261 H_{2\theta_{sat}} - 0.12511932 H_{3\theta_{sat}} + 0.30045553$$

$$H_{1\theta_{sat}}, H_{2\theta_{sat}}, \text{and } H_{3\theta_{sat}} = f(MBV \text{ and } pfc)$$

Typical Compaction Curve as Tested in the Laboratory and as Modeled



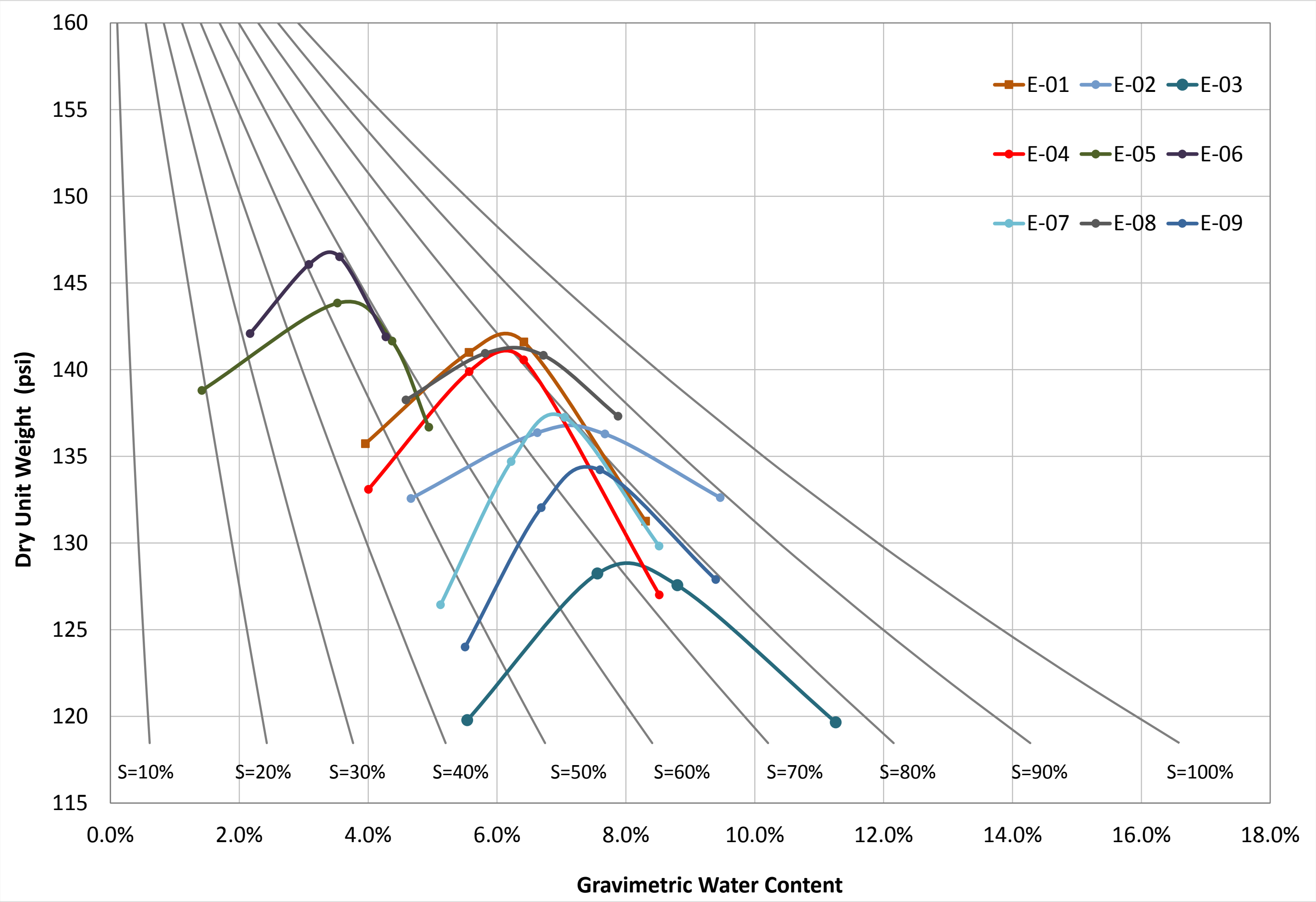
Optimum Moisture Content

$$\theta_{opt}=\left(\frac{G_s\theta_{sat}\ln\left[\frac{1}{2}\left(1+\sqrt{1+4\left(\frac{2^{1-n_d}b_d}{a_dn_d}\right)^{\frac{2}{-1+n_d}}}\right)\left(\frac{2^{1-n}b_d}{a_dn_d}\right)^{-\frac{1}{-1+n_d}}\right]}{\theta_{sat}+G_s\ln\left[\frac{1}{2}\left(1+\sqrt{1+4\left(\frac{2^{1-n}b_d}{a_dn_d}\right)^{\frac{2}{-1+n_d}}}\right)\left(\frac{2^{1-n}b_d}{a_dn_d}\right)^{-\frac{1}{-1+n_d}}\right]}\right)$$

Optimum Moisture Content

A Family of Compaction Curves

Generated compaction density curves



Stress-Dependent Mechanistic-Empirical Permanent Deformation Model

- Proposed model (Gu, Zhang, et al. 2015)

$$\varepsilon_p = \varepsilon_0 e^{-\left(\frac{\rho}{N}\right)^{\beta}} \left(\sqrt{J_2}\right)^m \left(\alpha I_1 + K\right)^n$$

$$\alpha = \frac{2\sin\phi}{\sqrt{3}(3-\sin\phi)} \qquad K = \frac{c\cdot 6\cos\phi}{\sqrt{3}(3-\sin\phi)}$$

- Model components
  - Laboratory test design
  - Laboratory verification
  - Numerical verification
  - Hierarchical input level

Repeated Load Permanent Deformation Test

Test Equipment

Stress State	Confining Pressure, σ_3 (kPa)	Deviatoric Stress, σ_d (kPa)	Bulk Stress, I_1 (kPa)	Second Invariant of Shear Stress Tensor, J_2 (kPa^2)	Test Purpose
1	27.6	192.9	275.6	12406.0	Model Calibration
2	48.2	130.9	275.6	5712.5	
3	68.9	68.9	275.6	1582.4	
4	91.9	0	275.6	0	
5	48.2	192.9	337.6	12406.0	
6	68.9	192.9	399.6	12406.0	
7	89.6	192.9	461.6	12406.0	
8	34.5	172.3	275.6	9890.0	Model Validation
9	103.4	192.9	503.0	12406.0	

Test Protocol

Proposed AASHTO Standard for Permanent Deformation Test

Standard Method of Test for

Determining the Permanent Deformation Properties of Geosynthetic-Reinforced and Unreinforced Granular Material

AASHTO Designation: T xx-xx

1. SCOPE

1.1. The test method described is applicable to unbound granular materials and geosynthetic-reinforced granular materials prepared for testing by compaction in the laboratory.

1.2. The values of permanent deformation properties determined from this procedure recognize the stress dependent nonlinear characteristics of granular material.

1.3. Permanent deformation properties can be used with structural response analysis models to predict the permanent deformation of unbound base courses and geosynthetic-reinforced base courses under certain number of load repetitions.

1.4. *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety concerns associated with its use. It is responsibility of the user of this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. REFERENCED DOCUMENTS

2.1 AASHTO Standards:
- T 307, Determining the Resilient Modulus of Soils and Aggregate Materials
- T 296, Unconsolidated, Undrained Compressive Strength of Cohesive Soils in Triaxial Compression

3. SIGNIFICANCE AND USE

3.1. The permanent deformation test provides a basic relationship between stress and permanent deformation of pavement materials for the structural analysis and performance prediction of layered pavement systems.

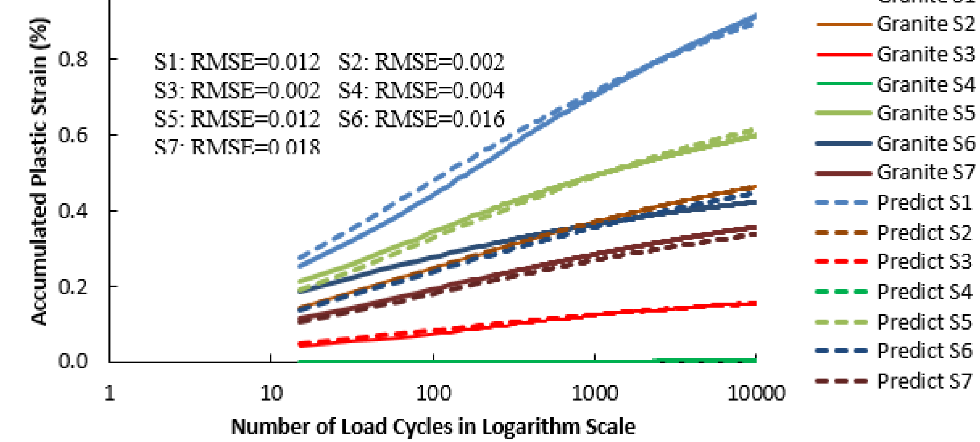
3.2. The permanent deformation test provides a means of characterizing pavement construction materials, including unbound granular materials, and geosynthetic-reinforced (i.e., geogrid and geotextile) granular materials, under a variety of conditions (i.e., moisture, density, etc.) and stress states that simulate the conditions in a pavement subjected to moving wheel loads.

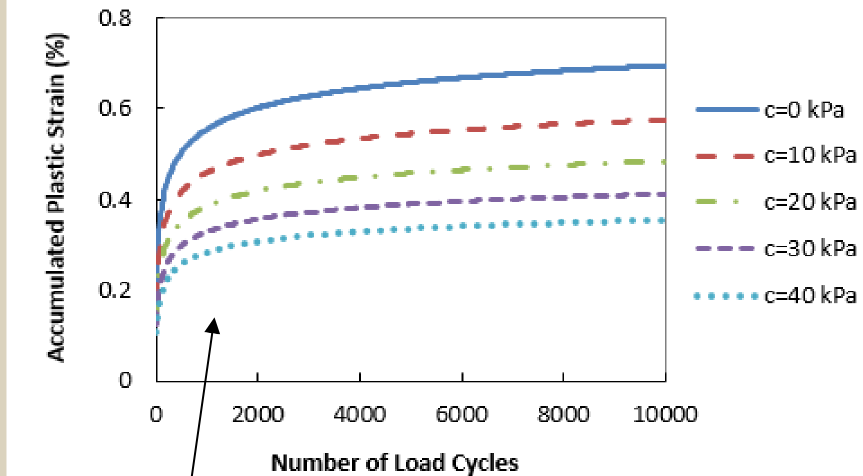
4. APPARATUS

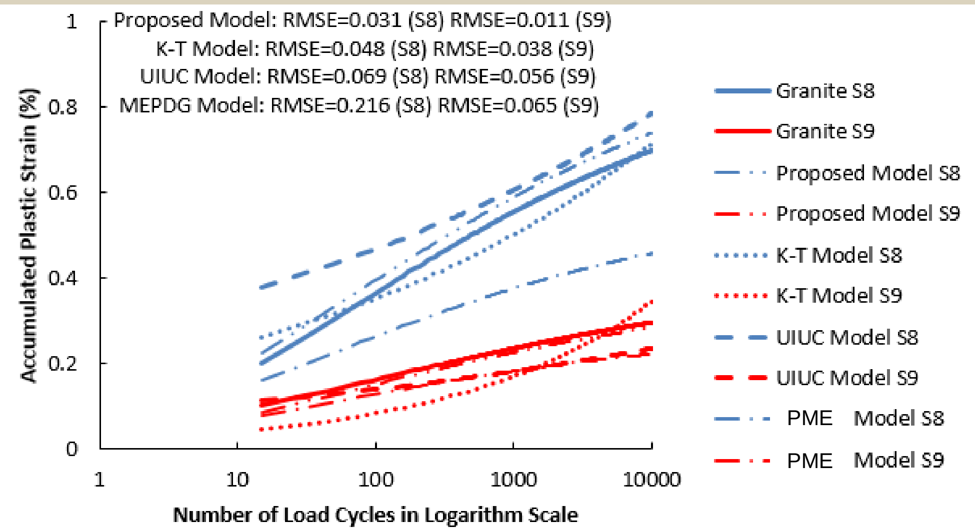
4.1. *Triaxial Pressure Chamber*-The pressure chamber is used to contain the test specimen and the confining fluid during the test. A typical triaxial chamber suitable for use in permanent deformation test of granular material shall be as described in T 307.

Repeated Load Permanent Deformation Test Results

ε0	ρ	β	m	n
0.149	72.4	0.247	1.70	-2.16







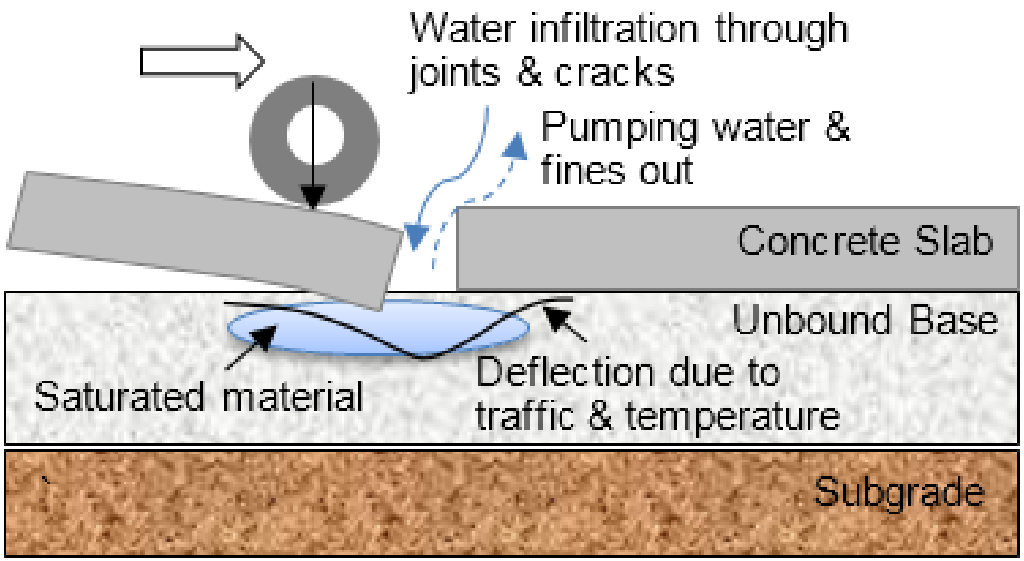
Proposed model is sensitive to cohesion. Moisture change results in change of cohesion.

Korkiala-Tanttu (K-T) model (Korkiala-Tanttu 2009)
UIUC model (Chow et al. 2014)

Role of Shear Strength Model

Erosion Enablers:

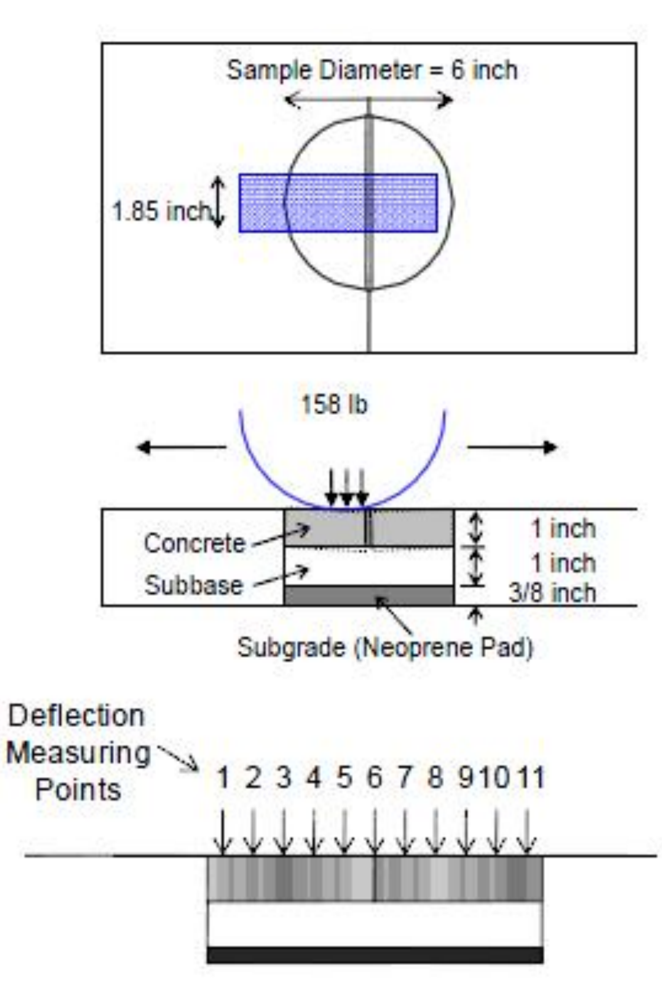
- Mechanical shear stress due to deflection
- Hydraulic shear stress due to pumping
- Permanent deformation (causing voids between slab & base)

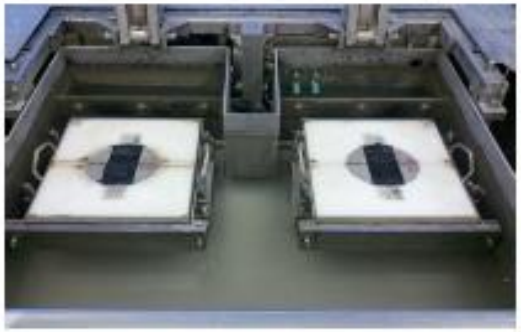


Erosion Resistors:

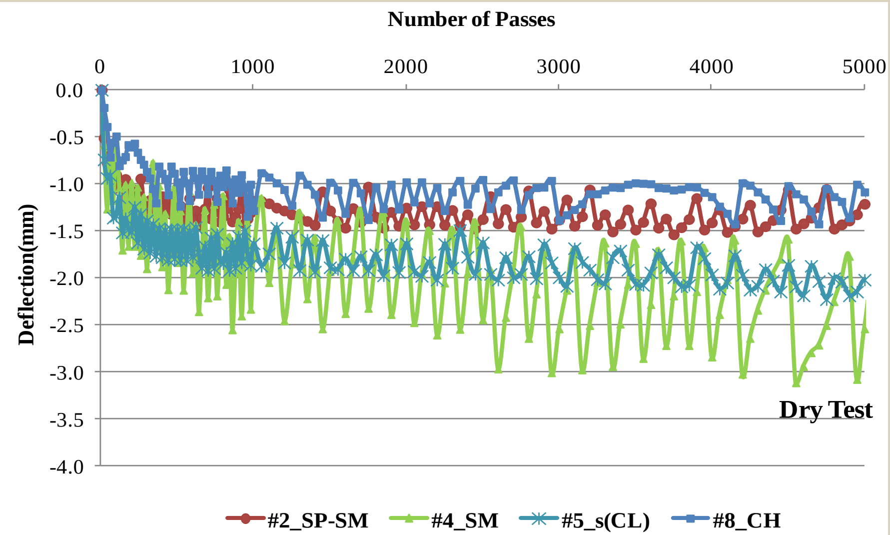
- Interface shear strength
- Interfacial bonding
- Resistance to permanent deformation
- Permeability

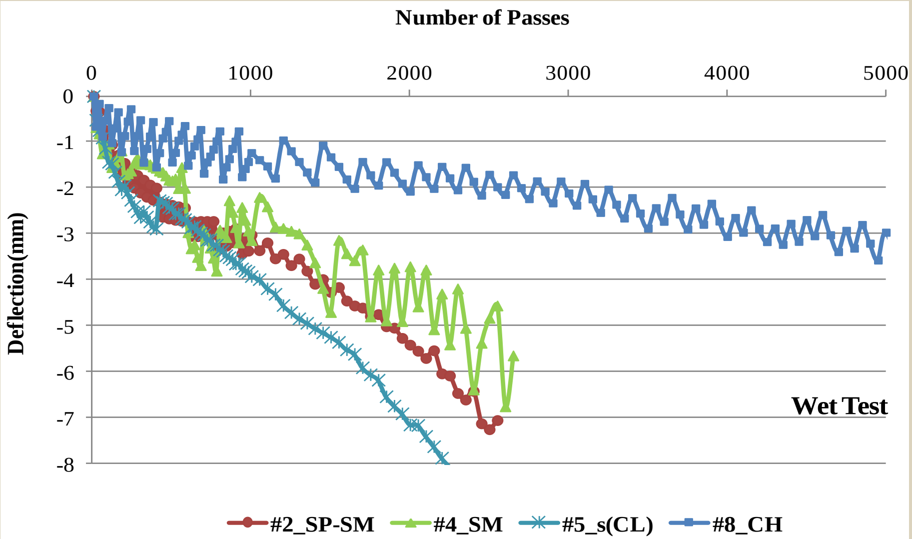
Hamburg Wheel-Tracking Device (HWTD) to Measure erodibility

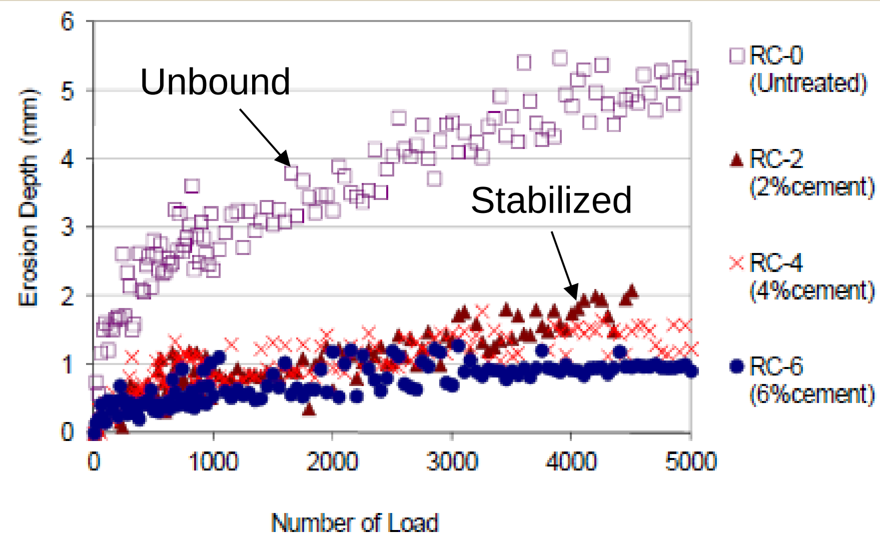


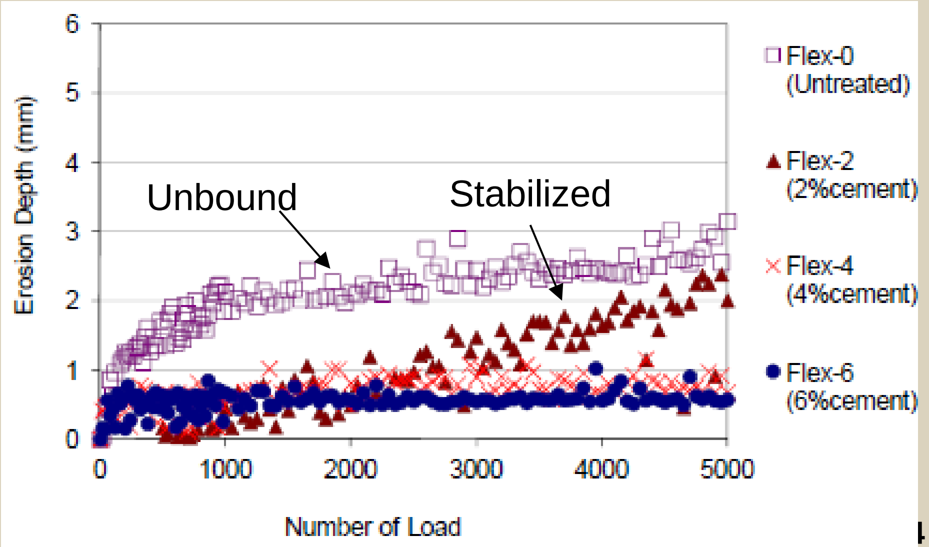


HWTD Test Results

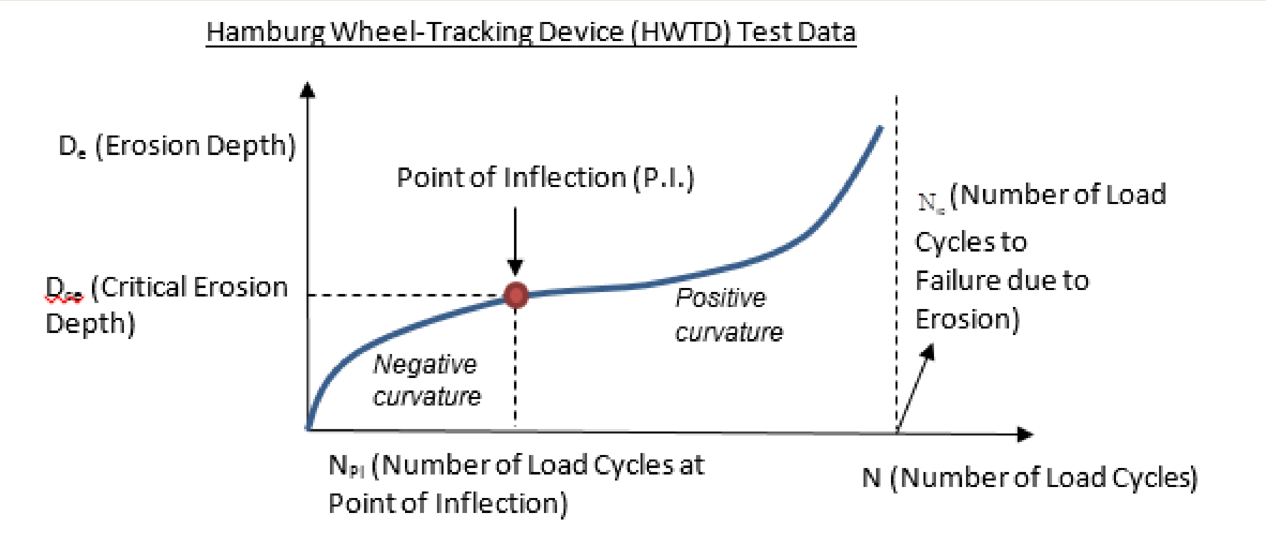








Critical Erosion Depth Model



Erosion depth curve:

$$N = N_{\infty} e^{-\left(\frac{\rho_e}{D_e}\right)^{\beta_e}}$$

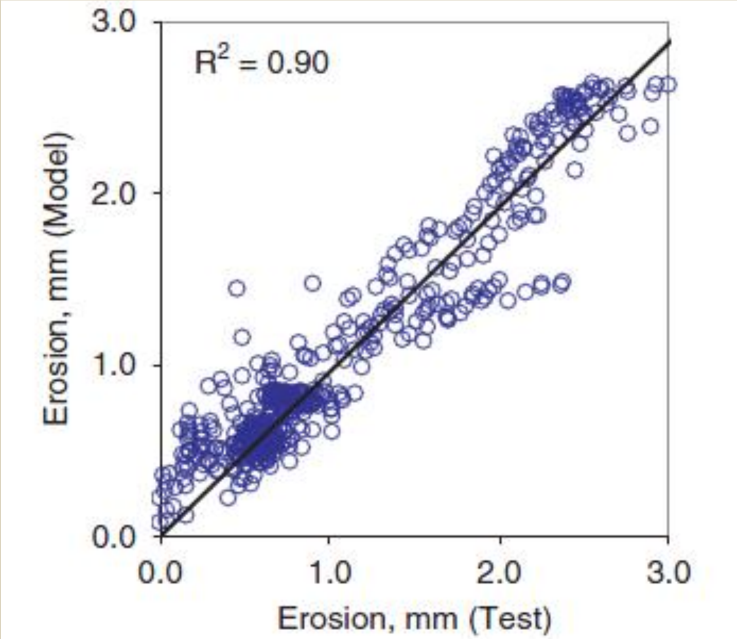
Critical erosion depth:

$$D_{ce} = \rho_e \left(\frac{\beta_e}{\beta_e + 1}\right)^{\frac{1}{\beta_e}}$$

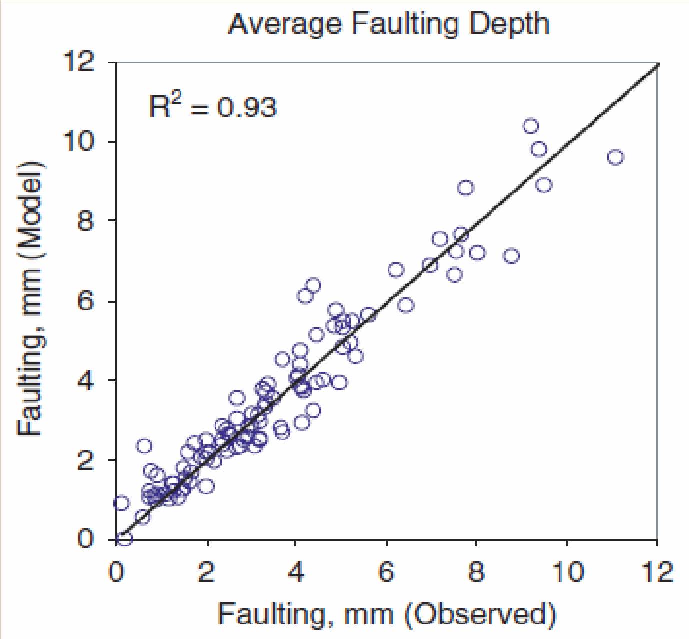
Number of load cycles at the point of inflection:

$$N_{PI} = N_{\infty} e^{-\left(\frac{\beta_e + 1}{\beta_e}\right)}$$

Validation of Erosion Model



Model prediction vs. lab measurements from HWTD



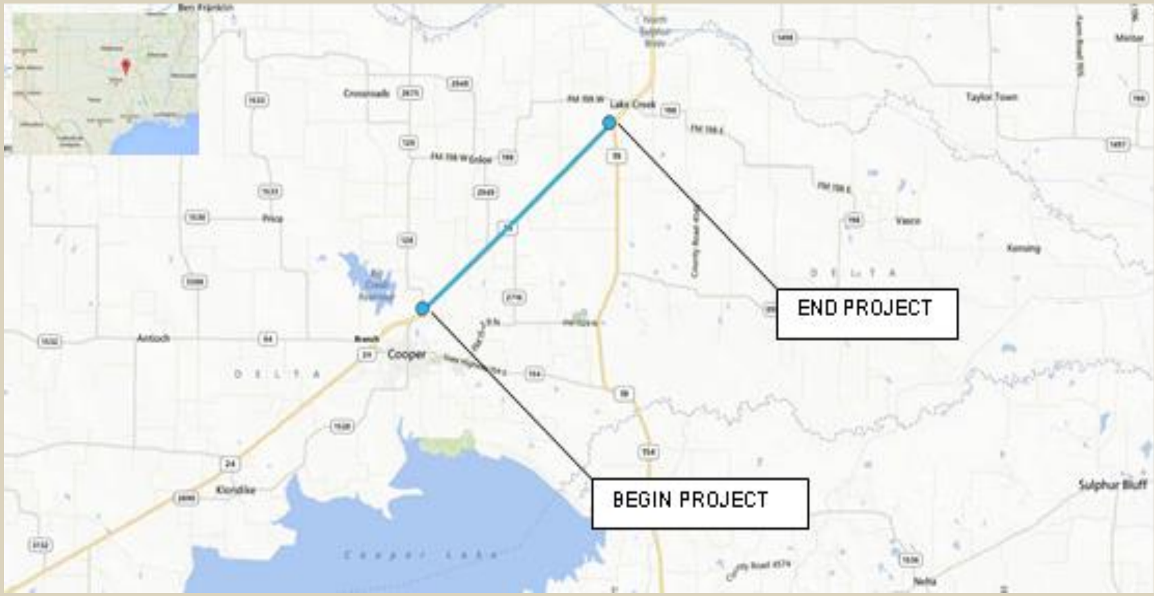
Model prediction vs. observed performance from 17 LTPP sections

LTPP Pavement Sections with Faulting Data

Unbound Base Course	351
Stabilized Base Course	359
Total	710

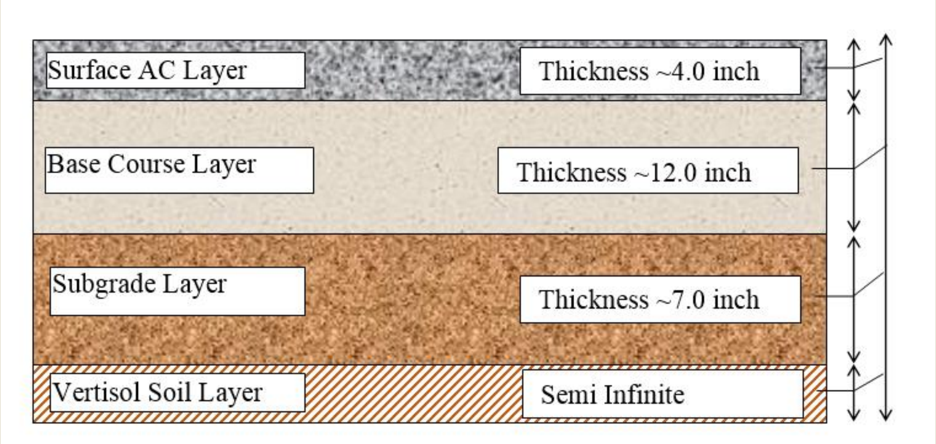
A Case Study: Verification GPR and FWD

Test Location



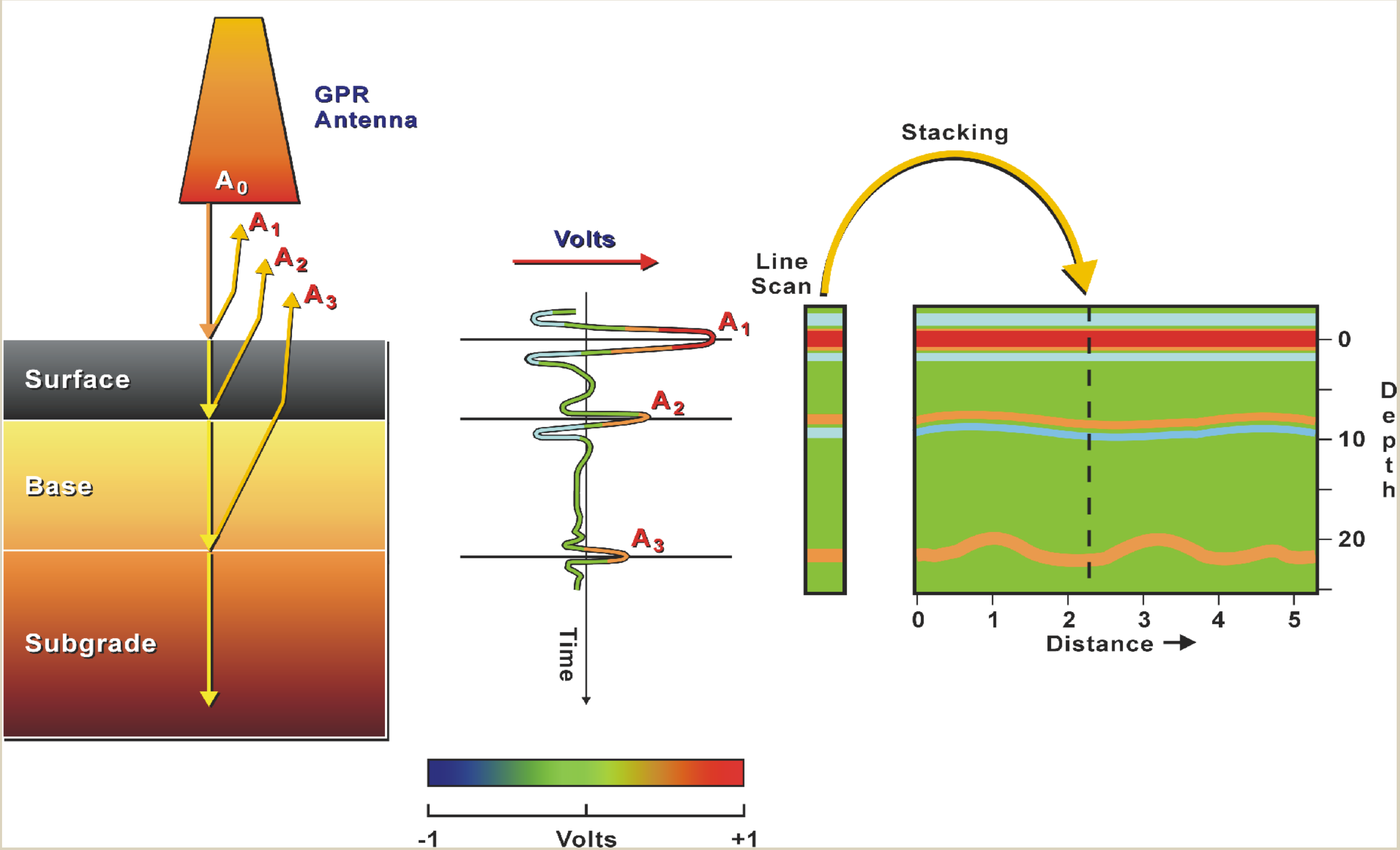
Delta county in Texas
Total length 4.5 miles (~24000 ft)

Martin Marietta Material in Oklahoma

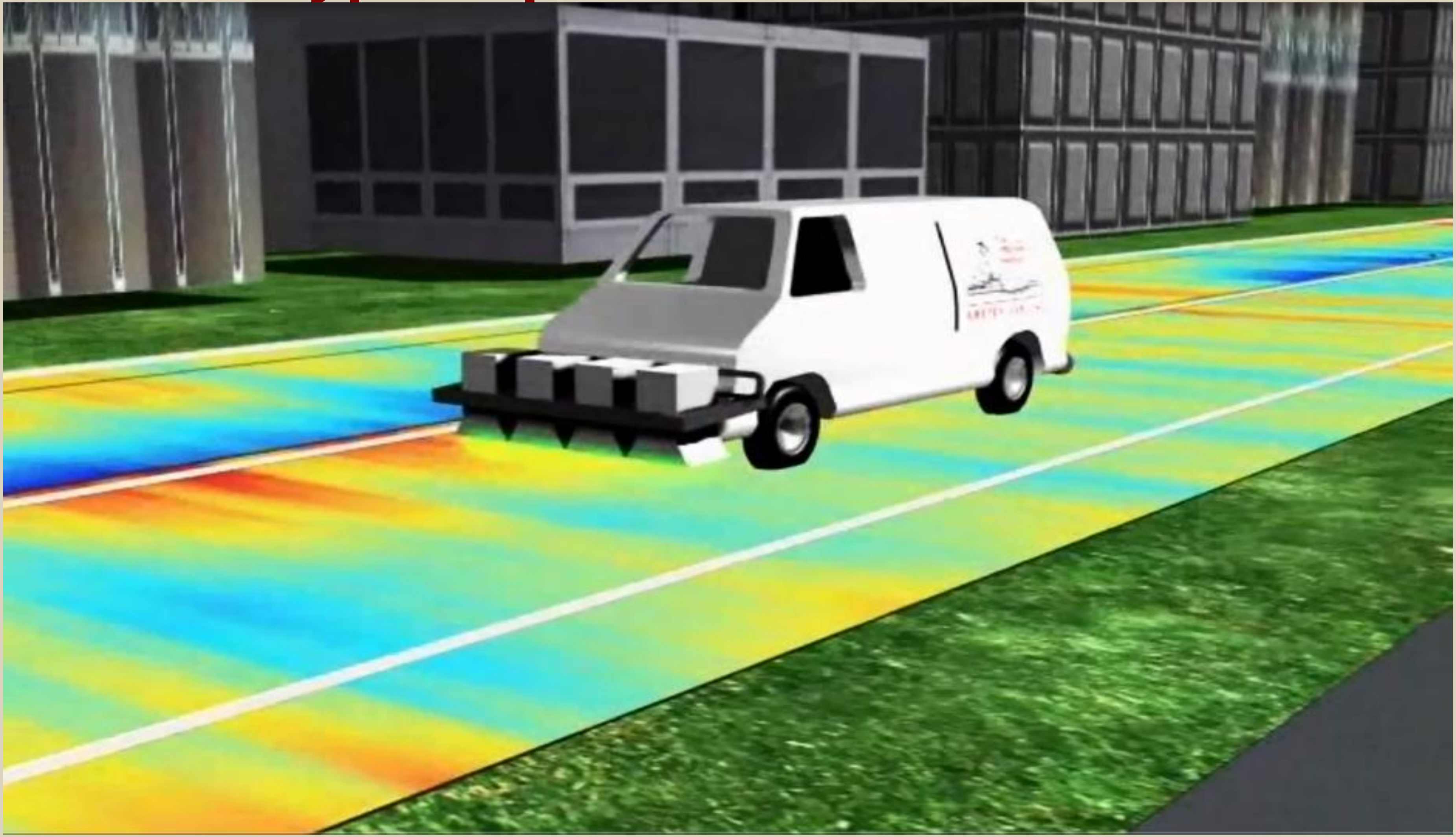


Ground Penetrating Radar Van

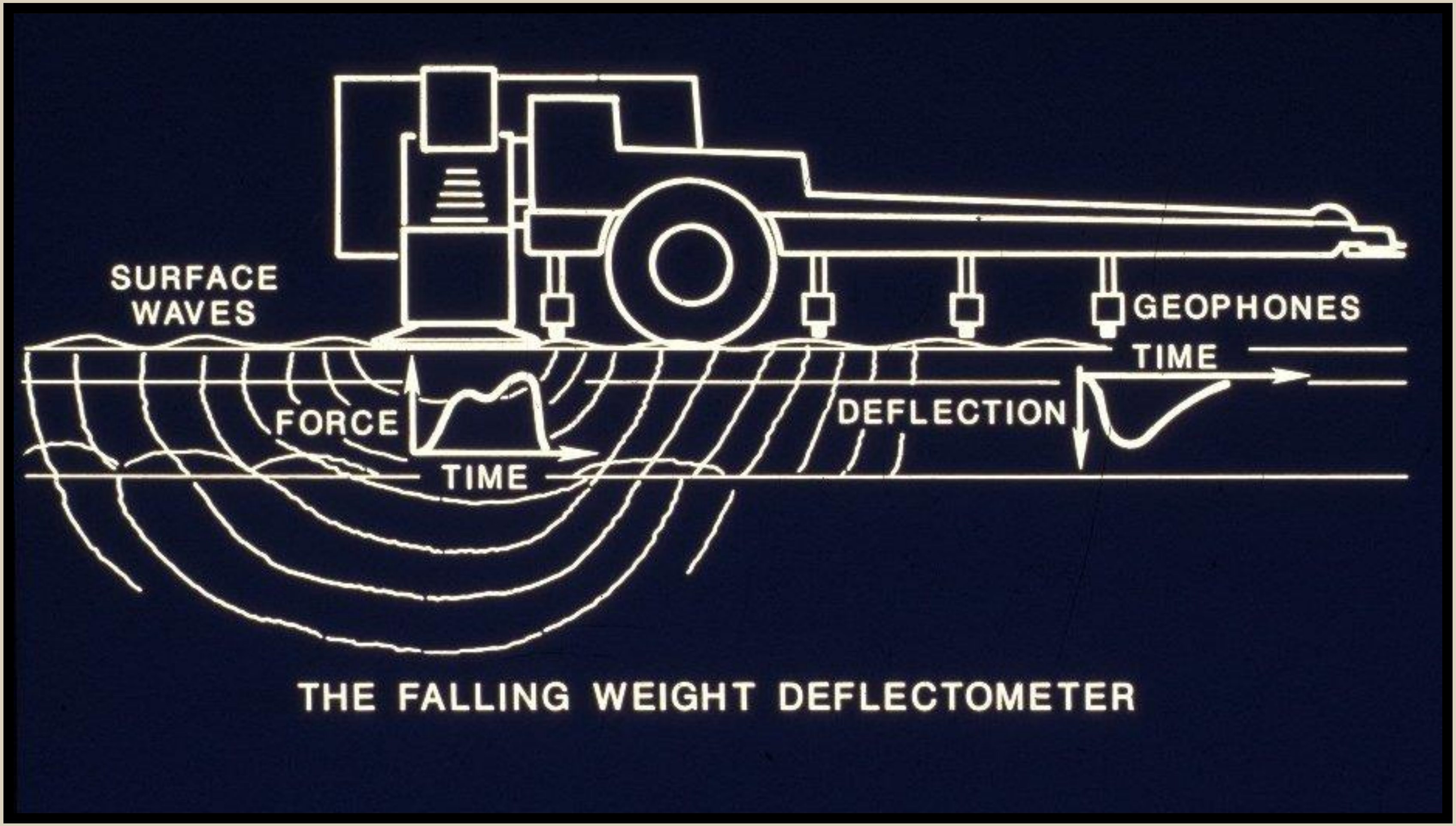
Return Reflection at Interfaces



Radar Hyper Optics Animation

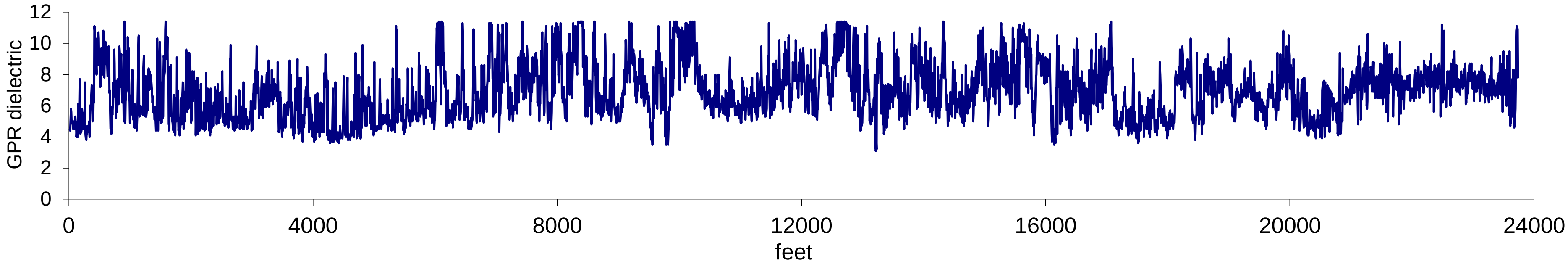


Falling Weight Deflectometer (FWD)

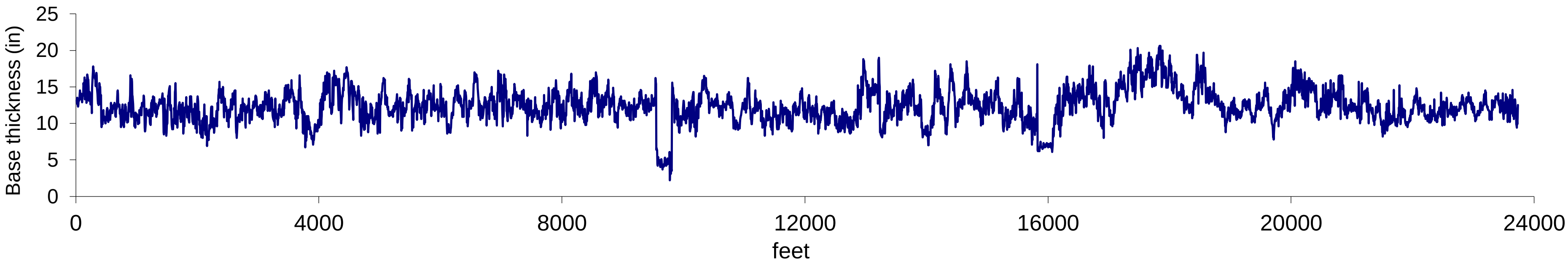


Information from GRP

Dielectric constant

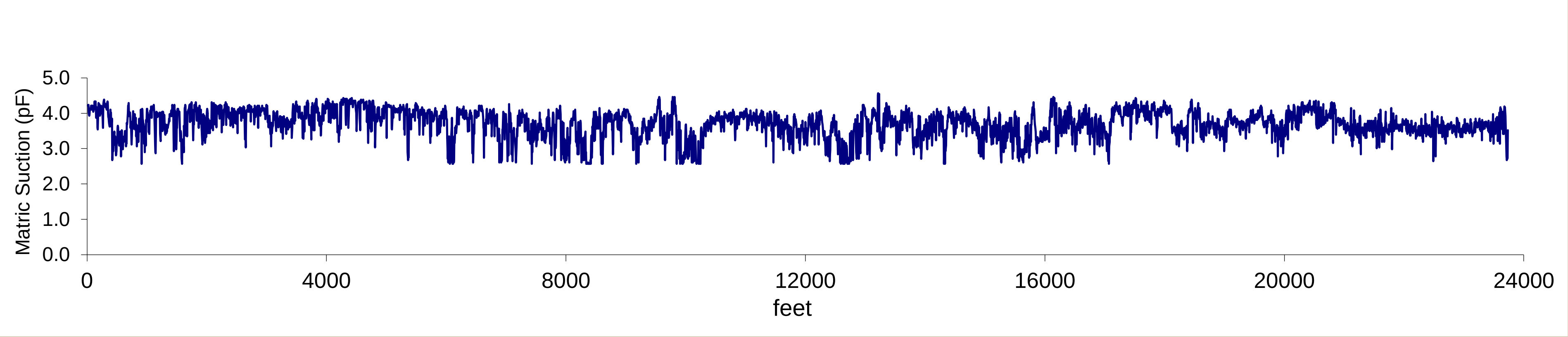


Base course thickness

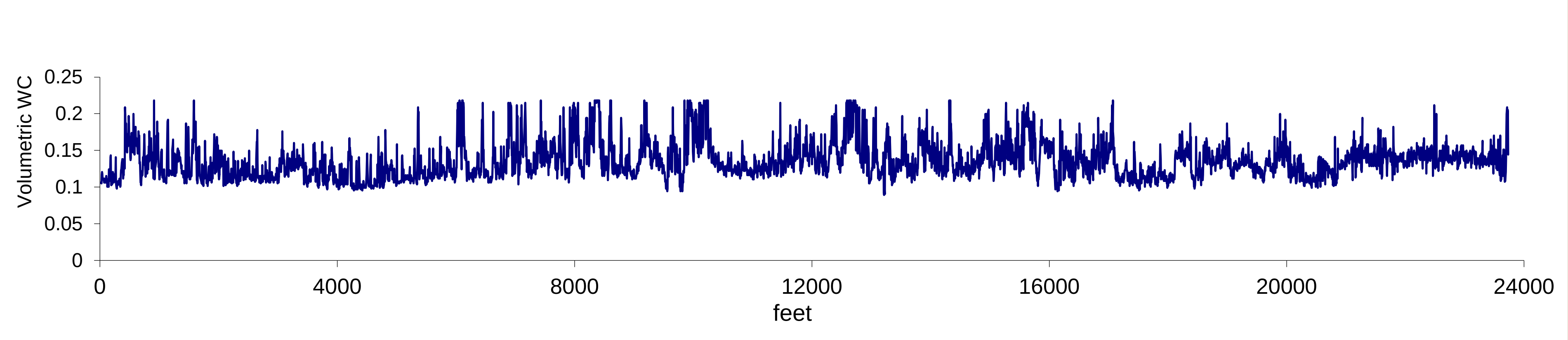


Information from GRP

Matric Suction

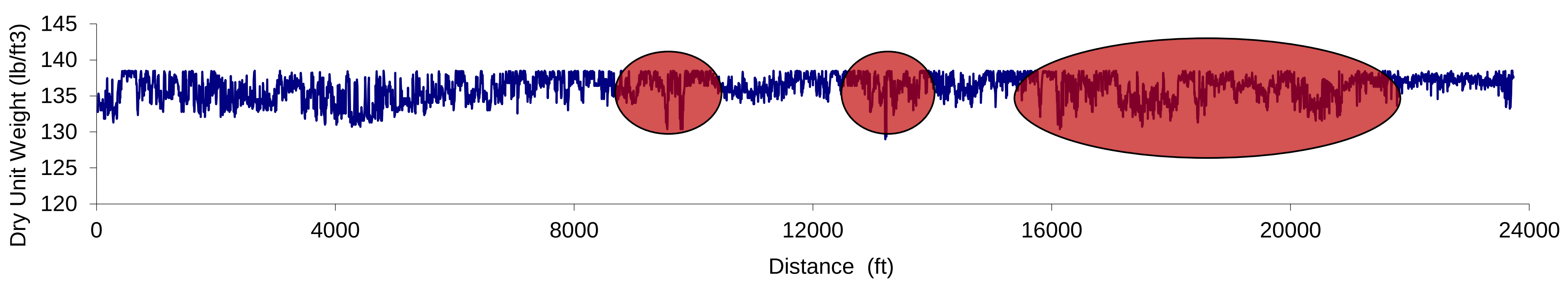


Volumetric Water Content

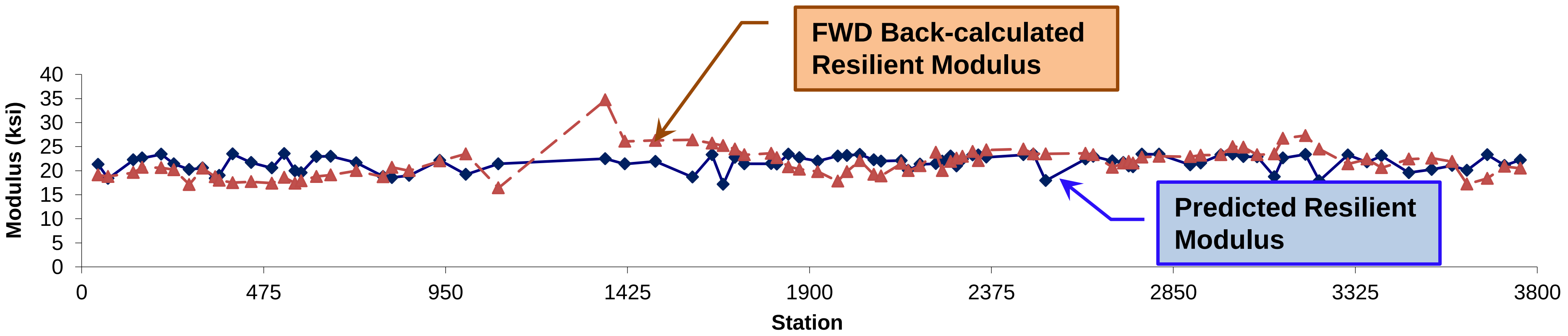


Information from GRP

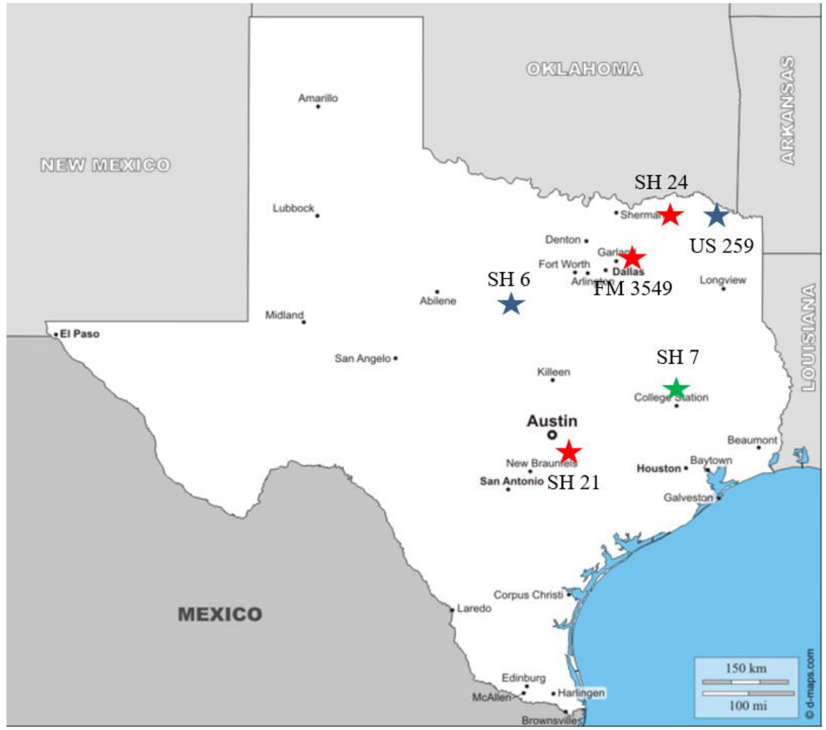
Dry Density



Resilient Modulus



Location of Identified Pavement Sections

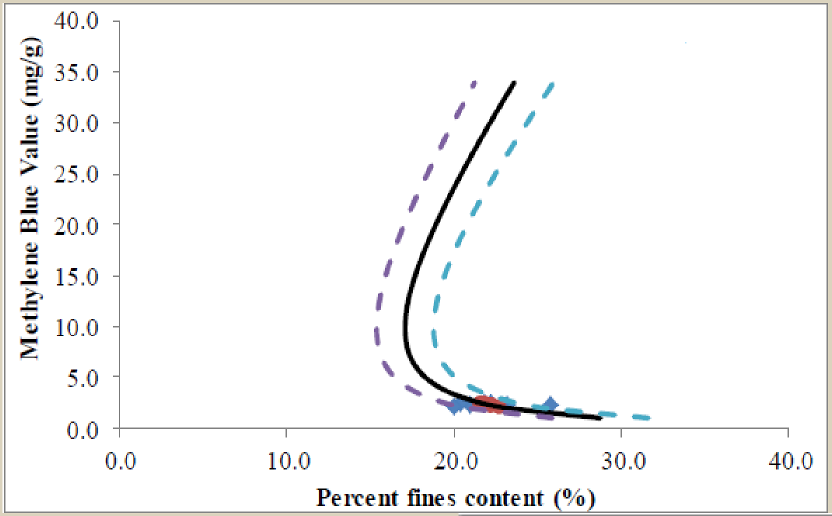


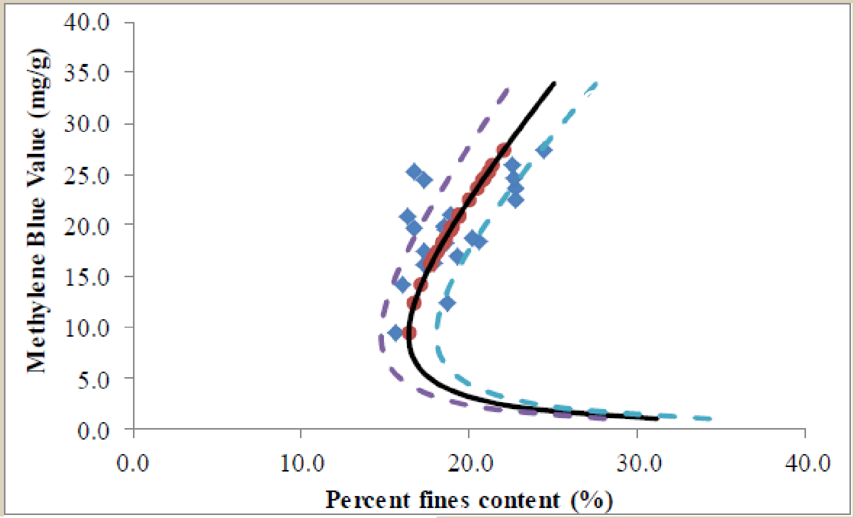
★ : only done by lab characterization;

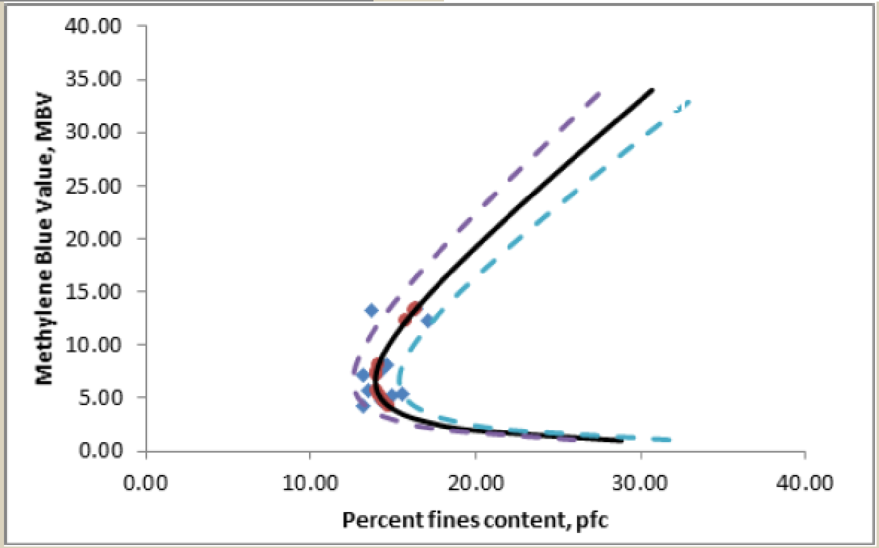
★ : done by lab characterization and field FWD and GPR testing;

★ : on-going lab characterization.

Relationship between MBV and pfc

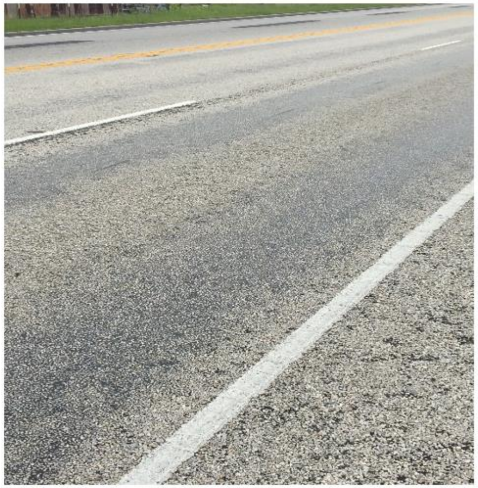






Identified Pavement Sections from SH 21

Hunter or Knife River Base Material

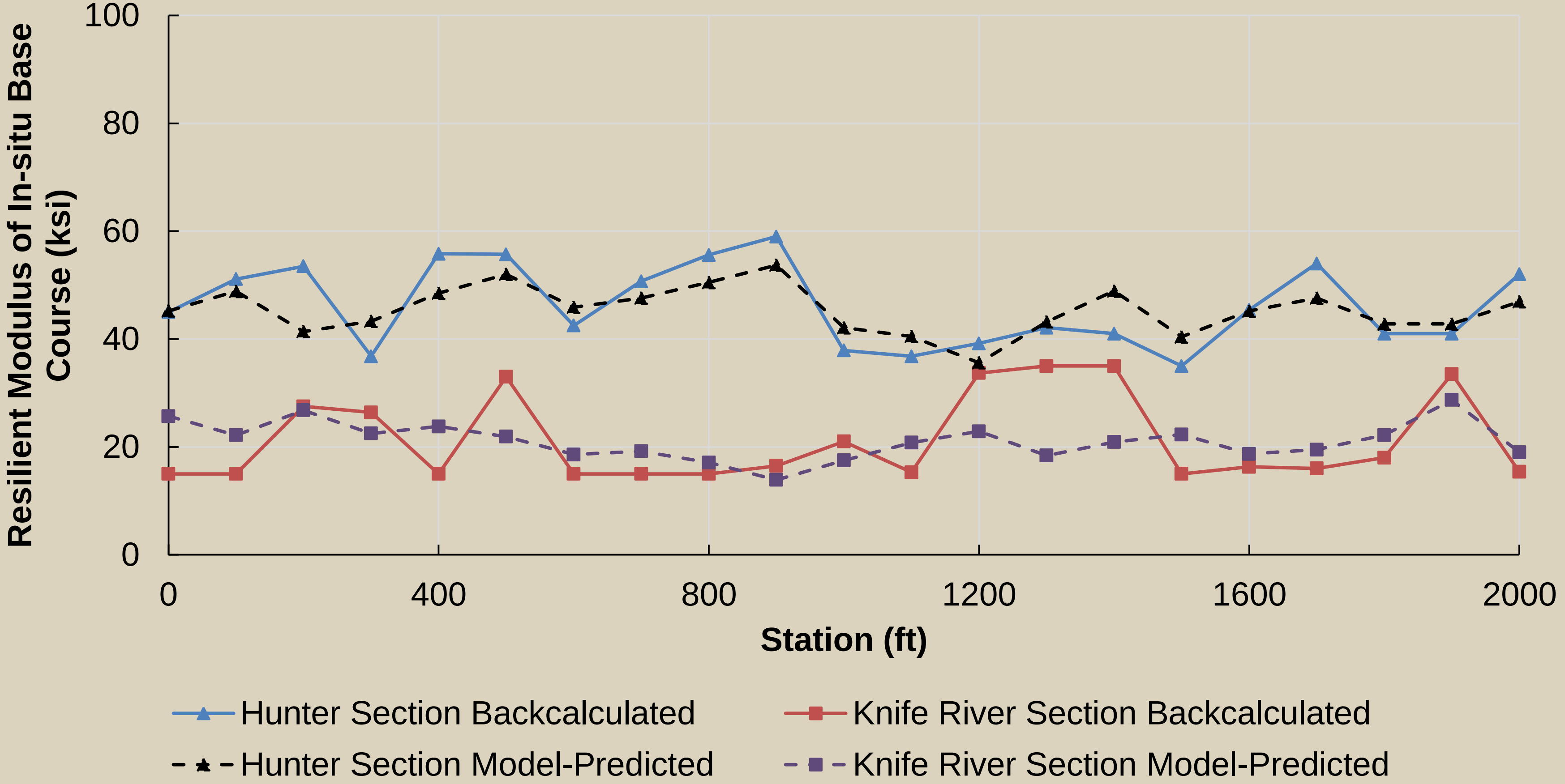


Hunter Base Material

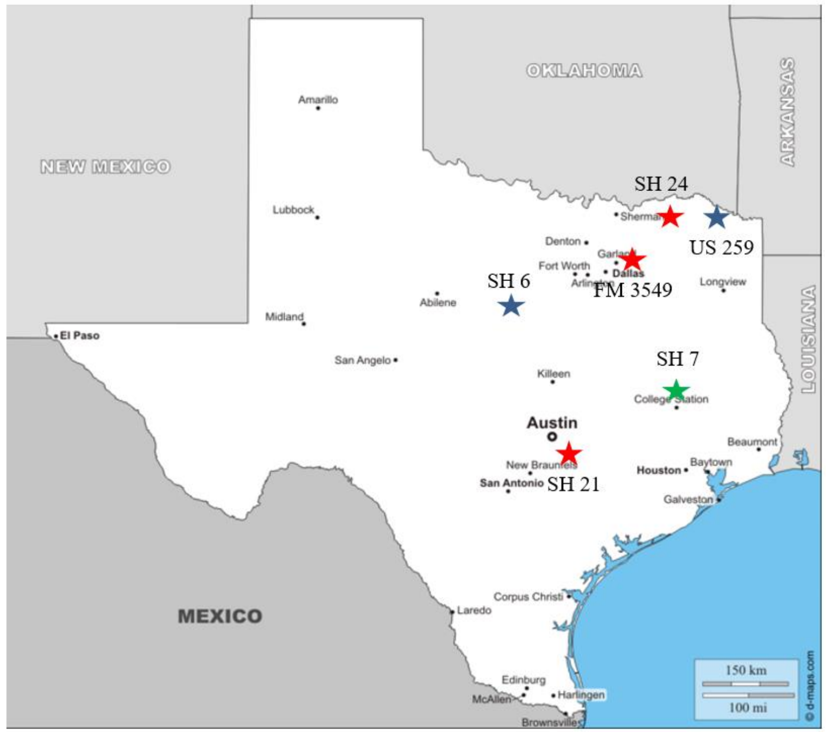
Alligator cracking

Knife River Base Material

Model-Predicted Mr Vs. FWD-Calculated Mr



Location of Identified Pavement Sections



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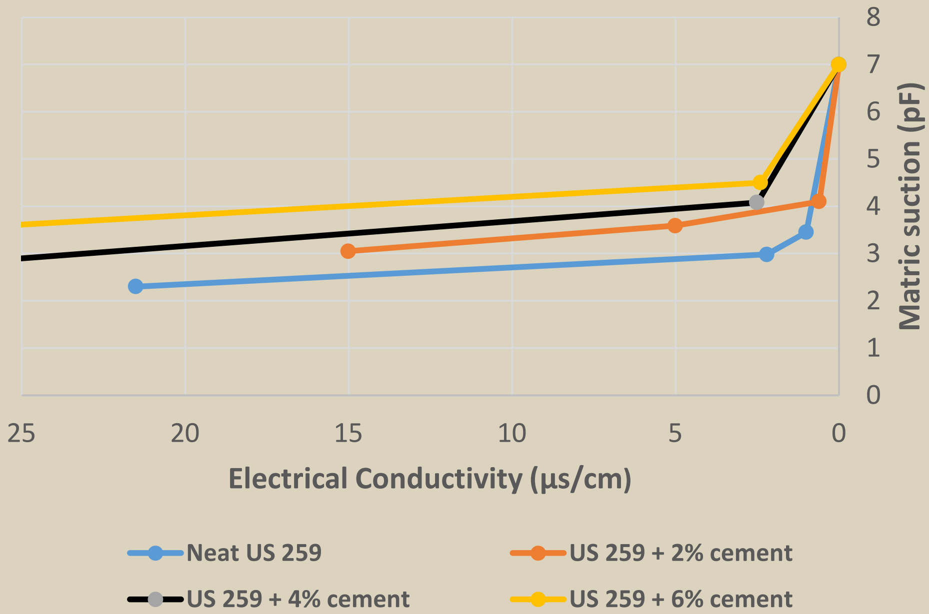
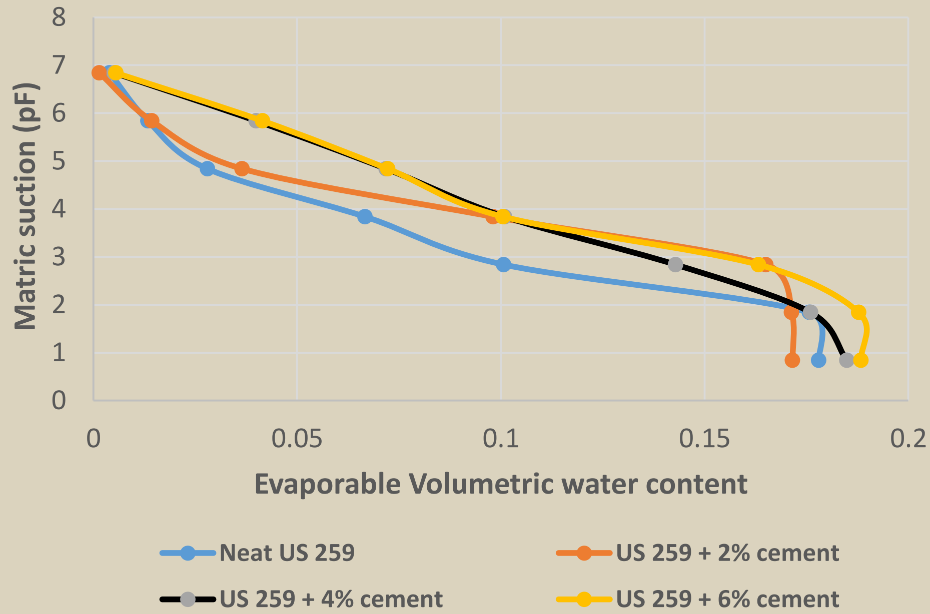
★ : done by lab characterization and field FWD and GPR testing;

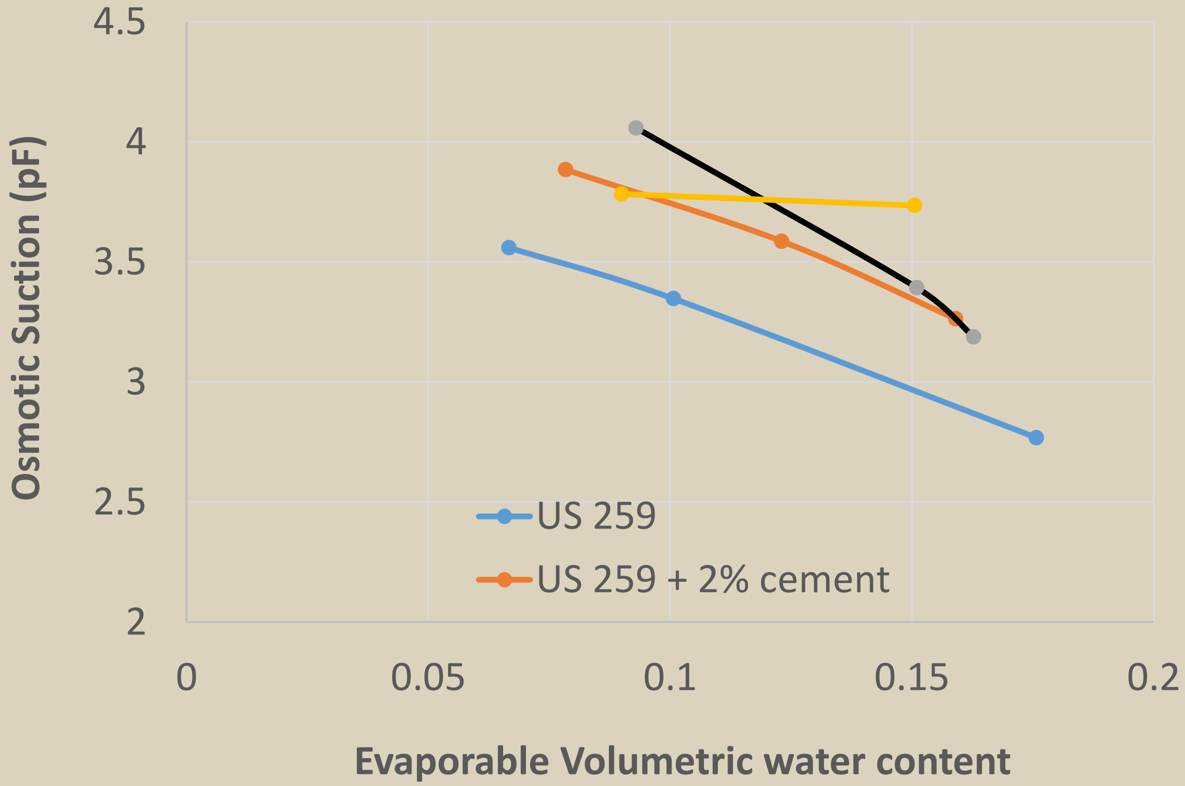
★ : on-going lab characterization.

Water Content Determination from Conductivity

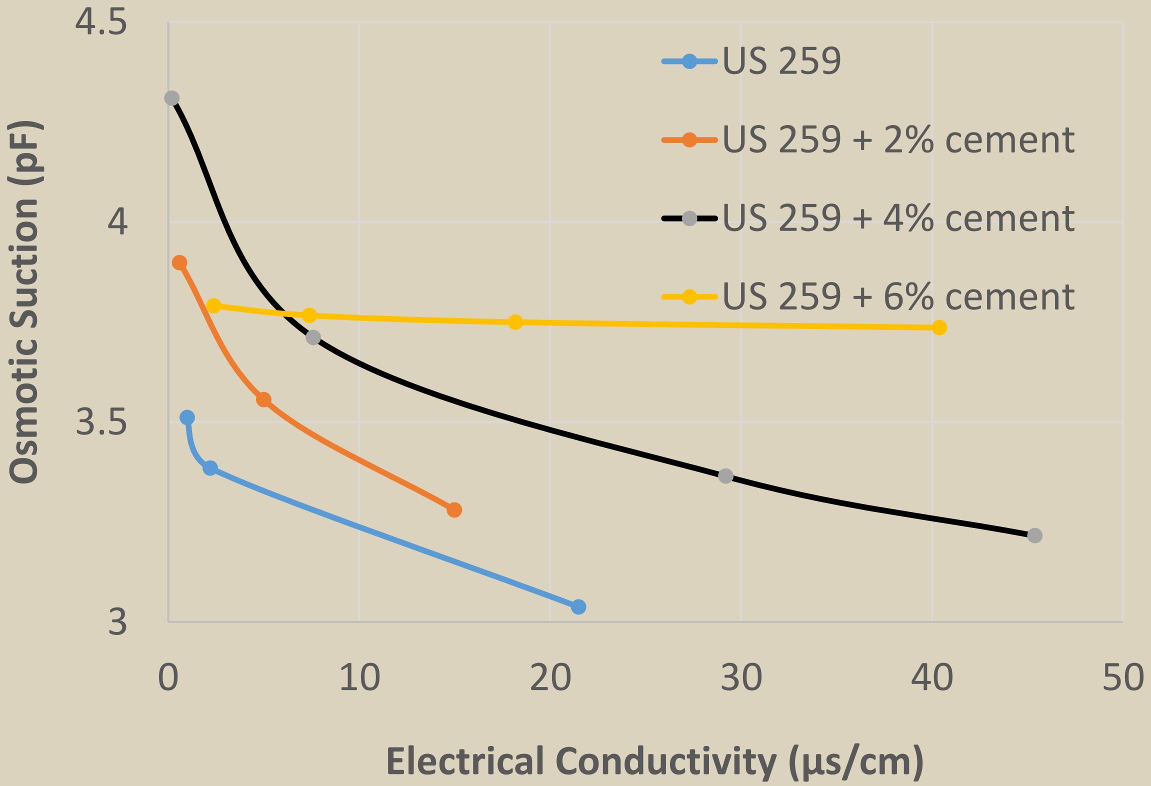




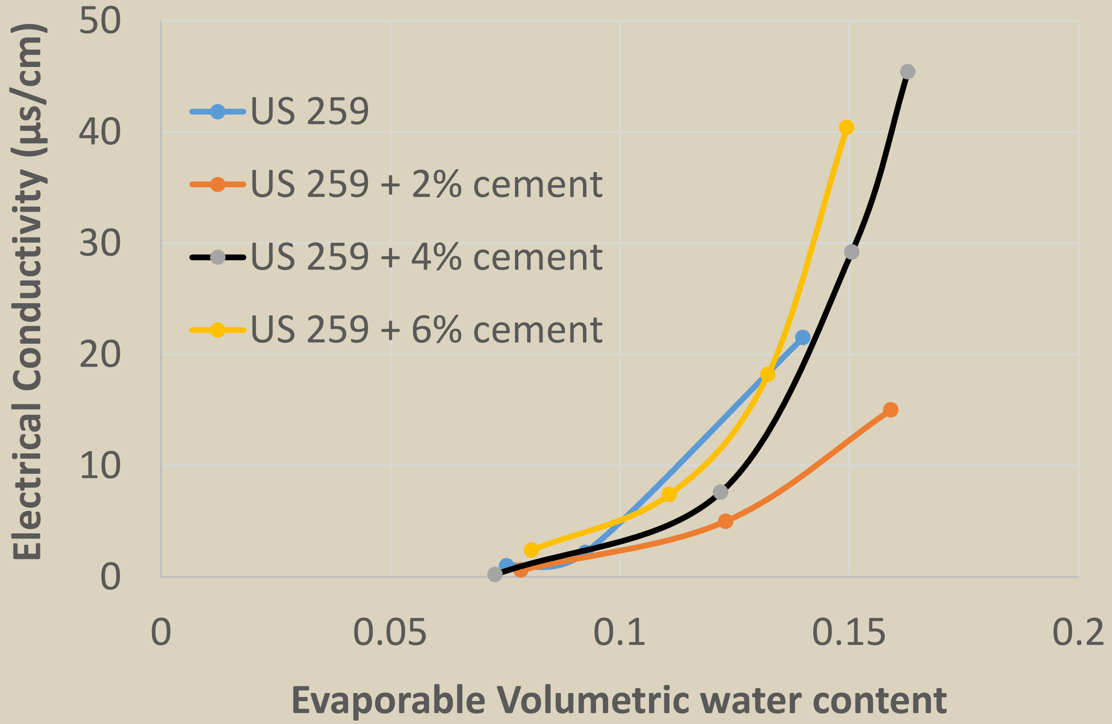
Osmotic Suction vs Water Content



Osmotic Suction vs Conductivity



Conductivity vs Water Content



Some Characteristic Curves

- Soil water characteristic curve
- Soil dielectric characteristic curve
- Soil conductivity characteristic curve
- Soil osmotic suction – evaporable water content curve
- Soil osmotic suction – electrical conductivity curve

TEXAS A&M ENGINEERING

DESIGNING BASES AND SUBGRADES FOR BETTER PAVEMENT PERFORMANCE

Robert L. Lytton

Houston Foundation Performance Association

December 13, 2017