NCHRP Project 10-84

Modulus-Based Construction Specification for Compaction of Earthwork and Unbound Aggregate

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Objectives

Develop a straightforward & well-defined modulus-based construction specification with following constraints:

1. Based on field measurement of modulus & moisture content.
2. Acceptance criteria correlated with design moduli.
3. Variation of modulus with moisture content and density are accounted for.
4. Principles of unsaturated soil mechanics considered
5. Available models, devices, and methods
6. Validity and practicality of proposed specification documented based on shadow specification of actual construction projects.

Presentation 1:
Pavement Foundation Quality Assurance
Lessons Learned by a State DOT

An Introduction to NCHRP 10-84
"Modulus-Based Construction Specification for Compaction of Earthwork and Unbound Aggregate"

John Siekmeier P.E. M.ASCE

Minnesota Department of Transportation

Presentation 2:
NCHRP Project 10-84

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and a large number of other folks

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Acknowledgements

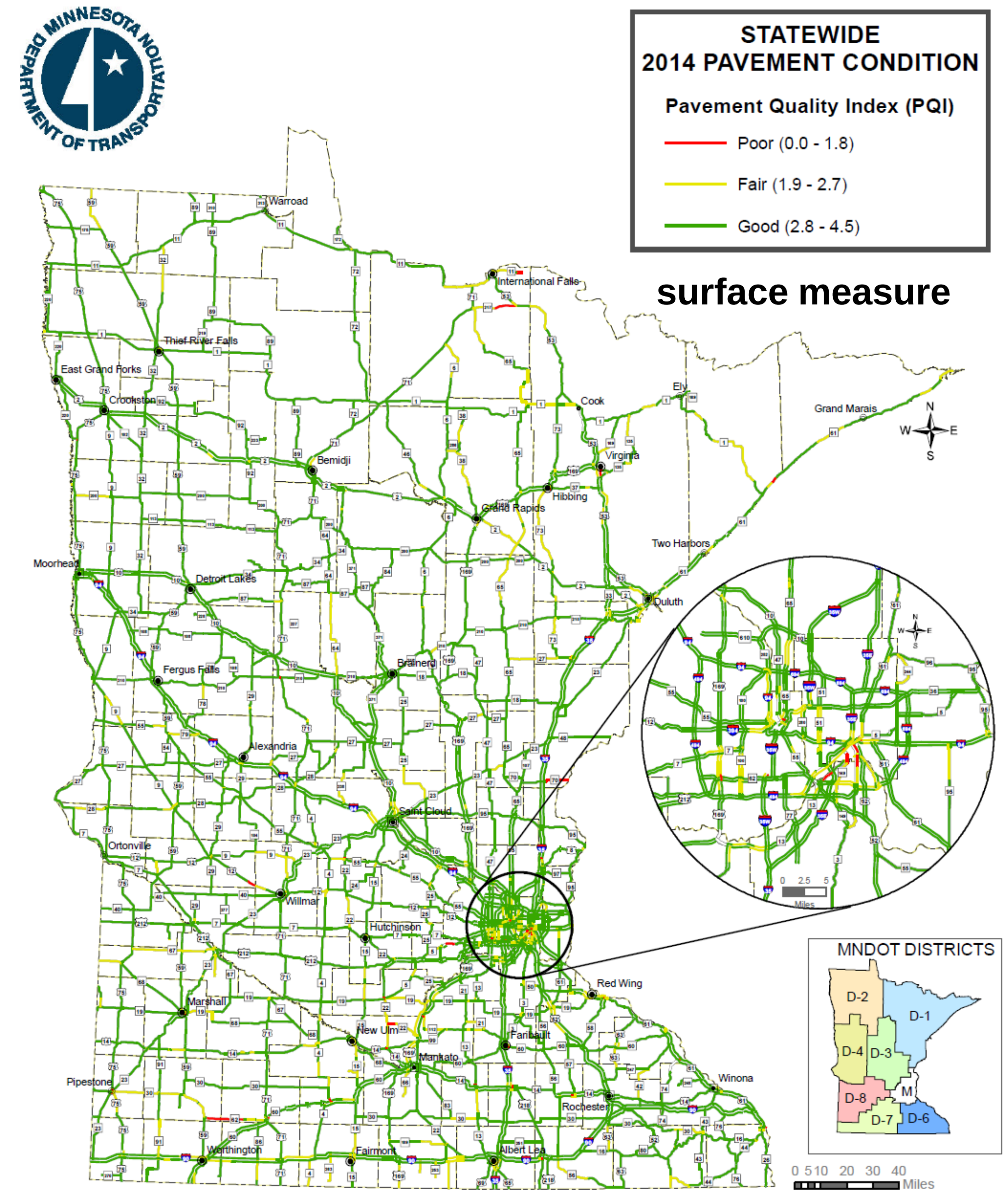
- NCHRP 10-84 Project Team
- NCHRP Staff and Technical Panel Members

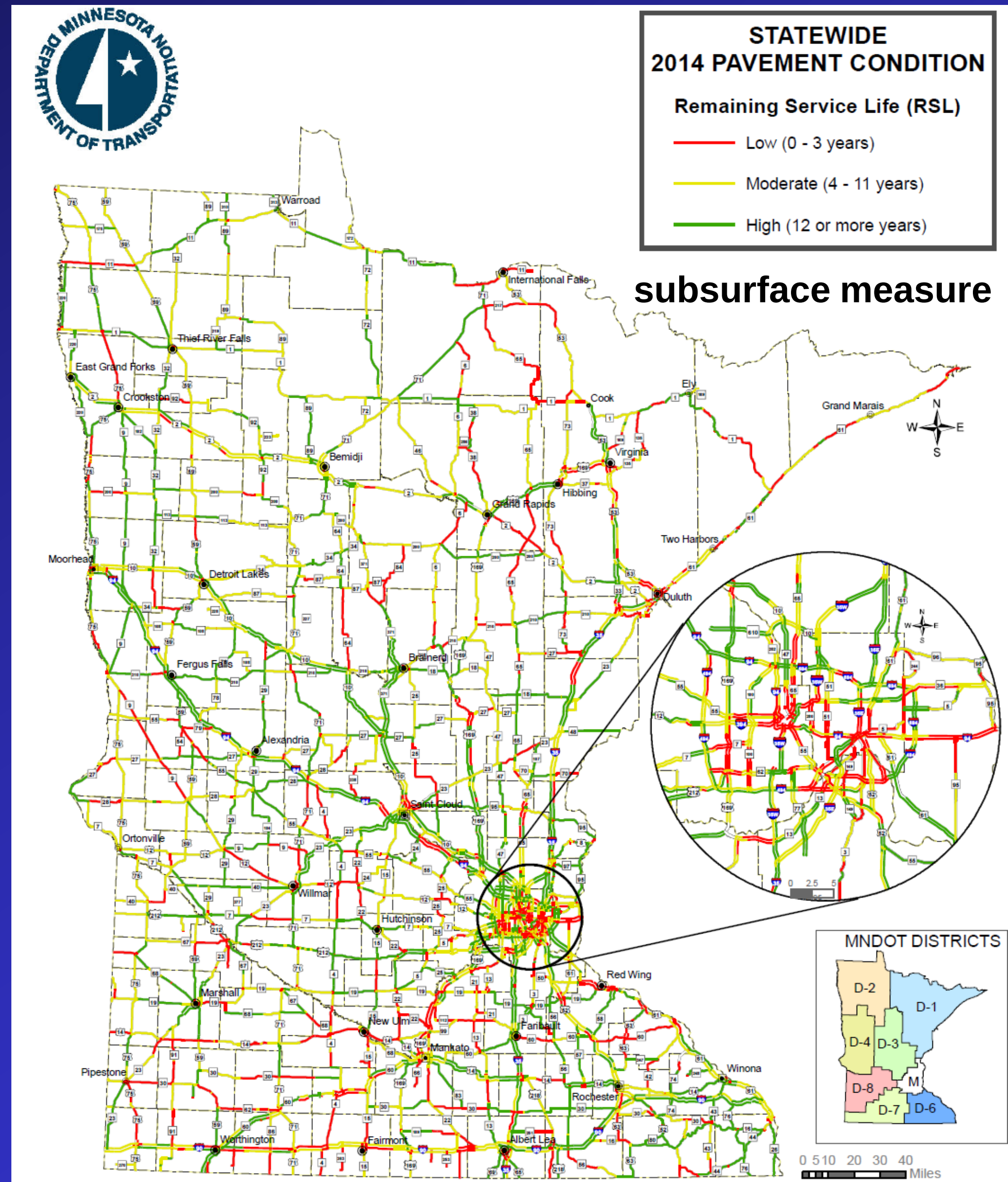
  Ed Harrigan, Terrie Bressette, Ray Brown, Michael Buchanan, Norm Dennis, Wan Soo Kim, Dan Sajedi, and John Siekmeier
- State DOTs and Federal Highway Administration
- U.S. Congress "MAP-21 Performance Required"

Why would we replace a density-based specification with a modulus-based specification?

- Road foundations are important.
- Poor performance has consequences.
- Testing has NOT "always been done this way."
- Building financially effective highways for the 21st century requires 21st century technology.

Road Foundations are Important





Poor Performance has Consequences

- Unable to maintain our public assets.
- Waste labor, energy, and natural resources.
- Public confidence reduced.
- New investments (higher gas tax) difficult.

Ralph Proctor reminds us.

- Strength is not achieved by density alone.
- Optimum moisture is for compaction.
- Need to avoid rutting during construction.

photo courtesy of Dr. J. David Rogers
University of Missouri-Rolla

Ralph Proctor, 1945, Trans 110, ASCE

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

Proctor Penetrometer

Photo courtesy of Humboldt

Hveem and Carmany, 1948, HRB

- “It can easily be shown that the density of a granular mass is one to the least reliable and least informative of all determinations which can be made.”
- “The internal structure of the particle arrangement may vary considerably without any significant change in density.”

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Work Plan

- ***Three Phases***
  I. Development
  II. Calibration
  III. Validation
- ***Consisting of***
  – Laboratory testing
  – Small-scale testing
  – Field testing

- ***Motivation***

  to separate a number of complex and inter-related issues into a number of well-defined hypotheses that, when combined, can provide a practical and scientifically-sound specification.

Characteristics of Materials Used

Material		USCS Classification	Approx. Grain Size Distribution, %			Atterberg Limits	
			Gravel	Sand	Fines	LL	PL
Unbound Agg. Base	El Paso	GP	66	30	4	22	13
	LTRC	GW	56	36	8	NP	NP
Embankment/Subgrade	Mississippi	ML	0	41	59	NP	NP
	Minnesota	CH	0	3	97	86	33
	Austin	CL	8	28	64	27	13
	LTRC	CL	0	10	90	32	16
	El Paso	SM	0	73	27	NP	NP

Laboratory Study

MR and FFRC tests at

OMC

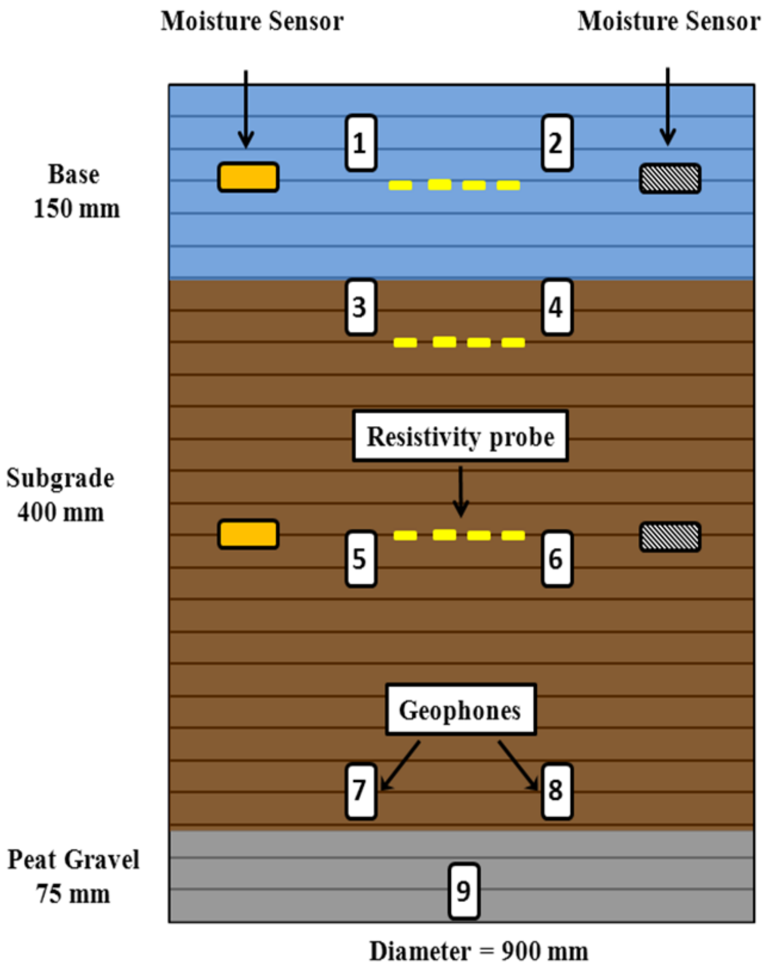
OMC±1% or OMC±10%OMC (if OMC>10%)

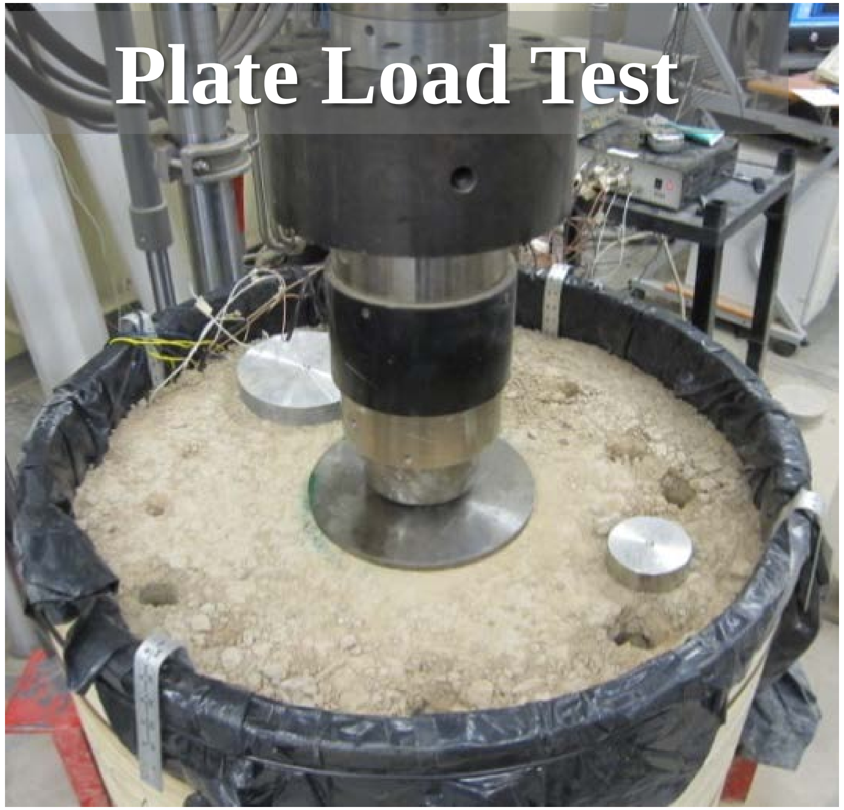
OMC±2% or OMC±20%OMC (if OMC>10%)

- ***Determine*** moduli and their variations with moisture.
- ***Validate*** selected moisture modulus relationships
- ***Compare*** FFRC moduli with MR moduli.
- ***Correlate*** small-strain modulus and resilient modulus

over 200 specimens

Small Scale Testing





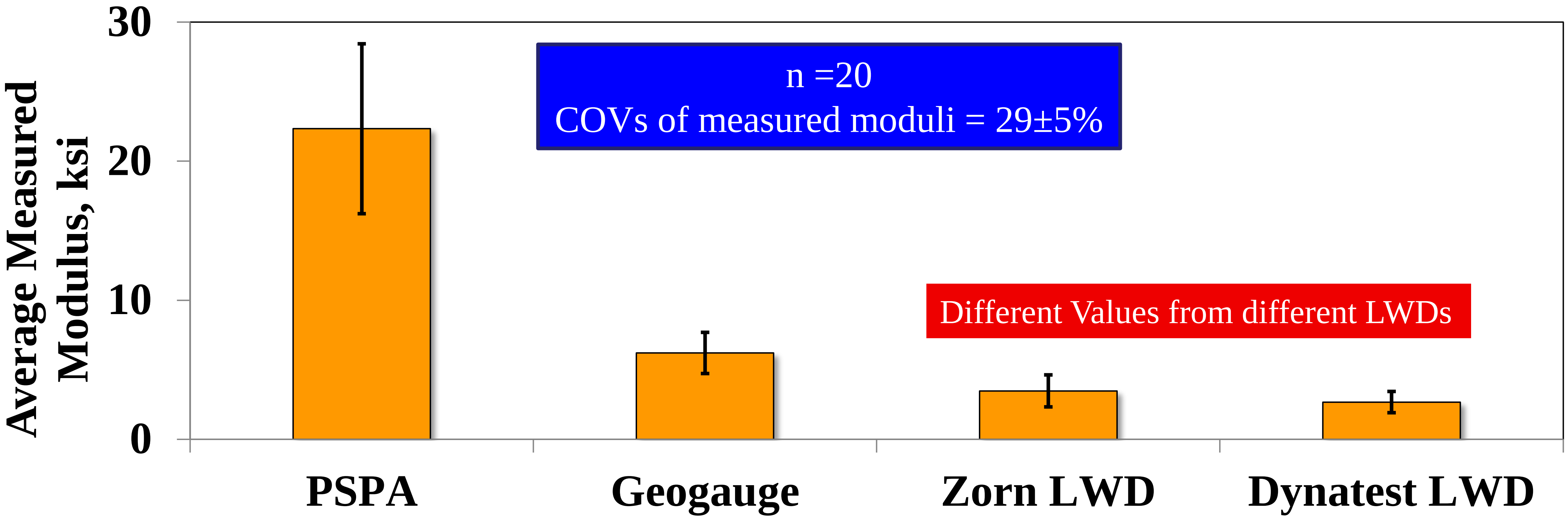
over 30 specimens

Candidate Devices for in situ Measurements

- **Modulus/Stiffness Devices**
  - DCP
  - Geogauge
  - LWD
  - PSPA

- **Moisture/Density Devices**
  - Soil Density Gauge (SDG)
  - Speedy Moisture Tester
  - DOT 600
  - Decagon Embedded Sensors

In-Depth Evaluation of Modulus Measuring Devices (Variation in moduli)



change in representative MR modulus of more than three times with change in moisture content from OMC-1% to OMC+1%

In-Depth Evaluation of Modulus Measuring Devices

Device	Total Variability	Distribution of Total Variability		
		Repeatability (3 repeats)	Reproducibility (2 operators)	Specimen Variability (6 locations)
Zorn LWD	28%	5%	4%	91%
Dynatest LWD	34%	1%	20%	78%
PSPA	29%	26%	3%	71%
Geogauge	24%	22%	8%	69%

Total Variability
- Repeatability
- Reproducibility
- Specimen Variability

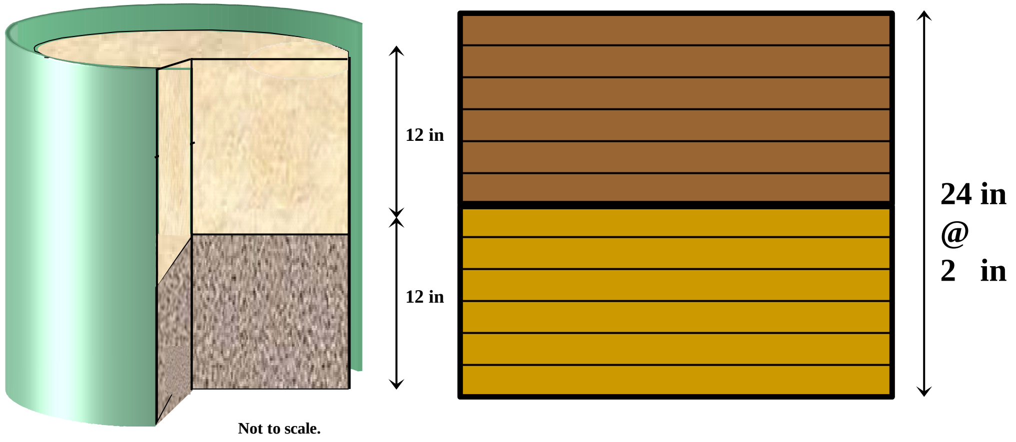
In-Depth Evaluation (Moisture Devices)

Repeatability/Reproducibility *(SDG on SM Subgrade)*

Repeatability	Reproducibility	Specimen Variation	Total Variation
9%	1%	4%	10%

- **Soil Density Gauge**
- **Speedy Moisture Tester**
- **DOT 600**

25 Additional Small-Scale Specimens



Major Steps for Anticipated Specification

1. Selecting Suitable Material
2. Selecting Design Parameters
3. Setting Target Field Moduli
4. Conducting Field Process Control
5. Acceptance Process

Step 1: Selecting Suitable Material

- **A stiff material does not correspond to a durable material.**
- Parameters, such as ***hardness of aggregates, percent fines and plasticity*** should be controlled for durability.
- Each agency to define their own ***specification limits***

Step 2: Estimating Design Parameters

Similar to MEPDG, a three-level approach.
For less rigorous methods it may be prudent to include a test strip

- Determine nonlinear parameters k_1 through k_3 for each material

$$MR = k_1 P_a \left[\frac{\theta}{P_a}\right]^{k_2} \left[\frac{\tau_{oct}}{P_a} + 1\right]^{k_3}$$

θ = bulk stress
τ_{oct} = octahedral shear stress
P_a = atmospheric pressure
$k_{1,2,3}$ = regression constants

Conducting laboratory resilient modulus tests before structural design → Utilizing results from a catalog of most common soils that have been tested → Estimating modulus based on calibrated models that are functions of index parameters → Using presumptive design values based on experience

Best Option → Worst Option

There is a need once and for all to standardize MR Test

Selecting Target Field Modulus (Single layer)

- Design
  - Estimate k_1, k_2, k_3
  - Calculate MR from

$$MR = k_1 P_a \left[\frac{\theta}{P_a}\right]^{k_2} \left[\frac{\tau_{oct}}{P_a} + 1\right]^{k_3}$$

Using prescribed θ and τ_{oct}

- Field Testing ***(LWD)***
  - Calculate modulus from

$$E = [(1 - \nu^2)\, F / (\pi\, a\, d)]\, f$$

  - Estimate d from Structural model

MR ? E

ν = Poisson's ratio
a = radius of load plate
F = applied load
d = surface deflection
f = shape factor

Selecting Target Field Moduli (Process)

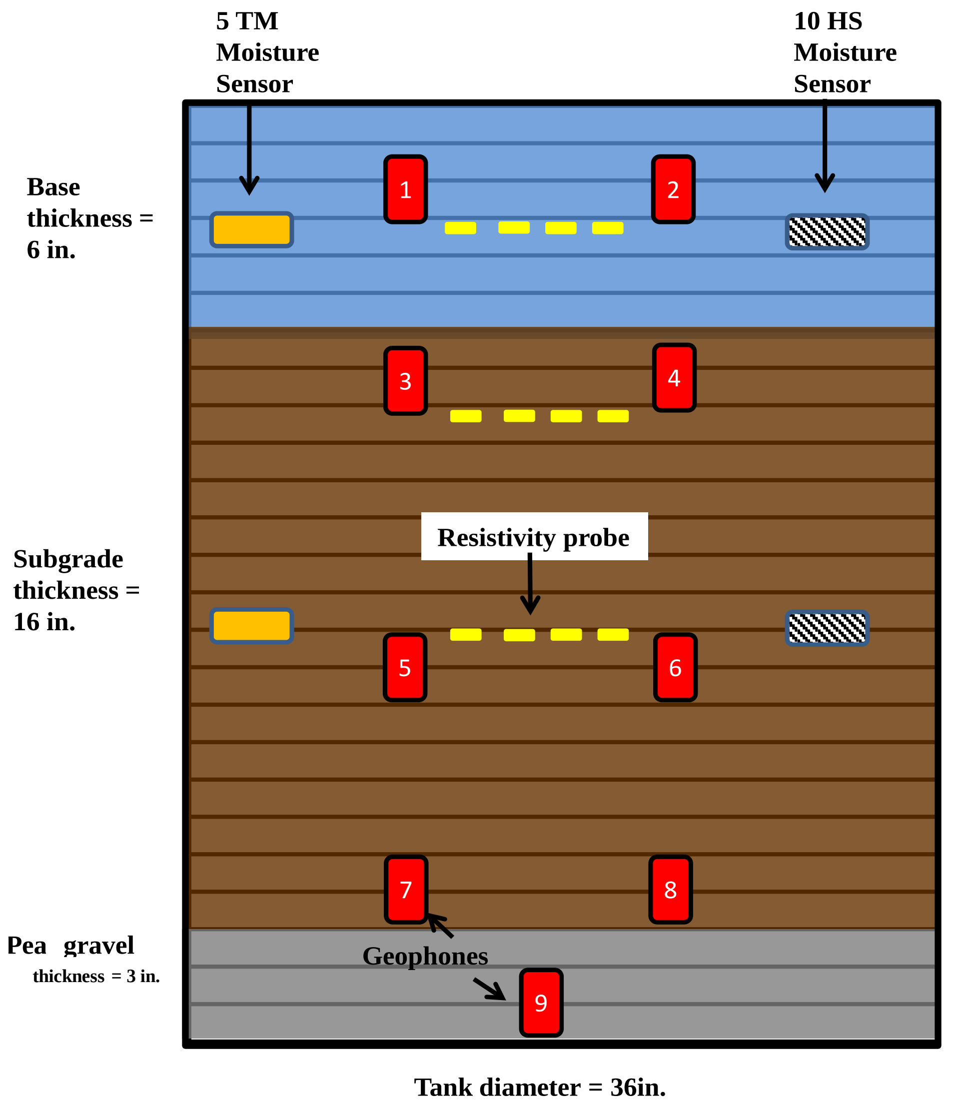
- **Input**
  - Thickness of each layer
  - Poisson’s ratio of each layer
  - Unit weight of each layer
  - k'_1, k'_2 and k'_3 of each layer

Use Structural Model	• for multilayer system or as best approximation
Use Closed form solution	• for single uniform layer
Use Artificial Neural Network algorithm	• for two-layer system

- **Output**
  - Target Deflection
  - Target Modulus

Calibration of Model (LWD, PLT)

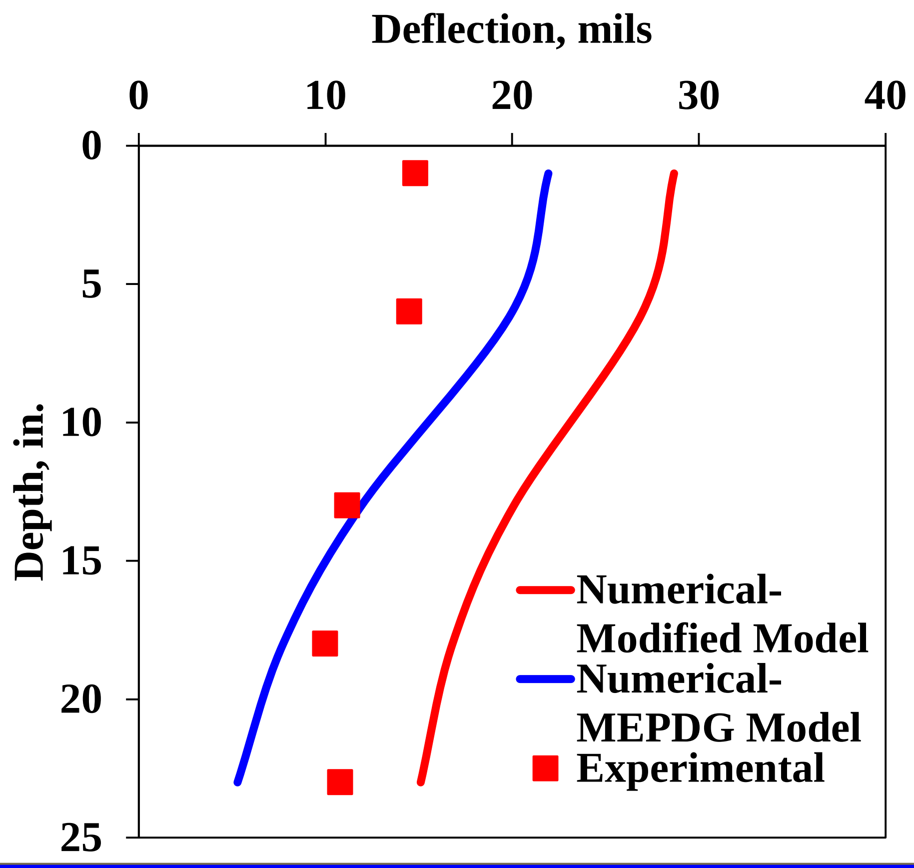
- Direct Comparison is not possible
- Proposed Process
  - Model small-scale specimens
  - Estimate deflections within the specimen
  - Compare deflections with geophone responses

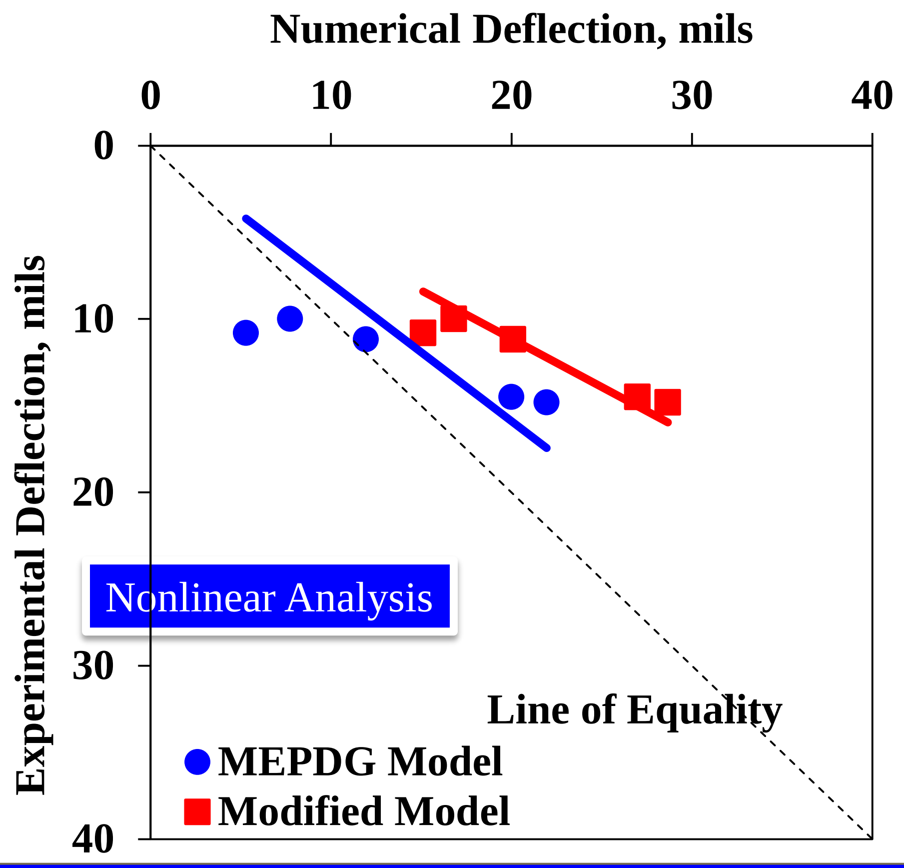


Calibration of Model (Constitutive Model)

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

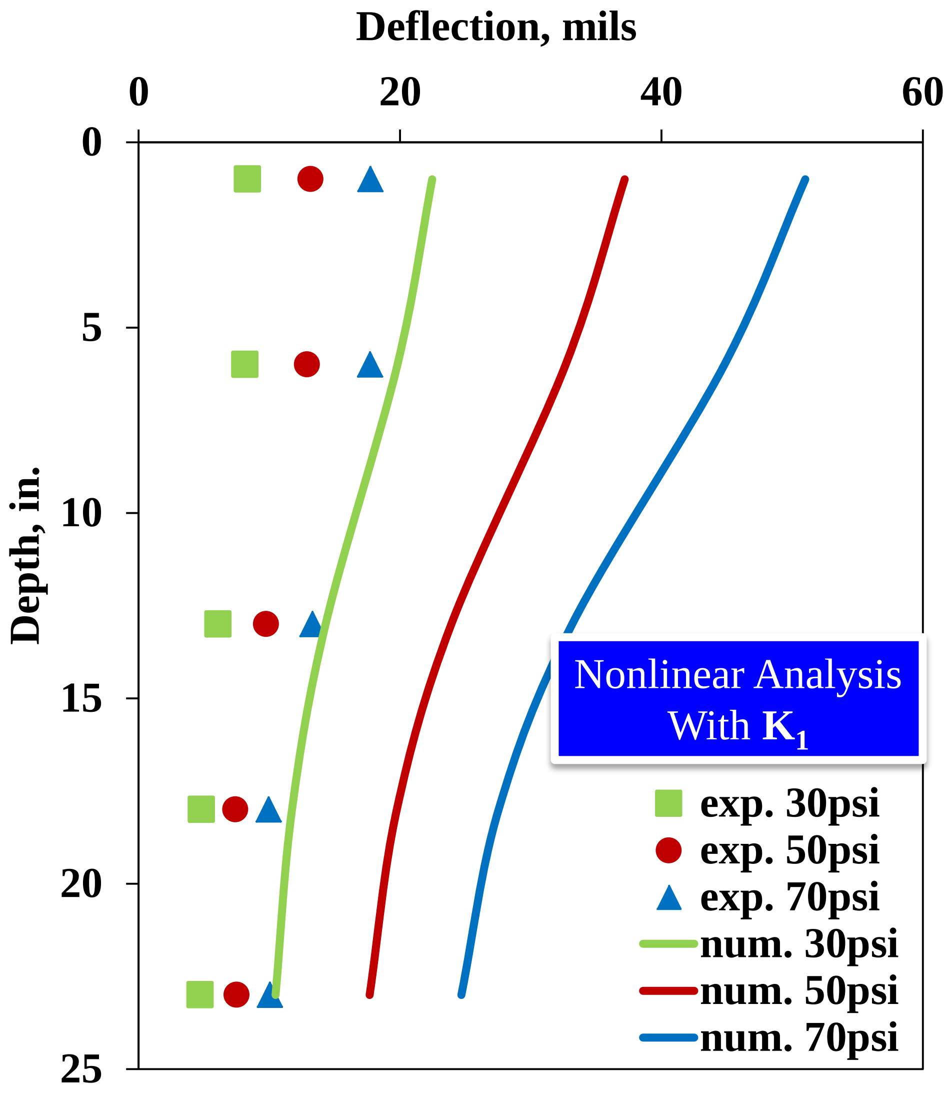
$$MR = k_1 P_a * \left(\frac{\theta}{P_a} + 1\right)^{k_2} * \left(1 + \frac{\tau_{oct}}{P_a}\right)^{k_3}$$

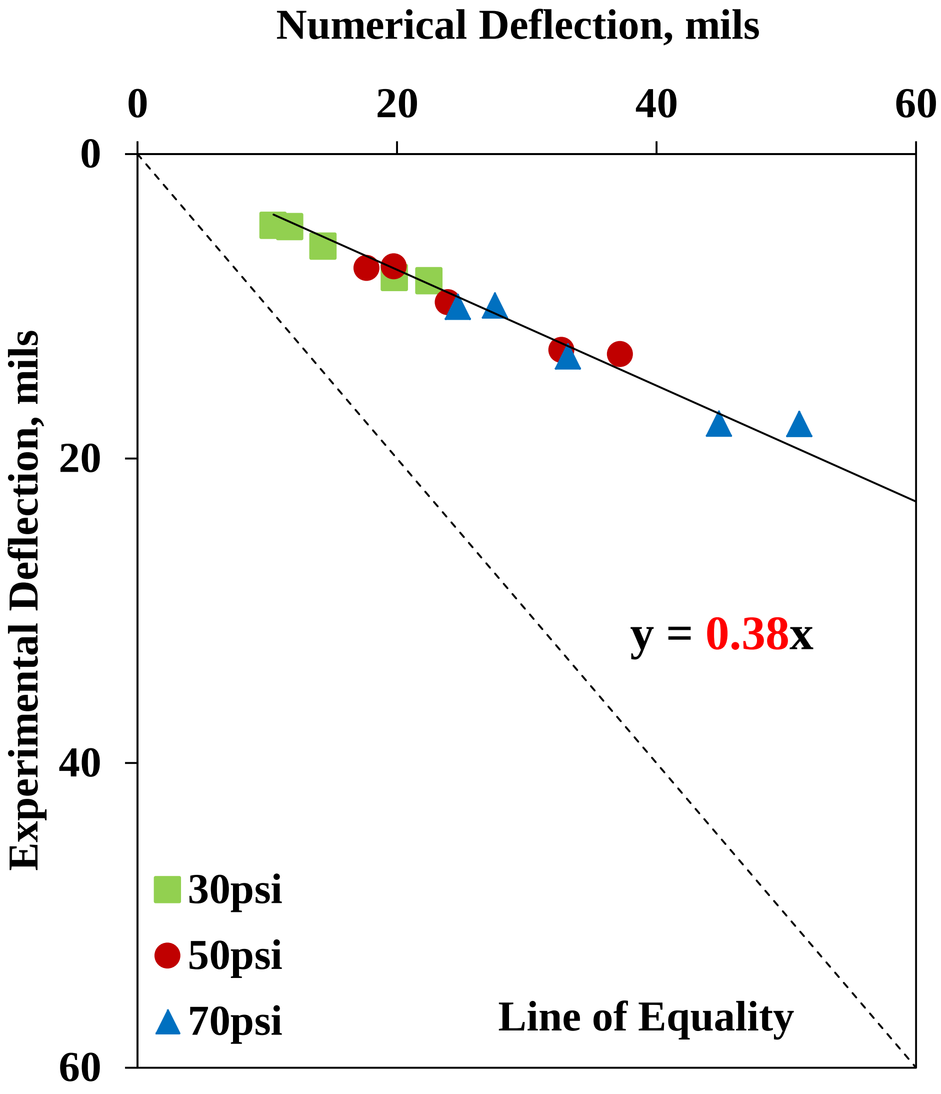




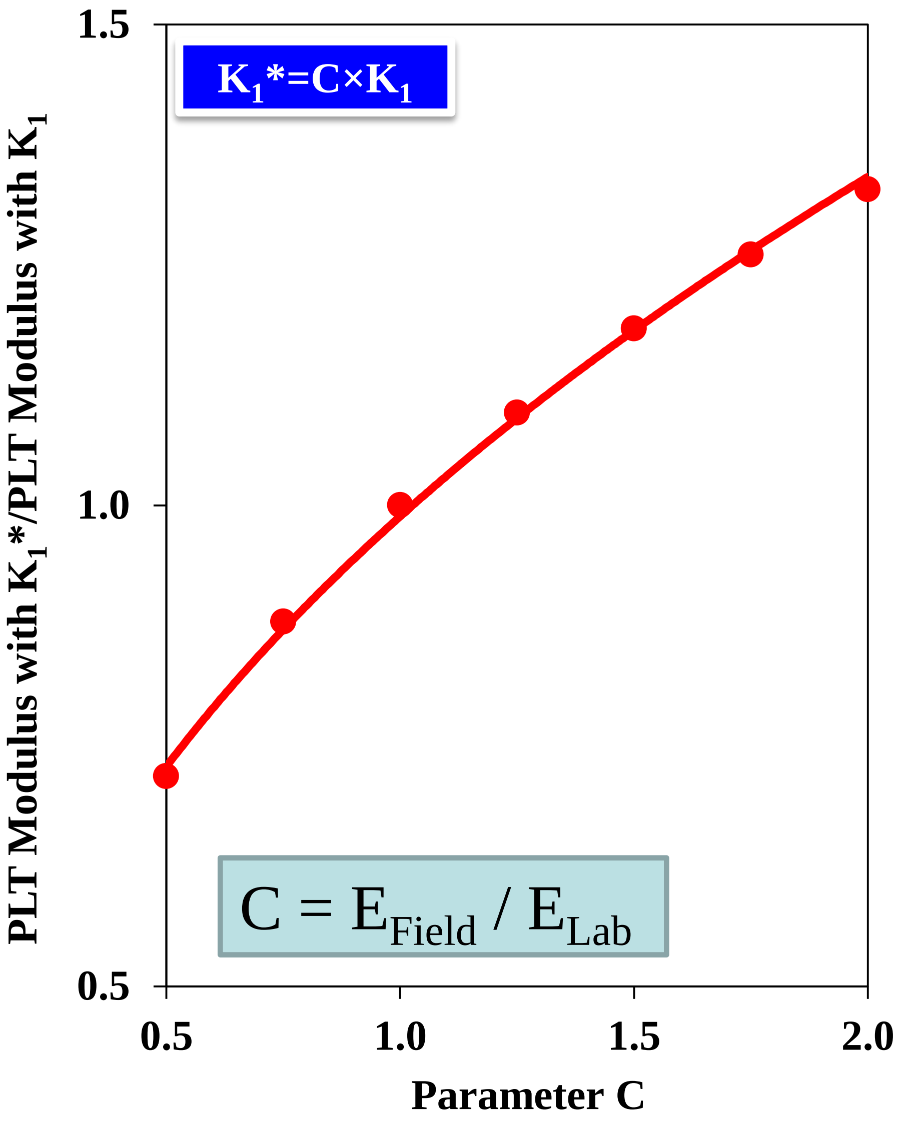
Typical PLT Results (SM Subgrade)

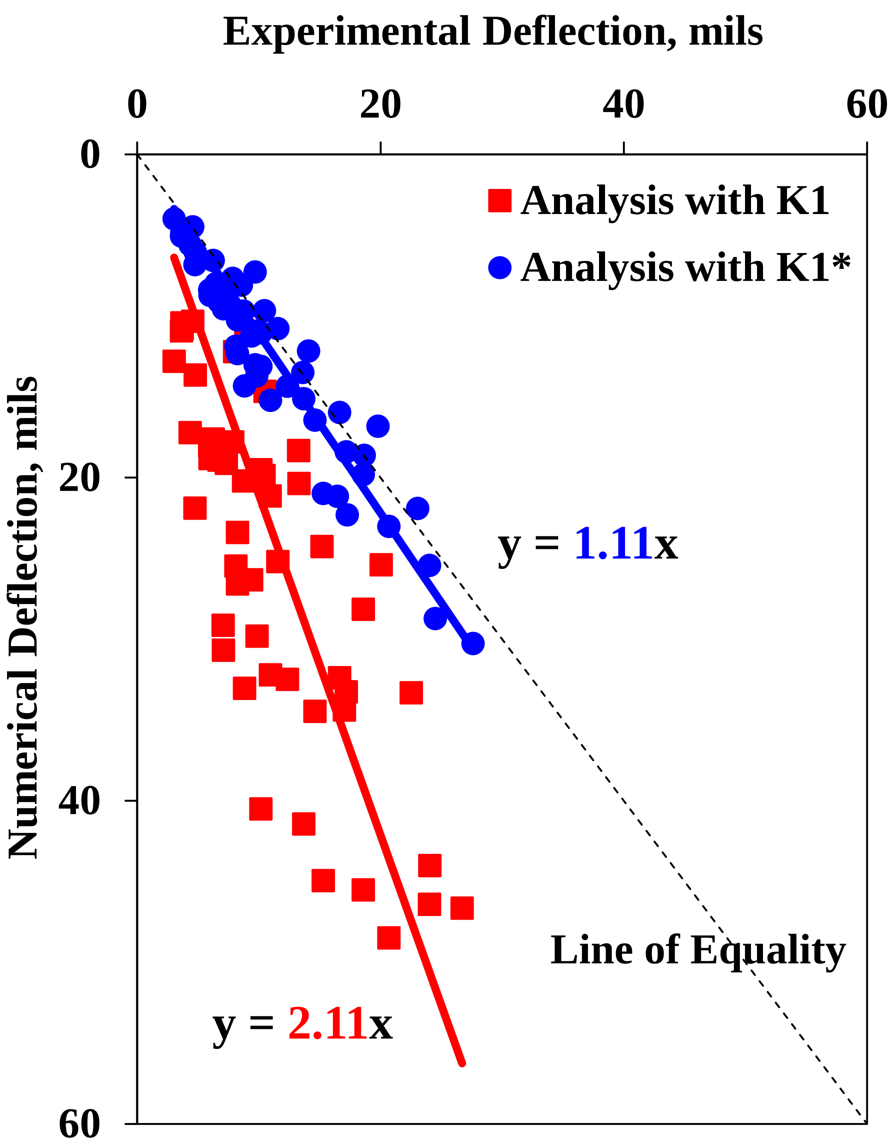
- 8 in. diameter plate
- 30, 50, 70 psi pressure
- at OMC and MDD





Partial Verification of Process (Use of K_1 vs. K_1)*





Rigorously Relating k_1-k_3 to E (Single layer)

- Options
  - Using nonlinear structural model estimate E from k_1-k_3
  - Using

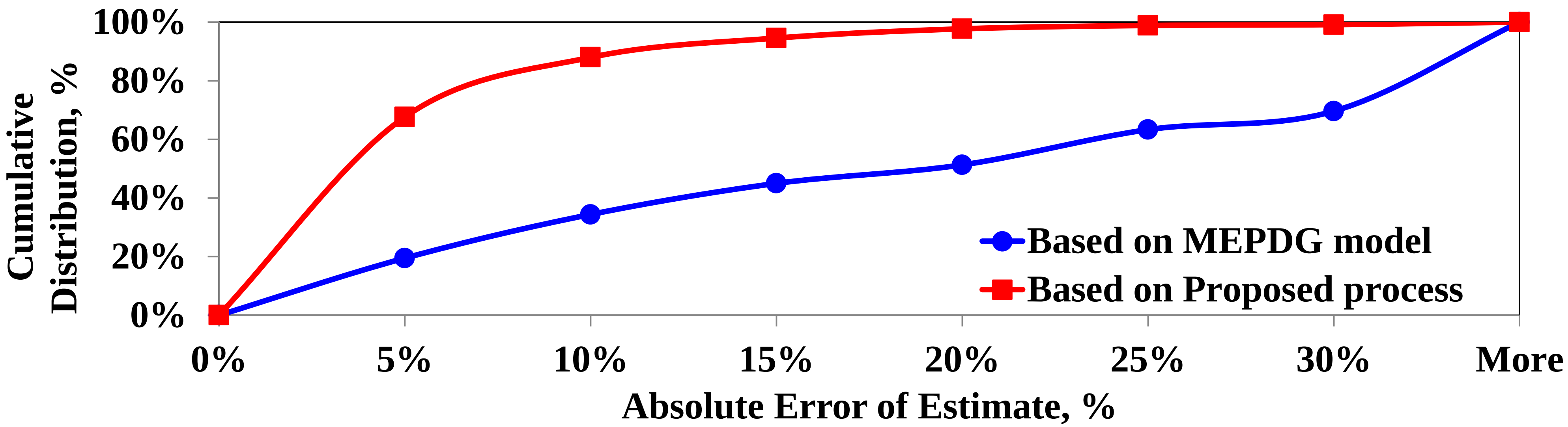
$\theta = \sigma_0\ [(0.001D^2 - 0.012D - 0.169)\ ln(k'_2) + (0.04D + 0.2)]$

$\tau = \sigma_0\ exp[(-0.01D - 1.47) + (k'_2)(-0.006D^2 + 0.066D - 1.269)]$

in

$$MR = k'_1 P_a * (\frac{\theta}{P_a} + 1)^{k'_2} * (1 + \frac{\tau_{oct}}{P_a})^{k'_3}$$

D = LWD Plate diameter
σ_0 = Surface stress



Step 4: Field Process Control

- Changes in **type and gradation** of materials and **moisture content at compaction** have significant impact on modulus.
- **Intelligent compaction** can also be marketed as a means of achieving uniformity.

Either through training or as a secondary requirement in process control this information should be considered by the SHAs and contractors.

Step 4: Field Process Control *(from Unsaturated Soil Principles)*

Degree of Saturation, %
120
115
110
105
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0

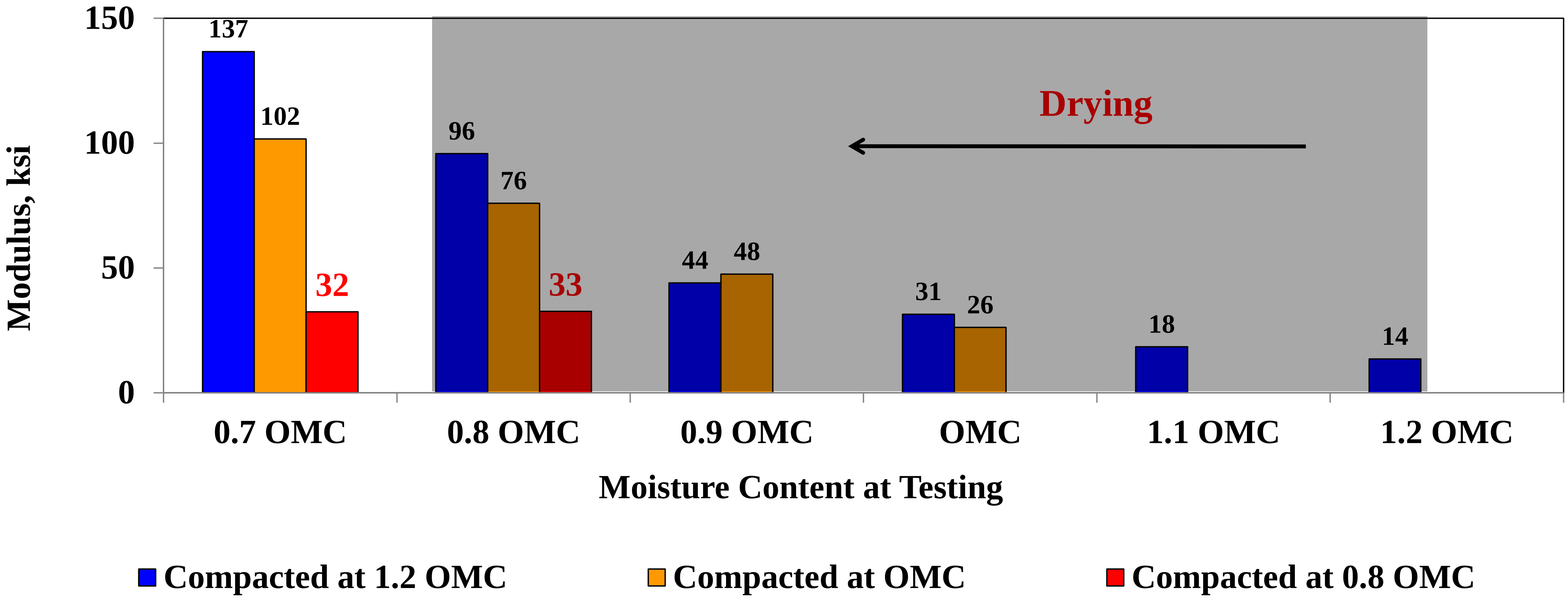
$$S_r = \omega\, G_s\, \rho_d / (G_s\, \rho_w - \rho_d)$$

G_s = specific gravity
ρ_d = dry mass density
ρ_w = mass density of water

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%

Impact of moisture content at time of testing relative to moisture content at time of compaction on modulus



Constant Density Specimens prepared at MDD

Step 5: Acceptance Process

- Acceptance based on **moisture-adjusted modulus** that accounts for:
  - Differences in compaction and testing moisture contents relative to OMC
  - Difference between lab and field moduli at same moisture content and density

- Calculate $E_{eff,}$ as suggested by manufactures

$$E_{eff} = [(1 - \nu^2)\, F / (\pi\, a\, d_{eff})]\, f$$

ν = Poisson's ratio
F = peak load
a = radius of load plate
d_{eff} = peak deflection
f = shape factor,

- Estimate adjusted modulus, E_{adj}

$$E_{adj} = E_{eff}\ K_{lab\text{-}field}\ K_{moist}$$

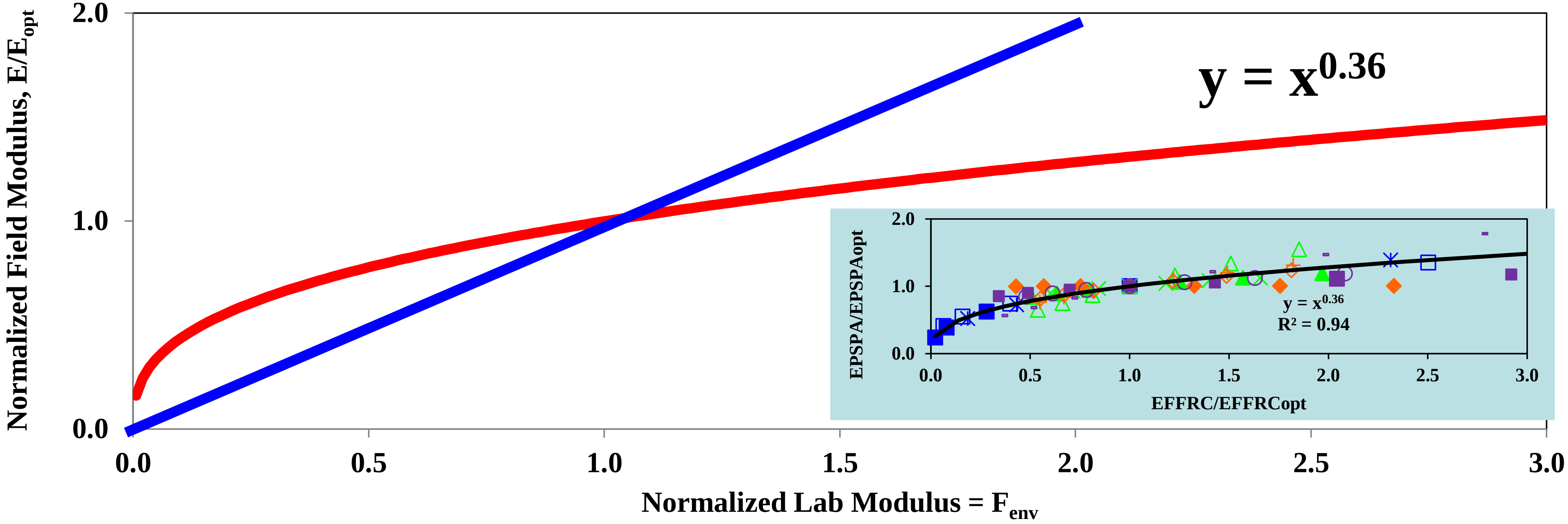
$K_{lab\text{-}field}$ accounts for differences in lab & field moduli (at same moisture content/density)
K_{moist} adjusts for differences in compaction and testing moisture contents.

Moisture-Adjusted Modulus (E_{adj}), cont.

- $K_{lab\text{-}field} = (F_{env})^{\lambda}$ **λ = - 0.36**

$$\log F_{env} = \left[(-0.40535) + \frac{1.20693}{1 + e^{\left[0.68184 + 1.33194 \times \left(\frac{S - S_{opt}}{100}\right)\right]}}\right]$$

S_{opt} = degree of saturation at OMC
S = degree of saturation at compaction moisture content



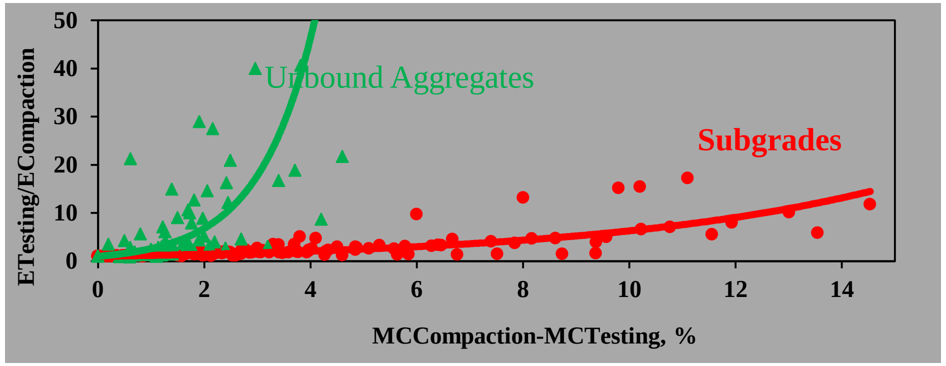
F_{env} = modified relationship proposed by Cary and Zapata (2010)

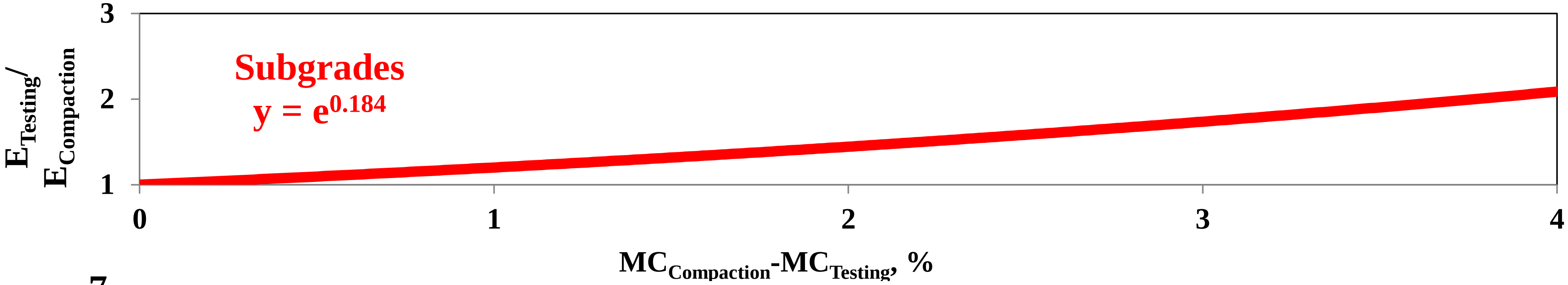
Moisture-Adjusted Modulus (E_{adj}), cont.

$$K_{moist} = e^{\eta(\omega C - \omega T)}$$

ω_T = moisture content at time of testing (%)
ω_C = moisture content at time of compaction (%)

η = 0.18 for subgrades
η = 1.19 for unbound aggregates





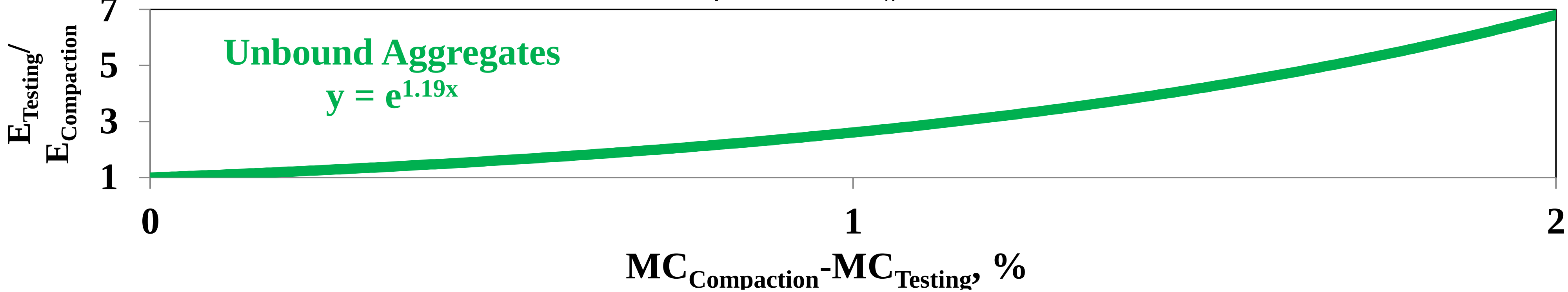
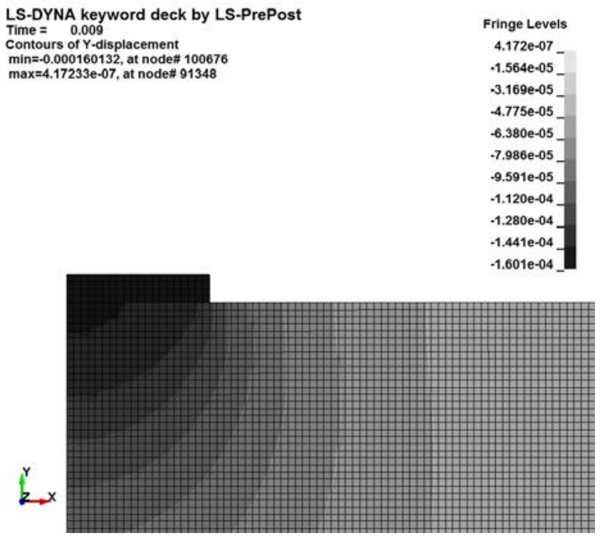


Plate Contact (Deflection)

8 in. diameter plate

Dynatest



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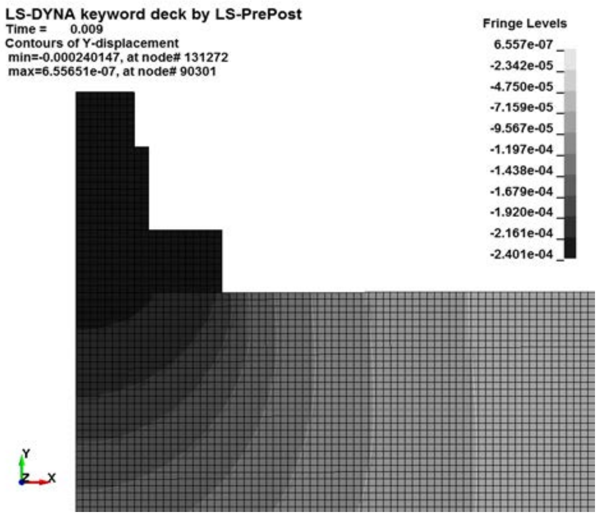
Zorn



*

* Units in m

- Surface deflection modulus E_{LWD}

$$E_{LWD} = \frac{(1-\nu^2)\sigma_0 a f}{d_0}$$

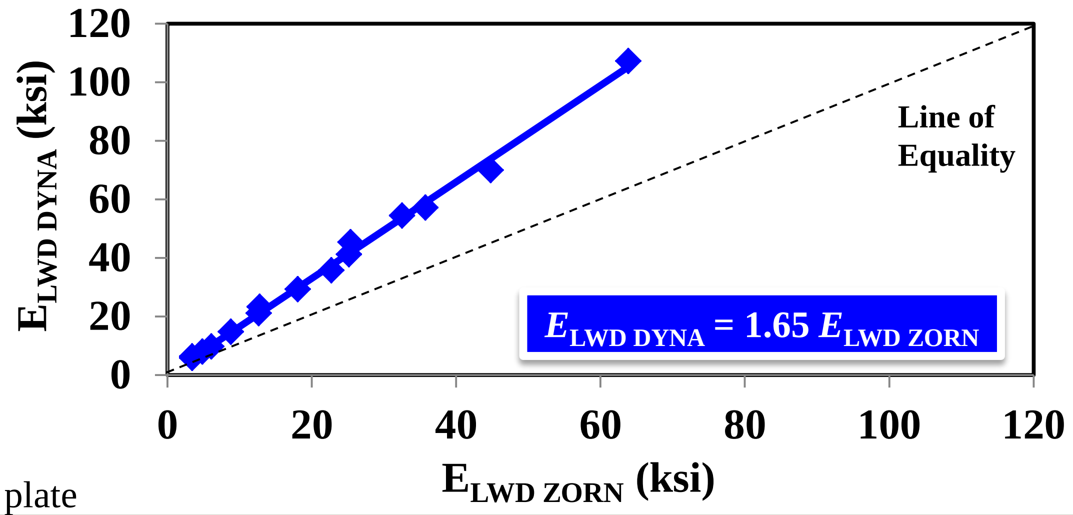
ν = Poisson's ratio

σ_0 = uniform stress distribution (30 psi)

a = radius of plate

f = shape factor ($\pi/2$ for inverse parabolic)

d_0 = measured settlement of soil at the center of plate



Depth of Influence

8 in. diameter plate

- Based on stress:
  - Varies between 15 in. and 19 in.
  - Decreases with
    - Higher k_1 (stiffer material)
    - Higher k_2 (more granular material)
    - Insensitive to k_3
  - Zorn LWD is less sensitive to nonlinear parameters as compared to Dynatest LWD.

- Based on deflection:
  - Varies between 24 in. and 32 in.
  - Decreases with
    - Higher k_3 (more clayey material)
    - Lower k_2 (less granular material)
    - Insensitive to k_1

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

Depth of influence is material and device dependent

Field Validation

Stage 1 - Documenting Shortcoming of Specification

- Documenting shortcoming and improving specification
- Collect relevant field data,
- Conduct proposed lab tests
- Compare results with current processes.

Stage 2 - Validating Specification

- work hand-in-hand with highway agencies

Sites for Phase III

Site I.1. US 67 in Dublin, TX

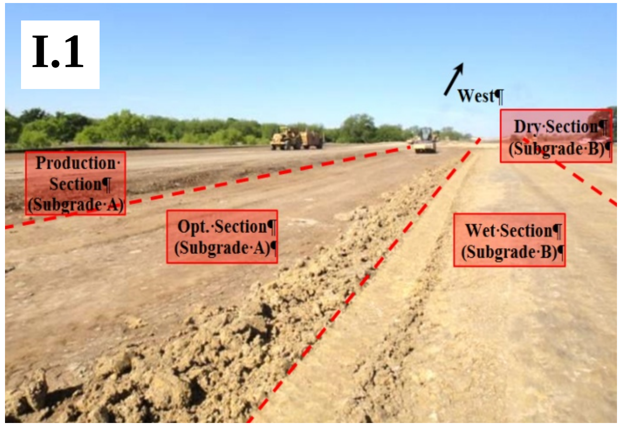
Site II.1. FAA Facility, Atlantic City, NJ

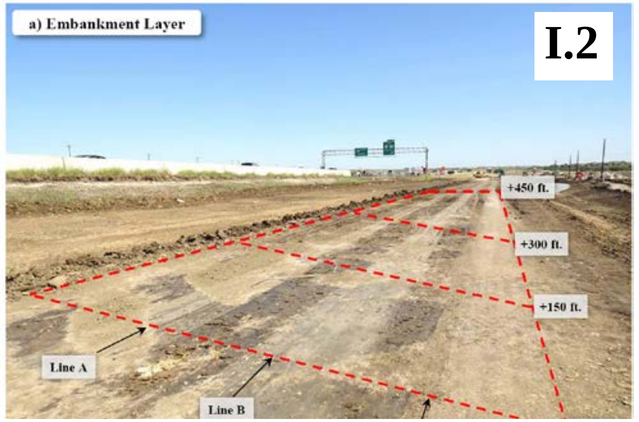
Site I.2. IH 35 W, Tarrant County, TX

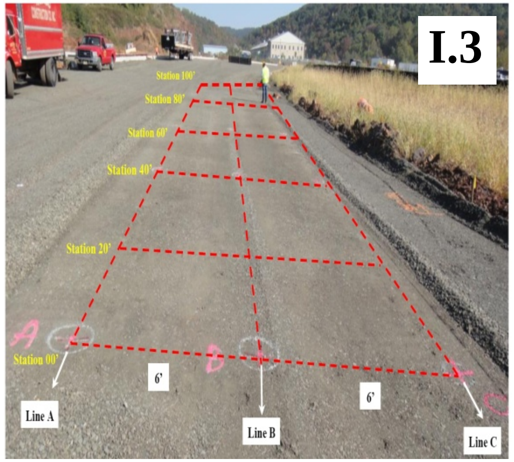
Site II.2. US-50, North Vernon, IN

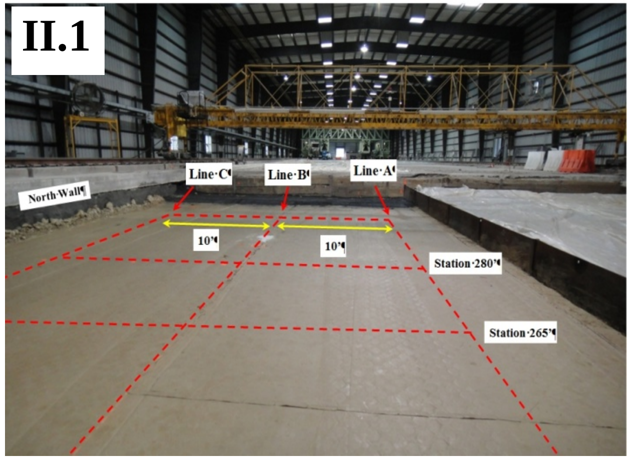
Site I.3. Route 22, Bridgewater, NJ

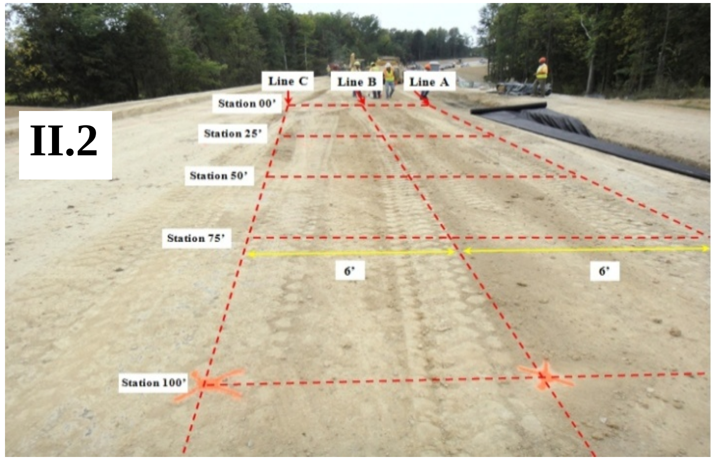
Sites for Phase III







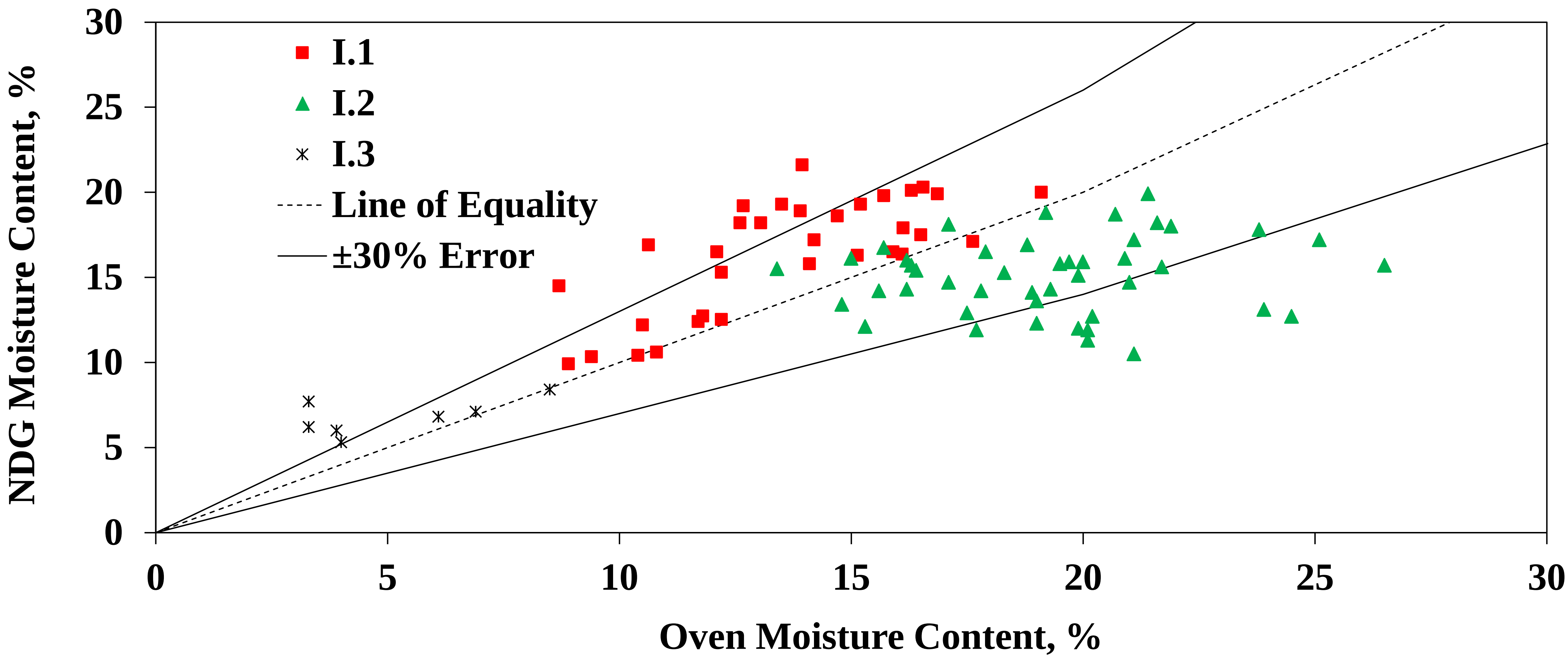




Index Properties of Phase III Geomaterials

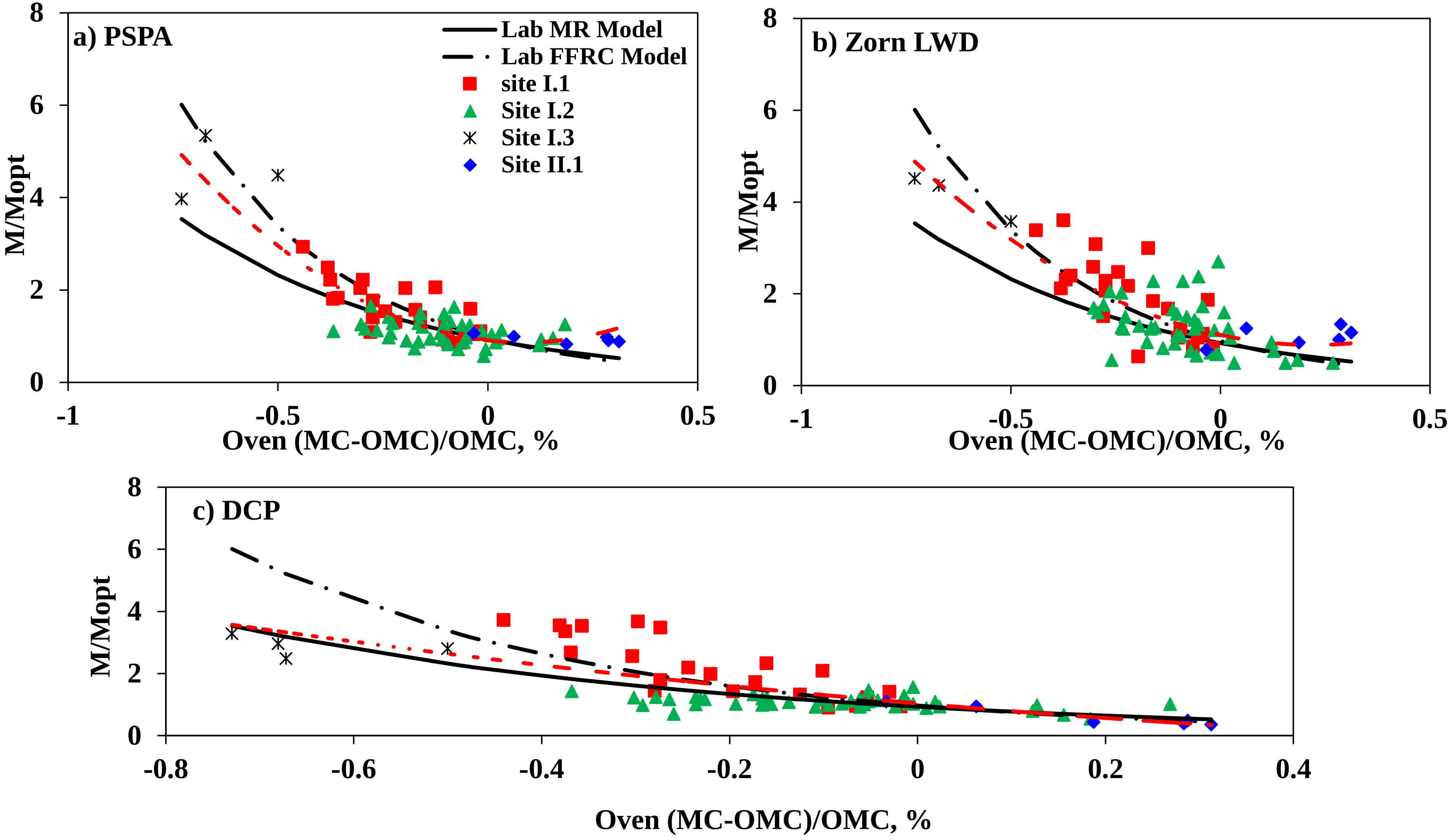
Site No.	Soil Type	Gradation %				USCS Class.	Atterberg Limits	
		Gravel	Coarse Sand	Fine Sand	Fines		LL	PL
I.1	Subgrade A	0	4	10	86	CL	41	14
	Subgrade B	0	5	11	84	CL	36	13
	Base	52	29	15	5	GW	28	16
I.2	Subgrade	0	8	3	89	CH	55	15
I.3	Subgrade	12	20	13	55	CL	32	18
	Subbase	63	26	10	1	GW	Non-Plastic	
	Base	59	32	7	1	GW	Non-Plastic	
II.1	Subgrade	5	4	2	89	CL	48	15
	Subbase	0	79	18	3	SP	0	0
II.2	Subgrade	5	8	22	65	CL	27	11
	Subbase	56	34	10	1	GW	0	0

Variability of Measurements on Subgrade Soils
(Moisture Content)



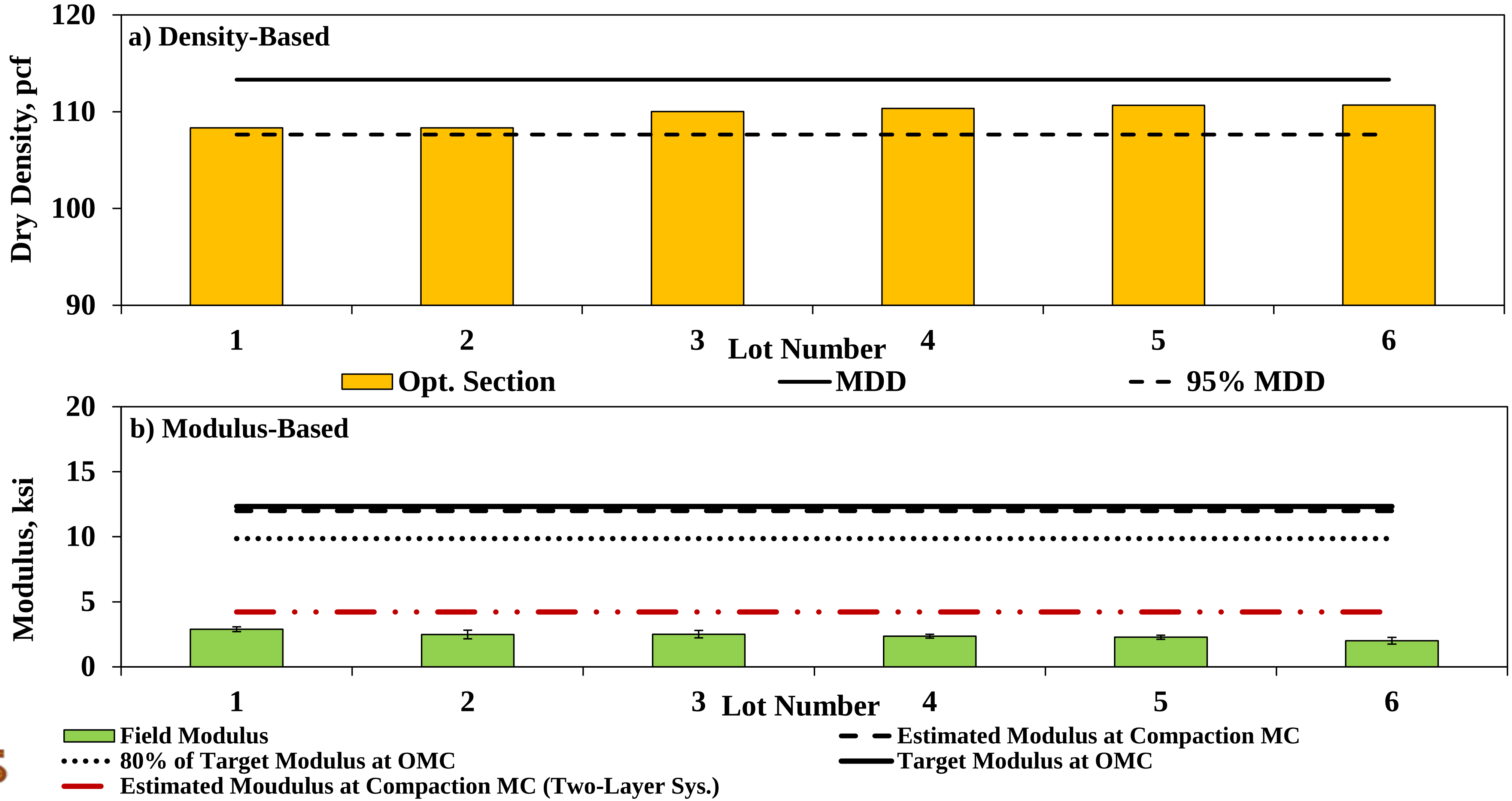
Variation of Field Moduli with Normalized Moisture Content

(Proposed Model) (Subgrade)



Field Evaluation: (OMC Section)

Construction Quality Acceptance Scenarios (Zorn LWD)



Conclusions and Recommendations

- Achieving quality compaction (defined as achieving adequate layer modulus) is weakly associated with achieving density.
- Most moisture-modulus models that are reasonable for (long term) pavement design may not be appropriate for (short term) quality control.
- Proposed model of correlating normalized modulus **(E/E_{opt})** vs. **[(MC-OMC)/OMC]** matched field data better.

Conclusions and Recommendations (Cont.)

- Among the modulus/stiffness-based devices, the **PSPA**, **LWDs** and **DCP** perform reasonably well with the following caveats:

  - ✓ The PSPA exhibits the **highest variability** and needs the most training, but provides the **most reasonable** layer-specific information.

  - ✓ Different LWDs estimate **different moduli** at the same test spot. As such, the specification should be clear which LWD should be used.

  - ✓ Properties of the **underlying layers should be considered** in setting the LWD target values, especially when the layer of interest is overlying a layer with significantly different modulus.

  - ✓ The DCP is simple to use and inexpensive. However, since DCP strictly measures the **strength** not the modulus of the layer, setting its target should be done with care. The DCP results were **not very sensitive** to moisture content and material changes.

Thank you

NCHRP 10-84 Panel

Ed Harrigan

Concluding Remarks

The Path Towards Greater Implementation

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 Empirical Pavement Design

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

MnPAVE - Deflection Test Simulation

Edit | Print Window | Help

Plate Diameter 200 mm   LWD Resistance Factor 0.67

Applied Load 6.3 kN

Restore Default Values

Units: English / SI

Input Data

Exit

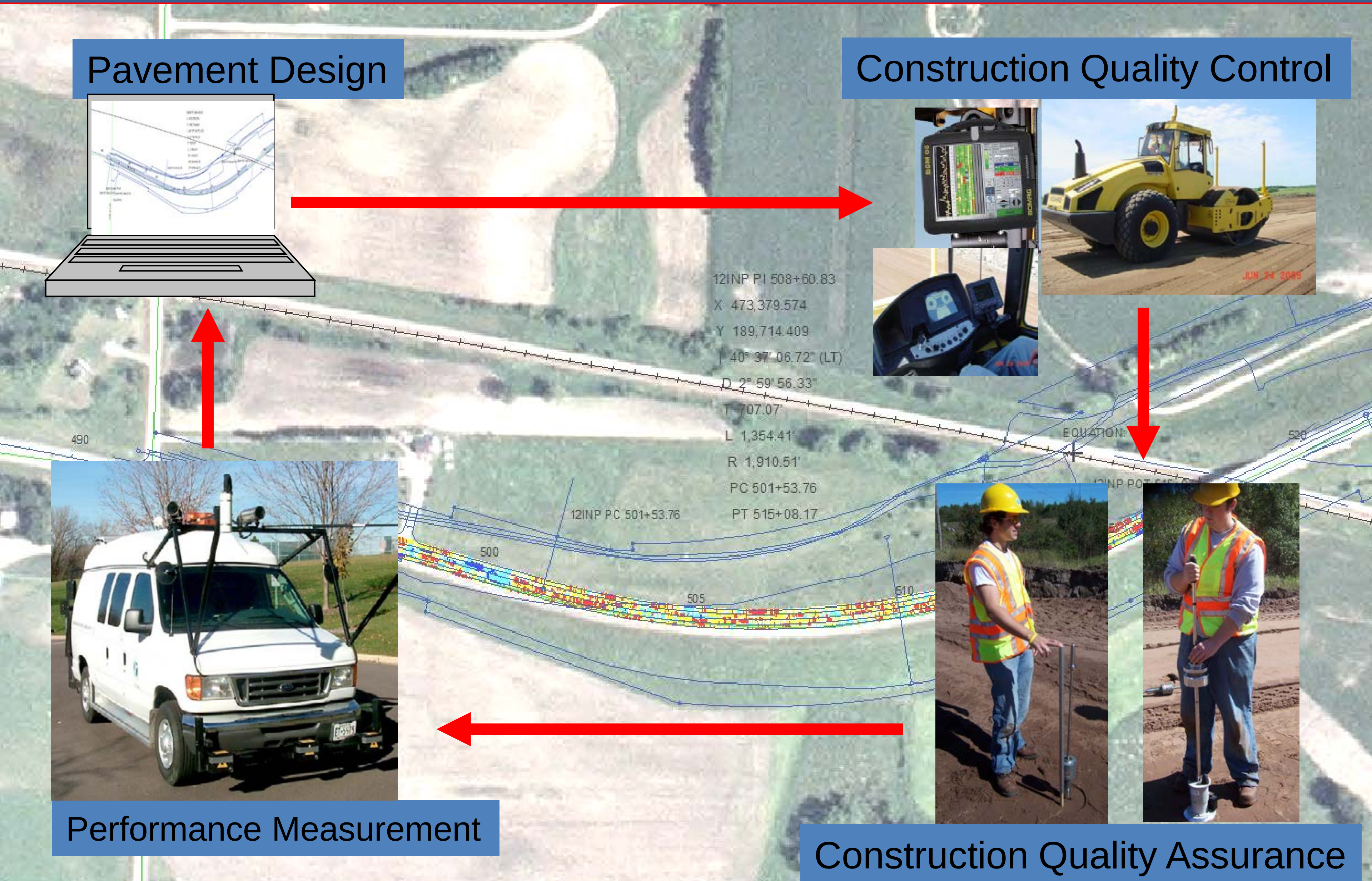
Surface Material	Field Modulus (MPa)	Field Resistance Factor	LWD Deflection (mm) at top of Surface Material				
			Degree of Saturation				
			Opt.-20%	Opt.-10%	Optimum	Opt.+10%	Opt.+20%
				Estimated Target Values			
AggBase	180.5	1.15	0.52	0.55	0.60	0.66	0.71
EngSoil	29.98	0.96				X	
UndSoil	19.23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

Simulated using material properties from Intermediate design level.

Light Weight Deflectometer Links Design to Construction

- Verifies pavement design inputs
- Empowers inspector with useful measures
- Creates as-built construction record

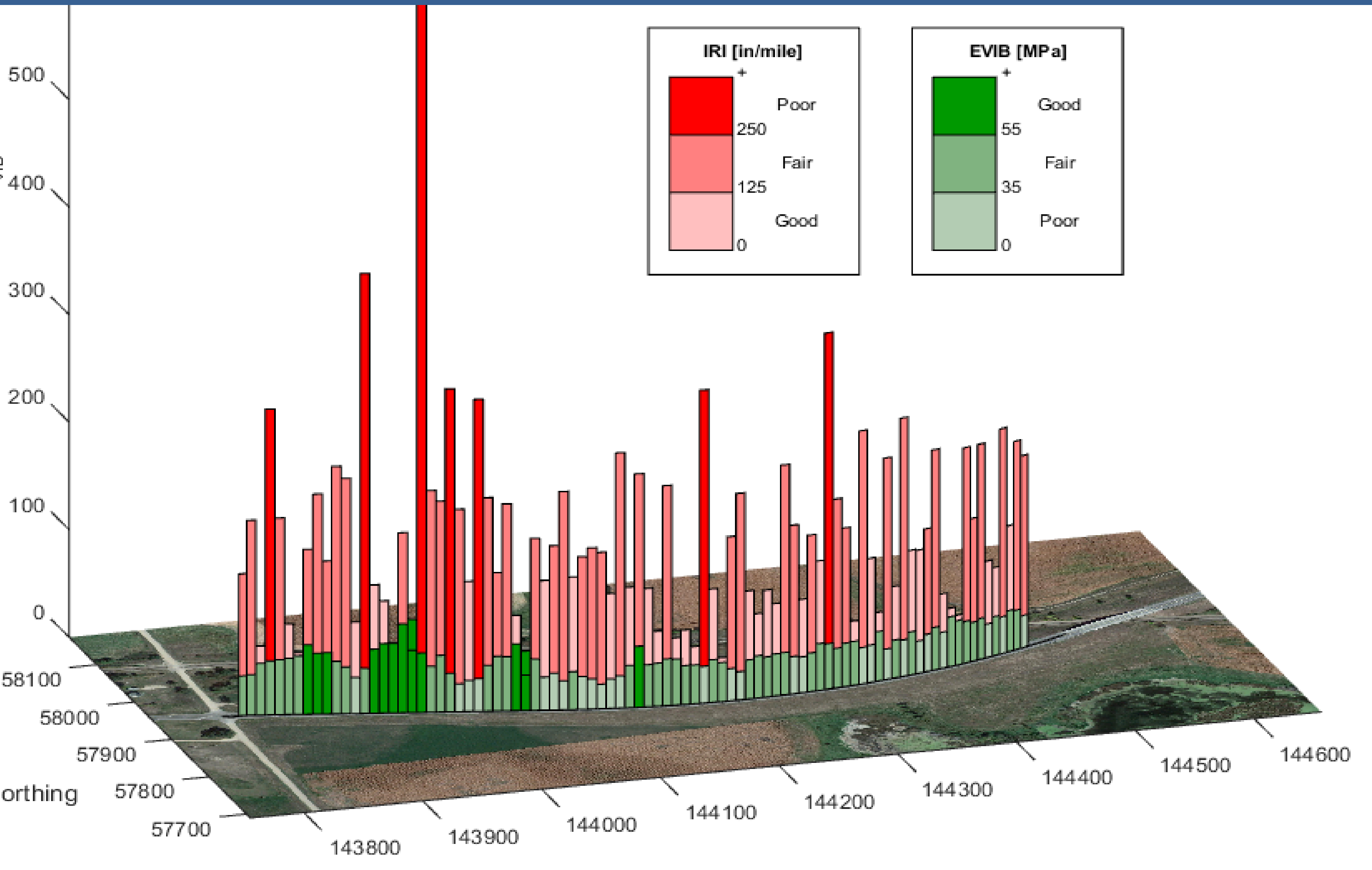
Design, Construction and Performance




BOMAG
VARIOCONTROL

Import Intelligent Compaction Data

Import Pavement Performance Data



Summary

- Compaction equipment and field tests are now available that can measure the properties used to design pavements and predict performance.
- LWDs and DCPs can be used during construction quality assurance to effectively verify design values.
- Several options exist to quantify moisture and more field measurement devices are coming.
- The time is now to accelerate implementation of performance based quality assurance so that our investments are well spent.

Action Items and Future Work

- Continue participation on national project teams.
  - TPF (5)285 Standardized LWD Measurements for QA
- Inspector certification training includes LWD.
- Educate designers, opportunity to optimize design.
- Enhance LWD and DCP target value prediction.
- Specification to include design-based LWD targets.
- Further development of moisture/suction field test.

Thank you. Questions?

Act Boldly.