The National Academies of
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TRANSPORTATION RESEARCH BOARD

TRB Webinar: Improving Pavement Geomaterial Performance with Unsaturated Soil Mechanics

August 3, 2021

2:00- 3:30 PM Eastern

@NASEMTRB
#TRBwebinar

PDH Certification Information:

- 1.5 Professional Development Hours (PDH) – see follow-up email for instructions
- You must attend the entire webinar to be eligible to receive PDH credits
- Questions? Contact Beth Ewoldsen at Bewoldsen@nas.edu

#TRBwebinar

The Transportation Research Board has met the standards and requirements of the Registered Continuing Education Providers Program. Credit earned on completion of this program will be reported to RCEP. A certificate of completion will be issued to participants that have registered and attended the entire session. As such, it does not include content that may be deemed or construed to be an approval or endorsement by RCEP.

REGISTERED CONTINUING EDUCATION PROGRAM

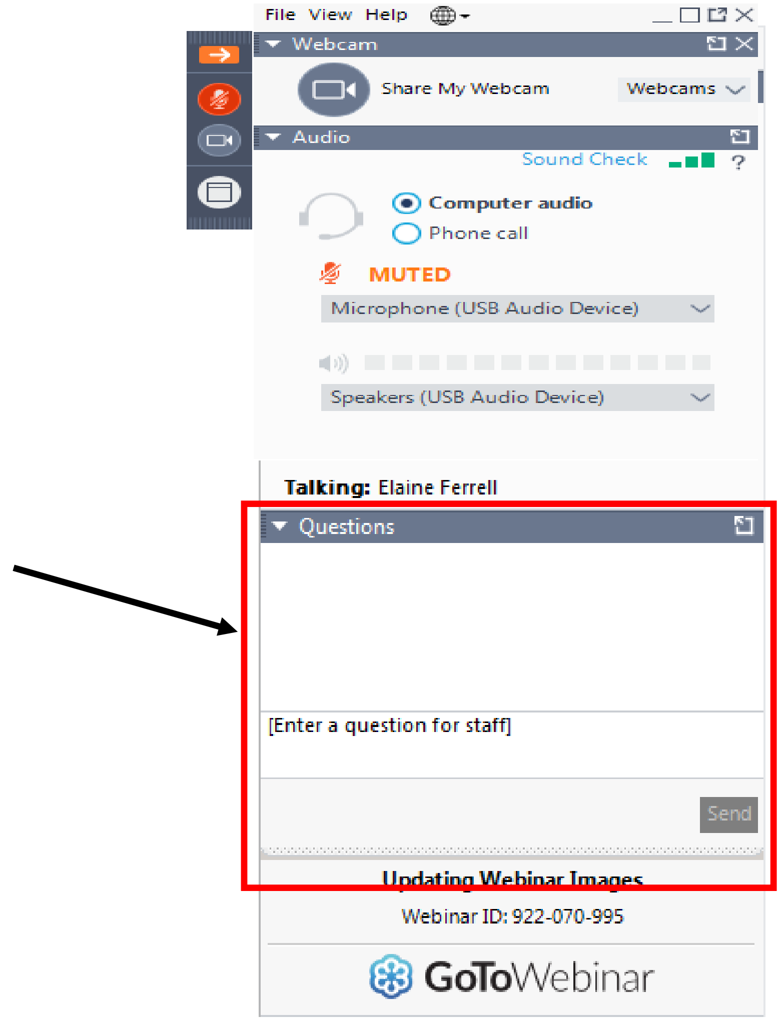
Learning Objectives

- Identify unsaturated geomaterial mechanisms
- Discuss the impact of moisture/matric suction on geomaterial performance
- Identify implementation options during pavement foundation design

#TRBwebinar

Questions and Answers

- Please type your questions into your webinar control panel
- We will read your questions out loud, and answer as many as time allows



#TRBwebinar

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Improving Pavement Geomaterial Performance with Unsaturated Soil Mechanics

Transportation Research Board

August 3, 2021

Sponsoring Committees

Aggregates (AKM80)

Mechanics & Drainage Saturated Unsaturated Geomaterials (AKG40)

Upcoming Tech Transfer

TRB Webinars

- Best Practices for Unsurfaced Road Evaluation and Rating
  August 25 (1pm eastern time)
- Light Weight Deflectometers for Construction Quality Assurance
  Date/time TBD

Workshop during TRB Annual Meeting

- Environmental Product Declarations for Pavement Materials
  Date/time TBD

Today's Agenda

Thesis

The performance of flexible and rigid pavements is closely related to properties of the base, subbase and subgrade.

Introduction and Opportunities (5 minutes)

Principles of Unsaturated Soil Mechanics

Impact of Matric Suction on Geomaterial Performance

Influence of Moisture Content on Compaction Quality

Discussion (20 minutes)

Opportunity to Address National Priorities

MAP-21, FAST and INVEST are federal laws and bills that require transportation investments to be based on performance based measured outcomes.

- Moving Ahead for Progress in the 21st Century (2012)
- Fixing America's Surface Transportation (2015)
- INVEST in America (2021)
- Performance Based Professional Standards

  Federal Highway Administration

  American Association of State Highway Transportation Officials

  American Society of Civil Engineers

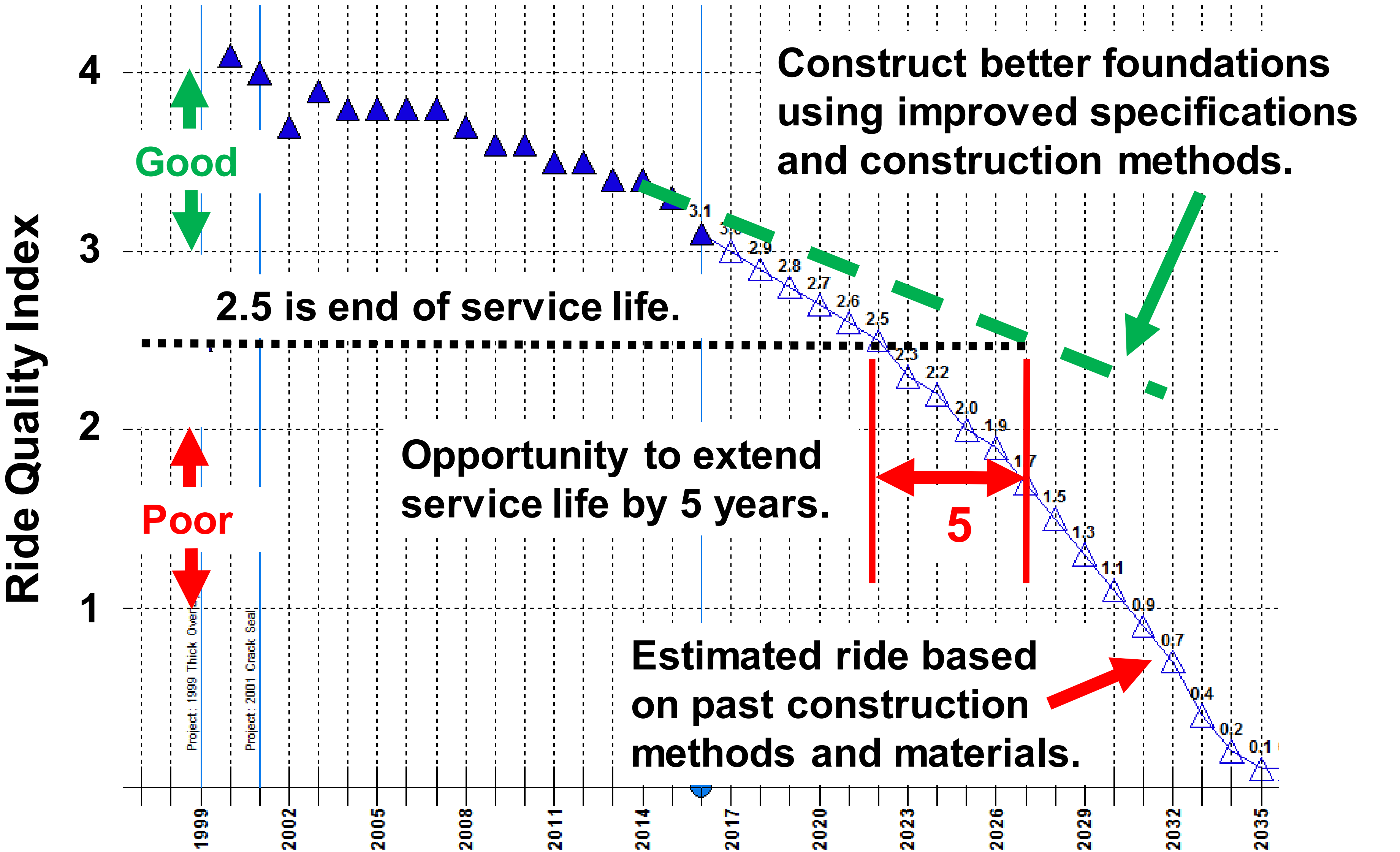
Code of Federal Regulations FHWA 2012

A state asset management plan includes:

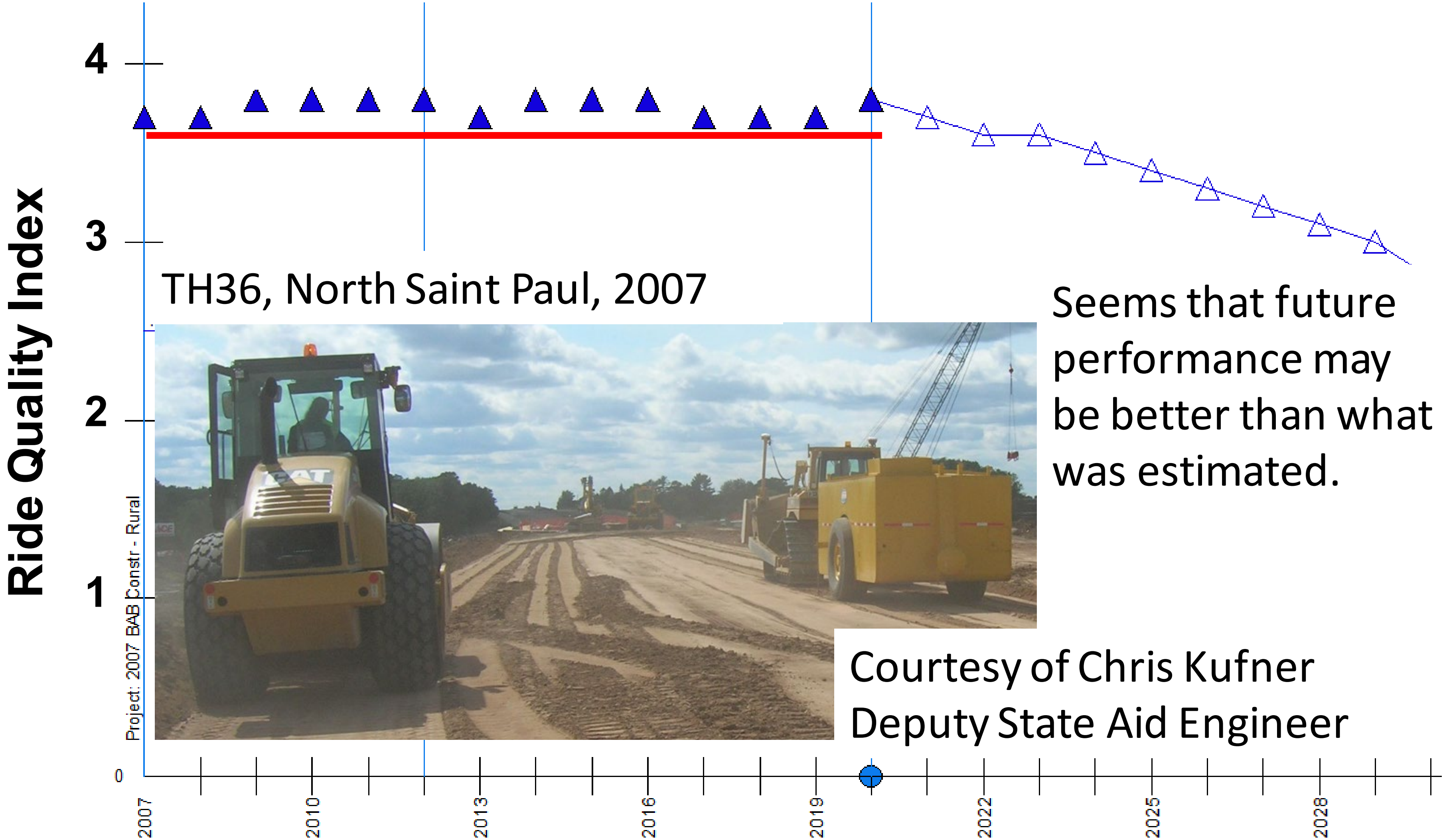
1. Summary of assets on NHS including condition;
2. Asset management objectives and measures;
3. Performance gap identification;
4. Lifecycle cost and risk management analysis;
5. Financial plan; and
6. Investment strategies.

23 U.S.C. 119(e)(4), MAP-21 § 1106

Opportunity to Improve Condition



Opportunity to Demonstrate Performance



TH36, North Saint Paul, 2007

Seems that future performance may be better than what was estimated.

Courtesy of Chris Kufner
Deputy State Aid Engineer

New Law in Minnesota 2021

Minnesota Statutes, 174.03, Subdivision 12.

Trunk highway performance, resiliency, and sustainability.

(a) The commissioner must implement performance measures and annual targets for the trunk highway system in order to construct resilient infrastructure, enhance the project selection for all transportation modes, improve economic security, and achieve the state transportation goals established in section 174.01.

(b) At a minimum, the transportation planning process must include:

(1) an inventory of transportation assets, including but not limited to bridge, pavement, geotechnical, pedestrian, bicycle, and transit asset categories;

Principles of Unsaturated Soil Mechanics

TRB Webinar: Improving Pavement Geomaterial Performance with Unsaturated Soil Mechanics
August 3, 2021

William J. Likos, PhD
Gary Wendt Professor and Department Chair
Department of Civil and Environmental Engineering
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What the &@#! Is Soil Suction and Why Should I Care?

TRB Webinar: Applying Unsaturated Soil Mechanics to Improve Pavement Geomaterial Performance

August 3, 2021

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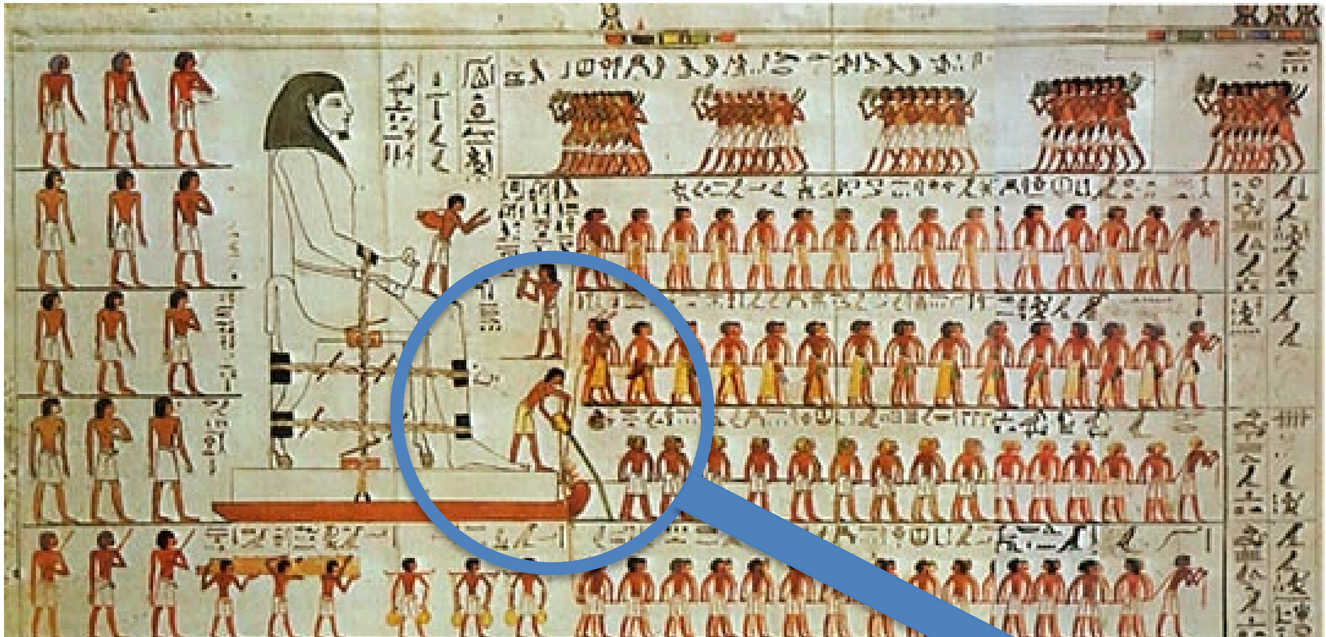
Unsaturated Soil Mechanics and the Great Pyramids?

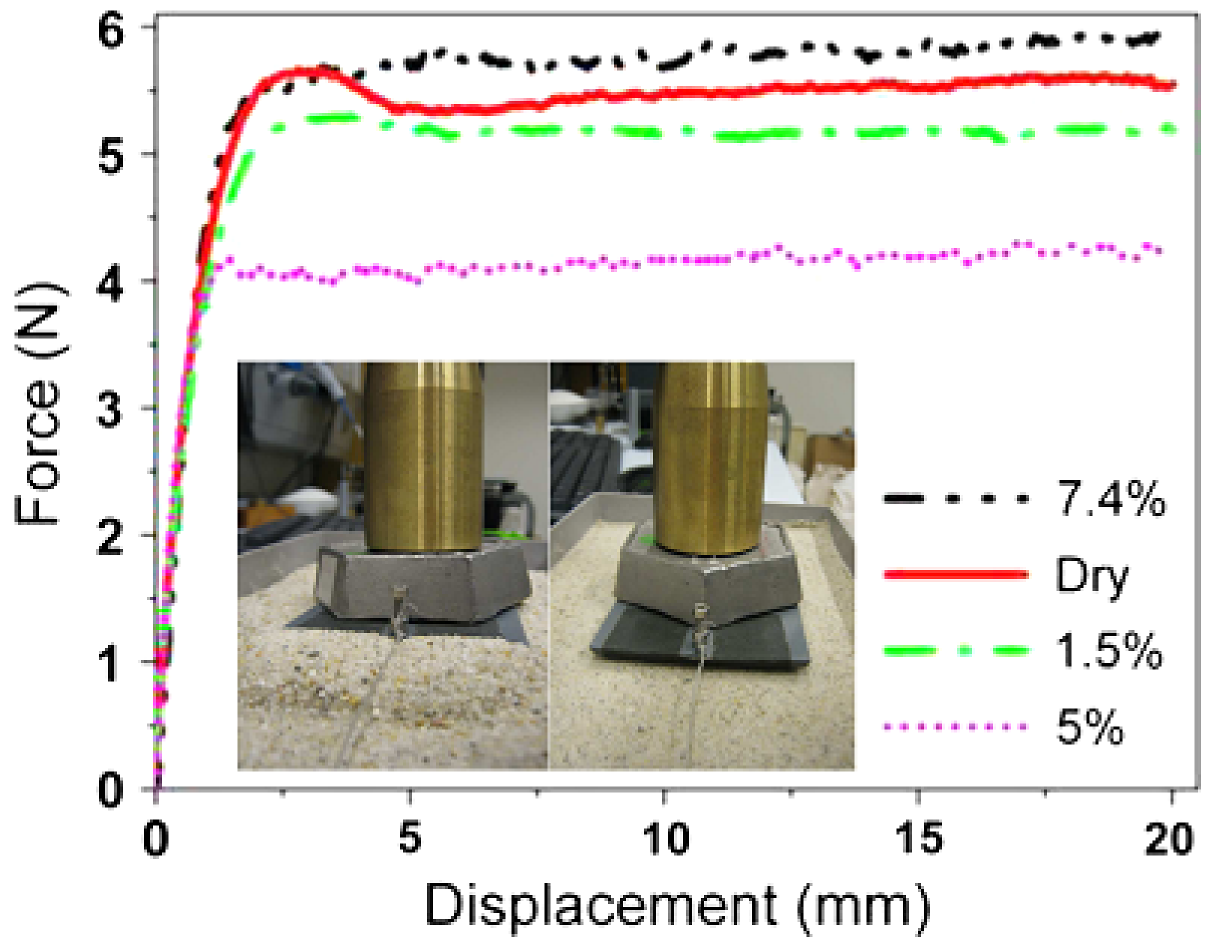
Wall painting from 1880 B.C. on the tomb of Djehutihotep in southeastern Egypt (Newberry, 1895).



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 an unsaturated soil?
- What are differences between saturated and unsat. soils?
- What is the relevance to pavement performance?

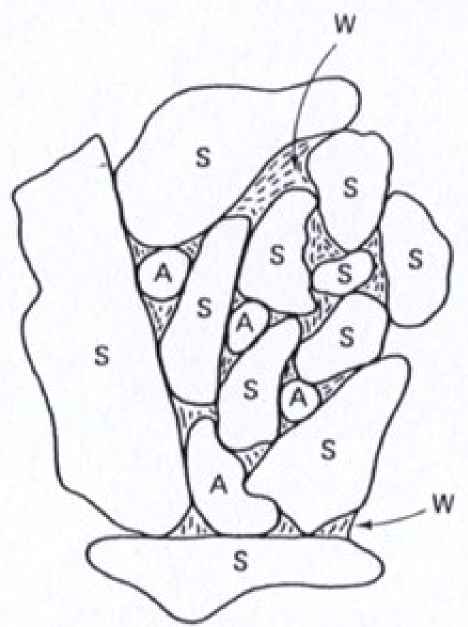
Soil is a multiphase system

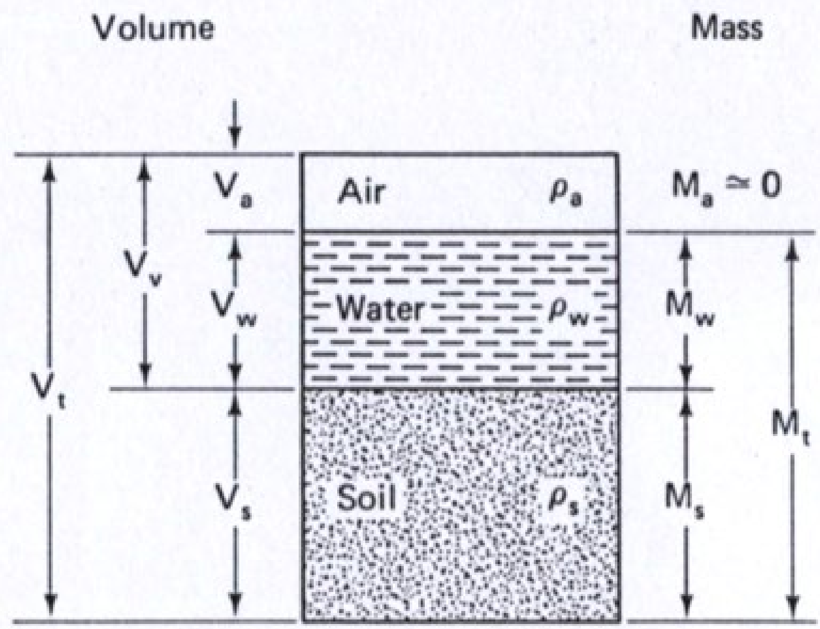
S = Solids

W = Water

A = Air

Relative amount of each phase will affect behavior





"block diagram"

Saturated Soil

- *2-Phase System*

- *Pore Fluid Pressure,* u_w

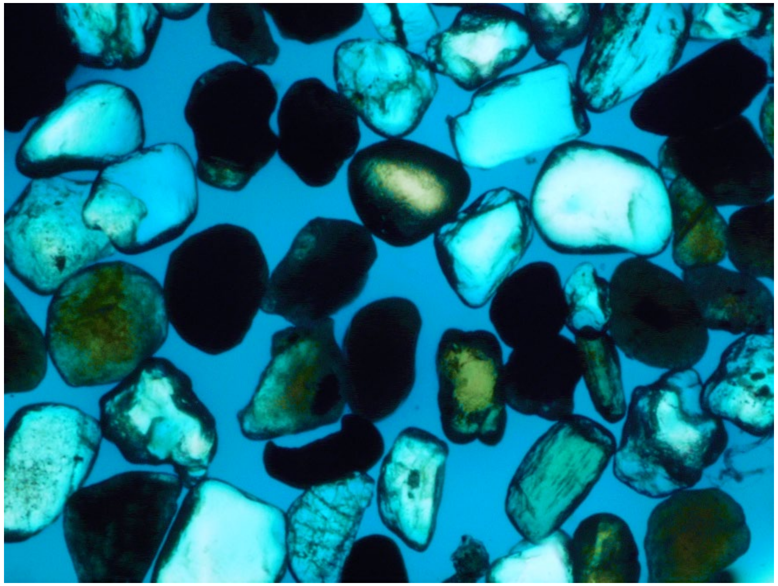
  u_w *(+)*

- *Volumetric Water Content,* θ

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

- *Degree of Saturation, S*

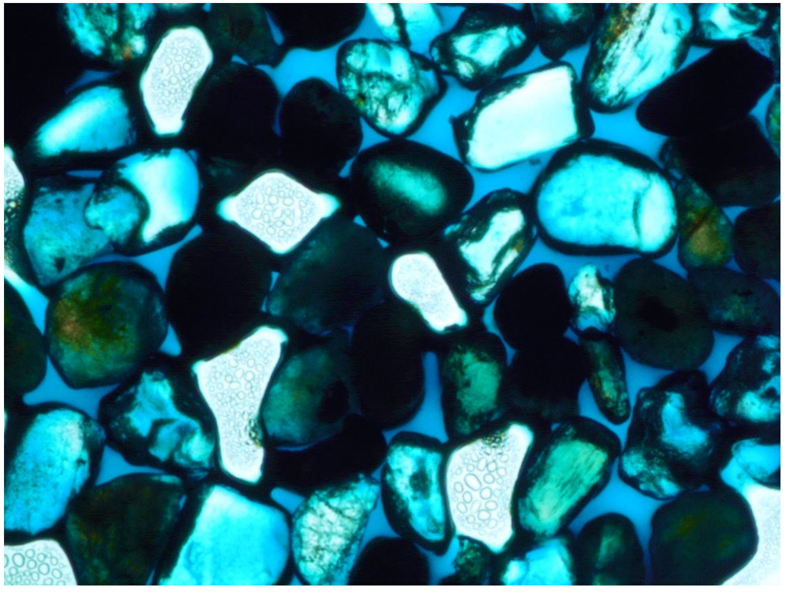
  $S = V_w/V_v = 1.0$ *(100%)*



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

Unsaturated Soil

- *3-Phase System*



- *Pore Fluid Pressure, u_w and u_a*

  $u_a = 0$ *(atmospheric)*

  $u_w < u_a$

  $\psi = u_a - u_w$ *(matric suction)*

- *Volumetric Water Content, θ*

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

- *Degree of Saturation, S*

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

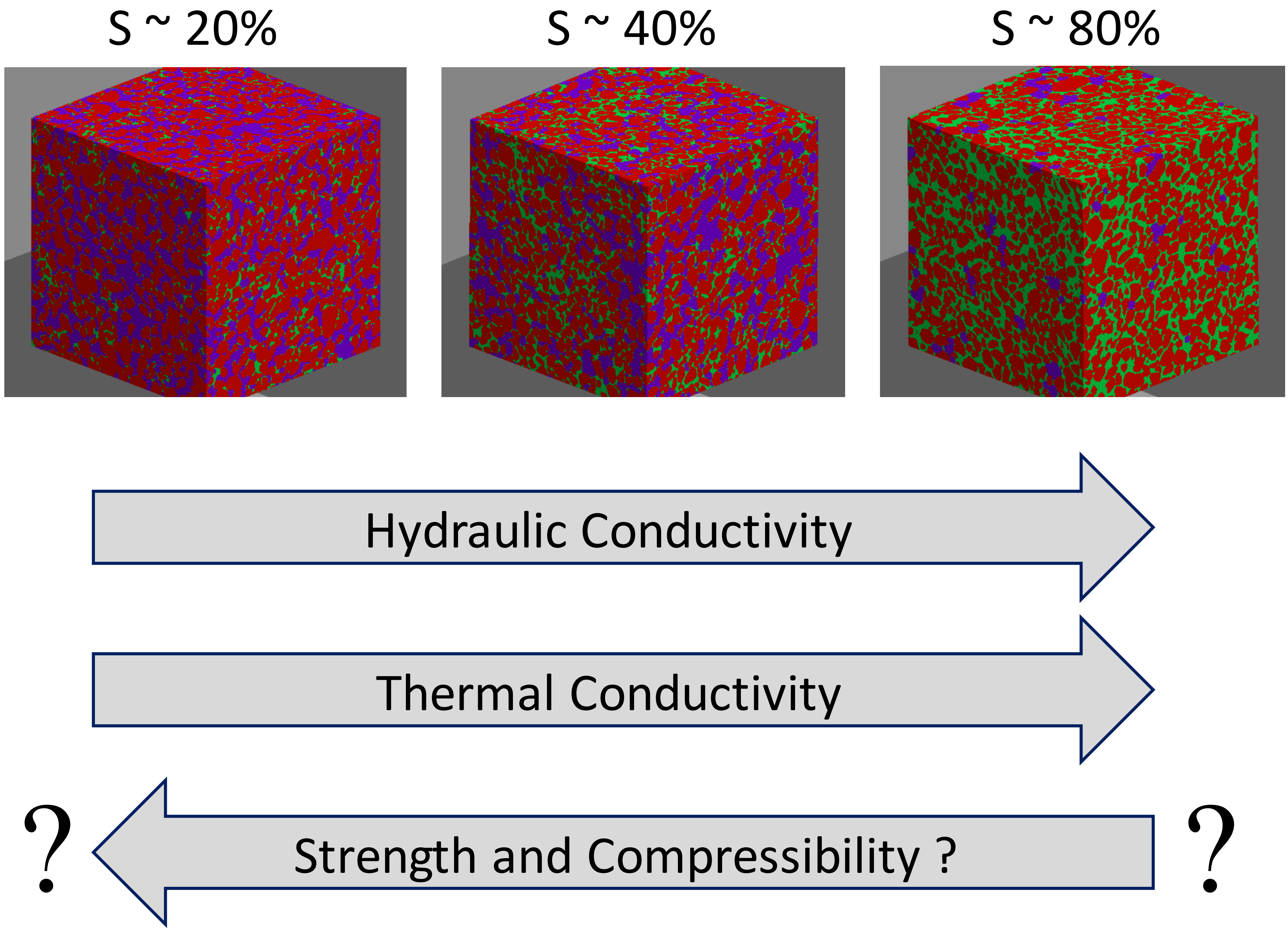
Soil-water characteristic curve (SWCC)

- *Hydraulic Conductivity, k*

  $k = f(\theta)$

  or $k = f(\psi)$

Hydraulic conductivity function (HCF)

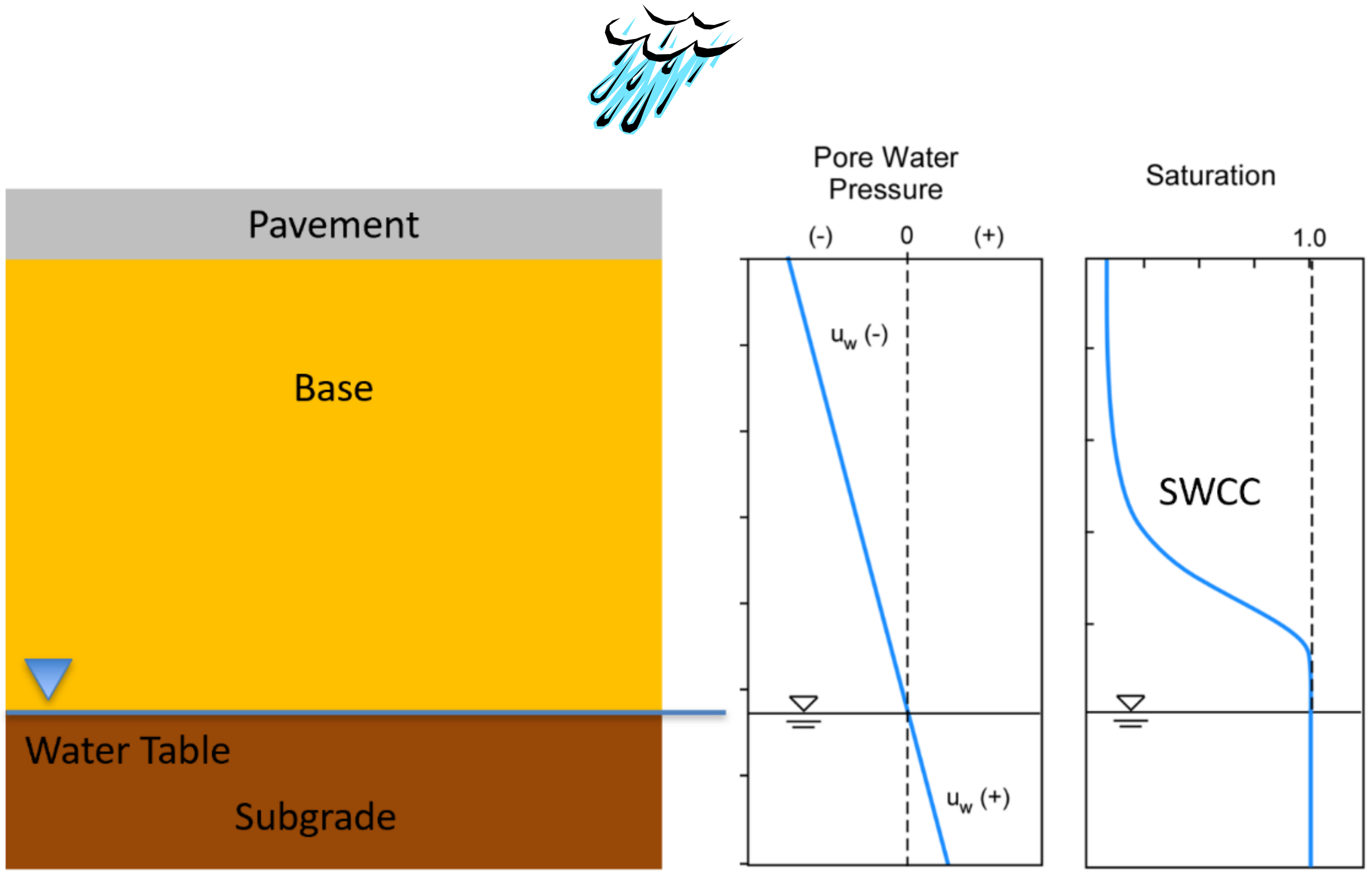

S ~ 20%
S ~ 40%
S ~ 80%
Hydraulic Conductivity
Thermal Conductivity
?
Strength and Compressibility ?
?

Unsaturated Soil Mechanics and Pavement Performance

1) Material Properties (Permeability, Water Retention Characteristics)

2) Pavement System Design (Layering, Slope, Drainage Boundaries)

3) Environmental Conditions (Precipitation, Temperature)



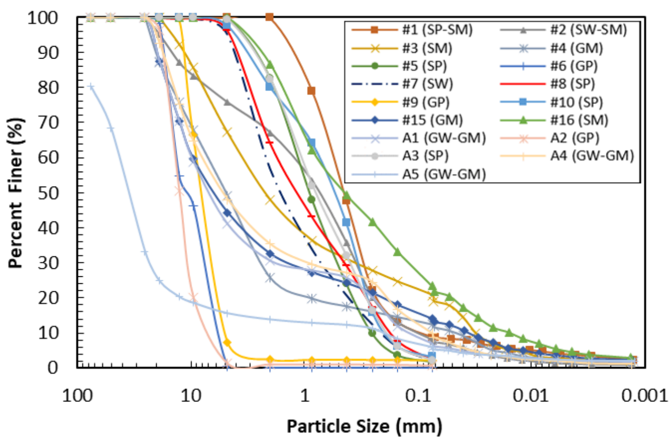
Qualitative Rating System for Base Drainability [NRRA TPF-5(341)]

- ***Measured K_{sat} and SWCCs for representative base materials***
- ***Established correlations between grain size properties, K_{sat} & SWCCs***
- ***Proposed rating system to qualify base material drainage performance***

16 Base Materials

MnDOT
MoDOT
WisDOT

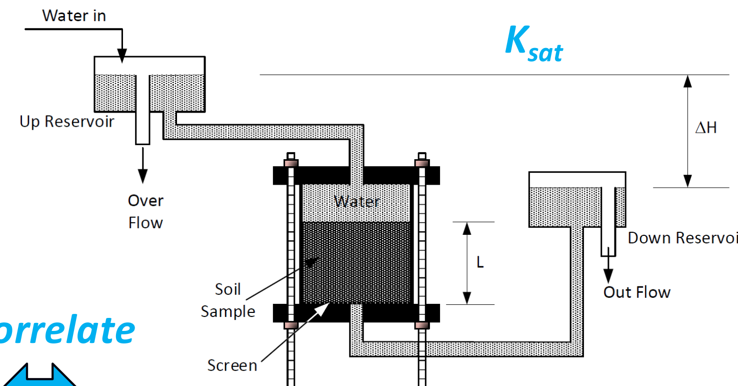
Grain Size Distribution



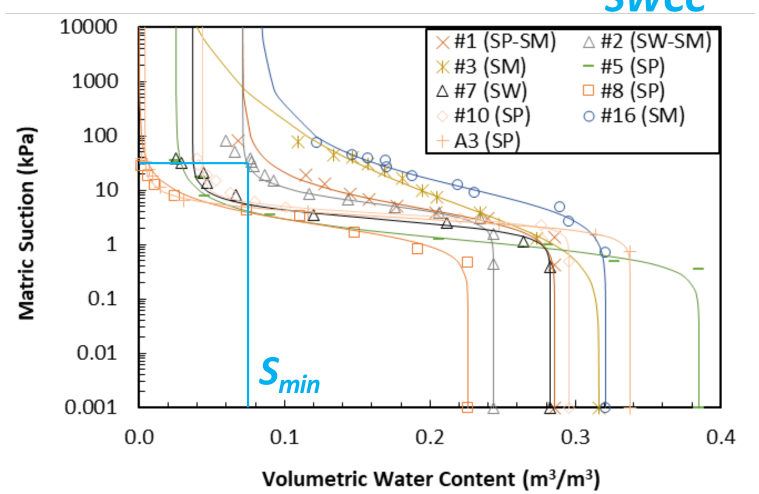
D_{10} D_{30} C_u

Correlate

K_{sat}



SWCC



Drainability Performance Criteria: K_{sat} > 0.35 cm/s, S_{min} < 0.10

Estimated from Grain Size Distribution

	Drainability Assessment				
Sample	K_{sat} (cm/s)	Minimum Saturation	K_{sat} Criterion	S_{min} Criterion	Overall Rating
#1 (SP-SM)	0.017	0.13	Poor	Excellent	Marginal
#2 (SW-SM)	0.021	0.35	Marginal	Excellent	Marginal
#3 (SM)	0.021	*(1.0)*	Marginal	Poor	Poor-Marginal
#4 (GM)	0.167	*(1.0)*	Marginal	Poor	Poor-Marginal
#5 (SP)	0.032	0.08	Poor	Excellent	Marginal
#6 (GP)	0.523	0.00	Excellent	Excellent	Excellent
#7 (SW)	0.045	0.22	Marginal	Excellent	Marg - Excellent
#8 (SP)	0.027	0.25	Marginal	Excellent	Marg - Excellent
#9 (GP)	0.447	0.00	Excellent	Excellent	Excellent
#10 (SP)	0.019	0.05	Marginal	Excellent	Marg - Excellent
#15 (GM)	0.005	*(1.0)*	Poor	Poor	Poor
#16 (SM)	0.120	0.78	Marginal	Marginal	Marginal
A1 (GW-GM)	0.023	*(1.0)*	Marginal	Marginal	Marginal
A2 (GP)	0.060	0.01	Marginal	Excellent	Marg - Excellent
A3 (SP)	0.017	0.12	Poor	Excellent	Marginal
A4 (GW-GM)	0.021	*(1.0)*	Marginal	Marginal	Marginal

#6 (GP)

#15 (GM)

Impact of Moisture/Matric Suction on Geomaterial Performance

TRB Webinar: Improving Pavement Geomaterial Performance
with Unsaturated Soil Mechanics
August 3, 2021

Bora Cetin, PhD
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Department of Civil and Environmental Engineering
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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

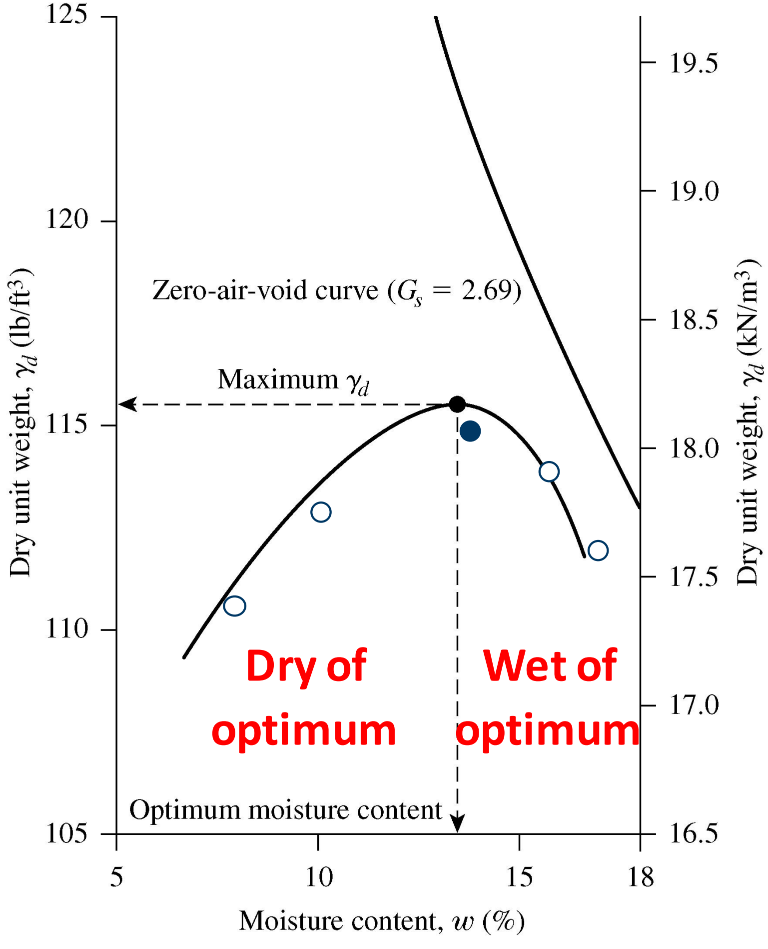
increase

Permeability

Collapsibility

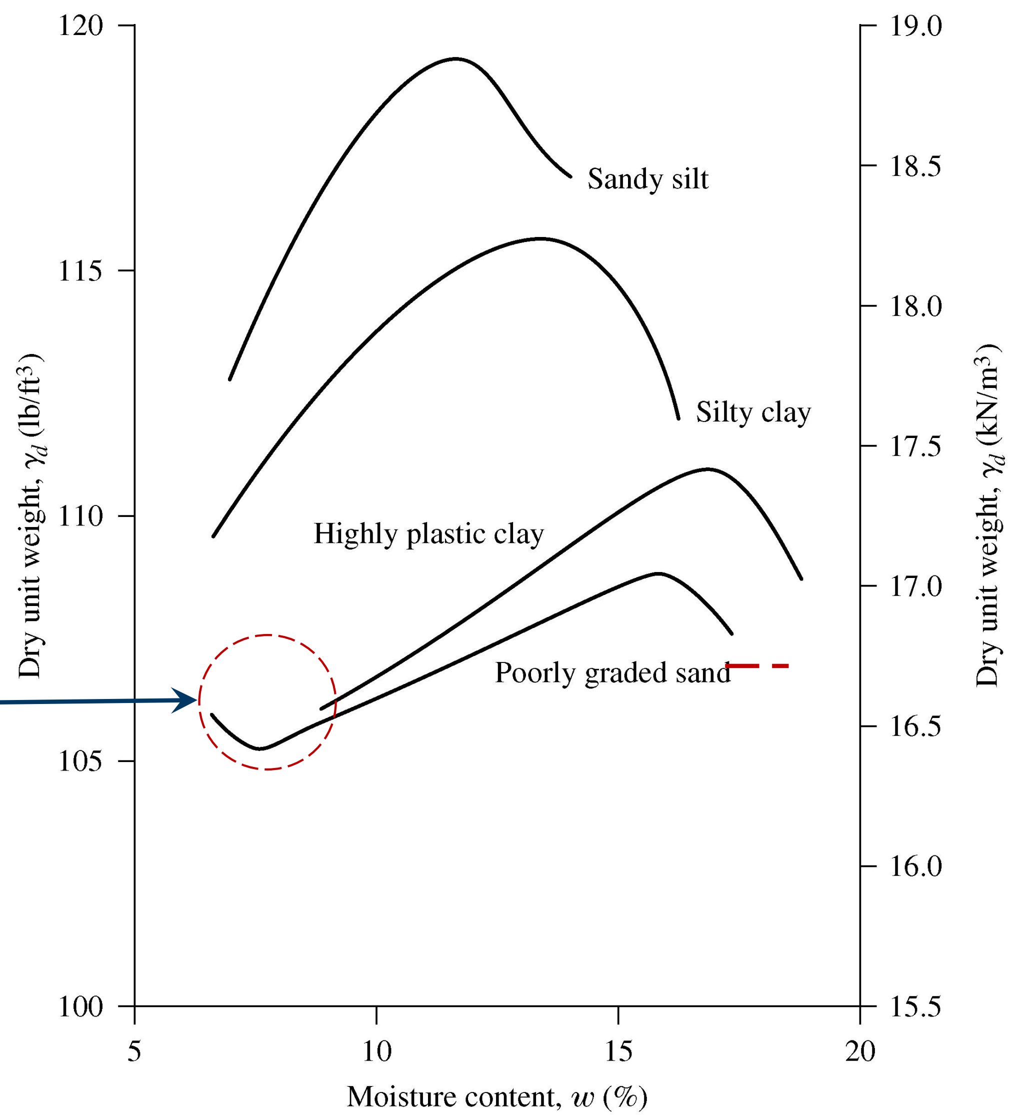
decrease

Dry Unit Weight vs. Moisture Content Curve

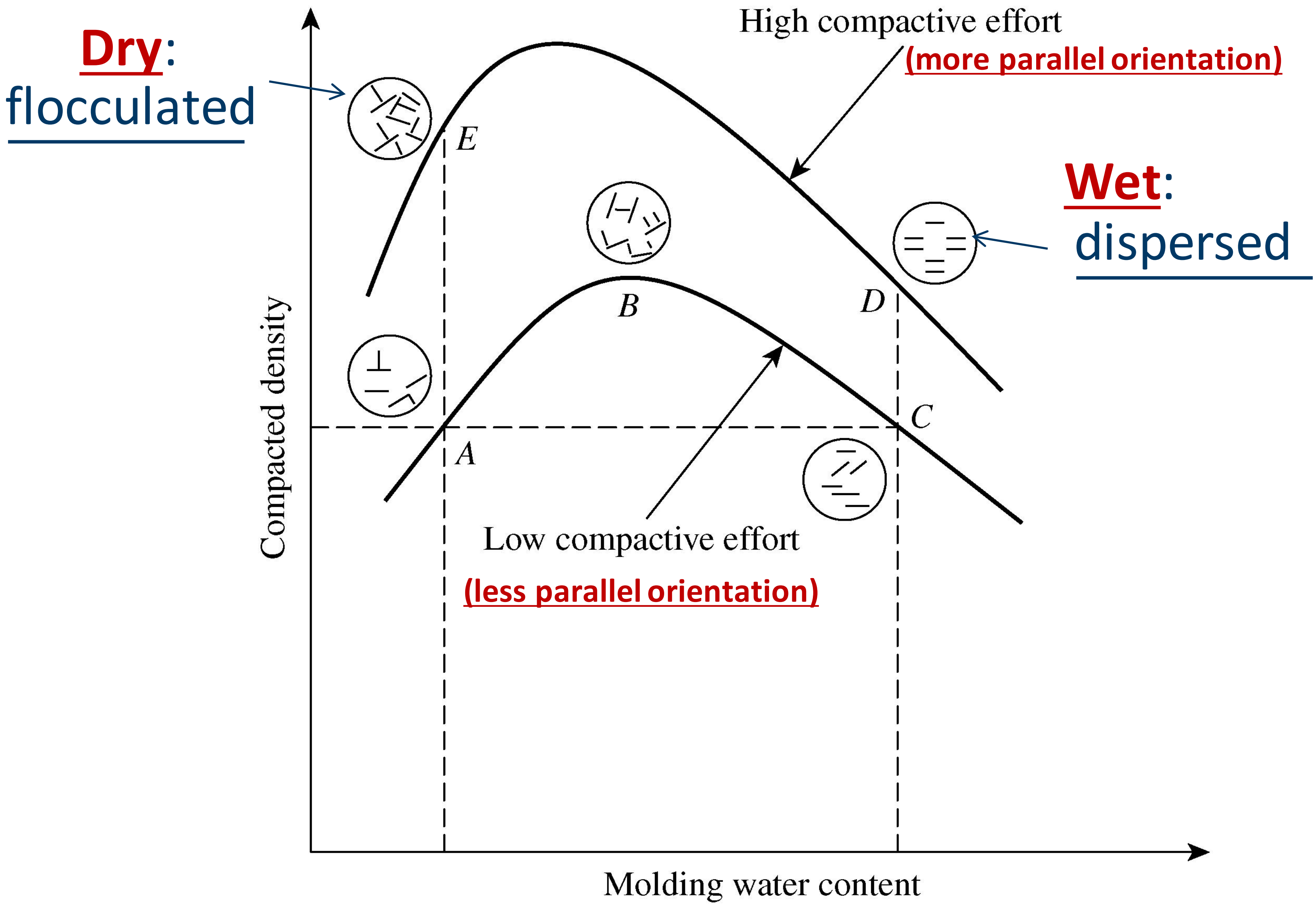


Effect of Soil Type

Particle rearrangement inhibited due to capillary tension



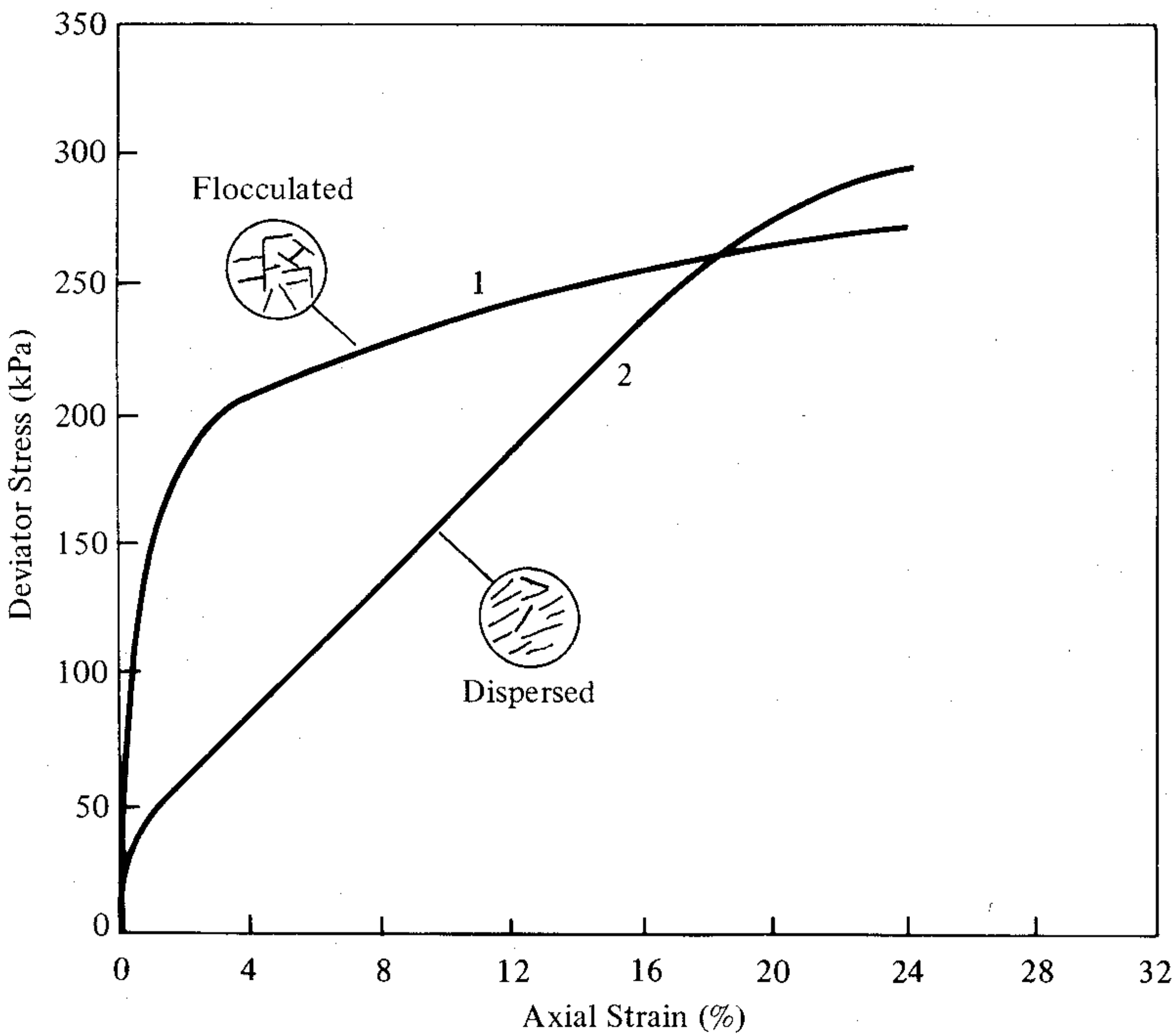
STRUCTURE OF COMPACTED CLAY SUBGRADE WITH MOISTURE



Effect of Moisture on Soil Properties

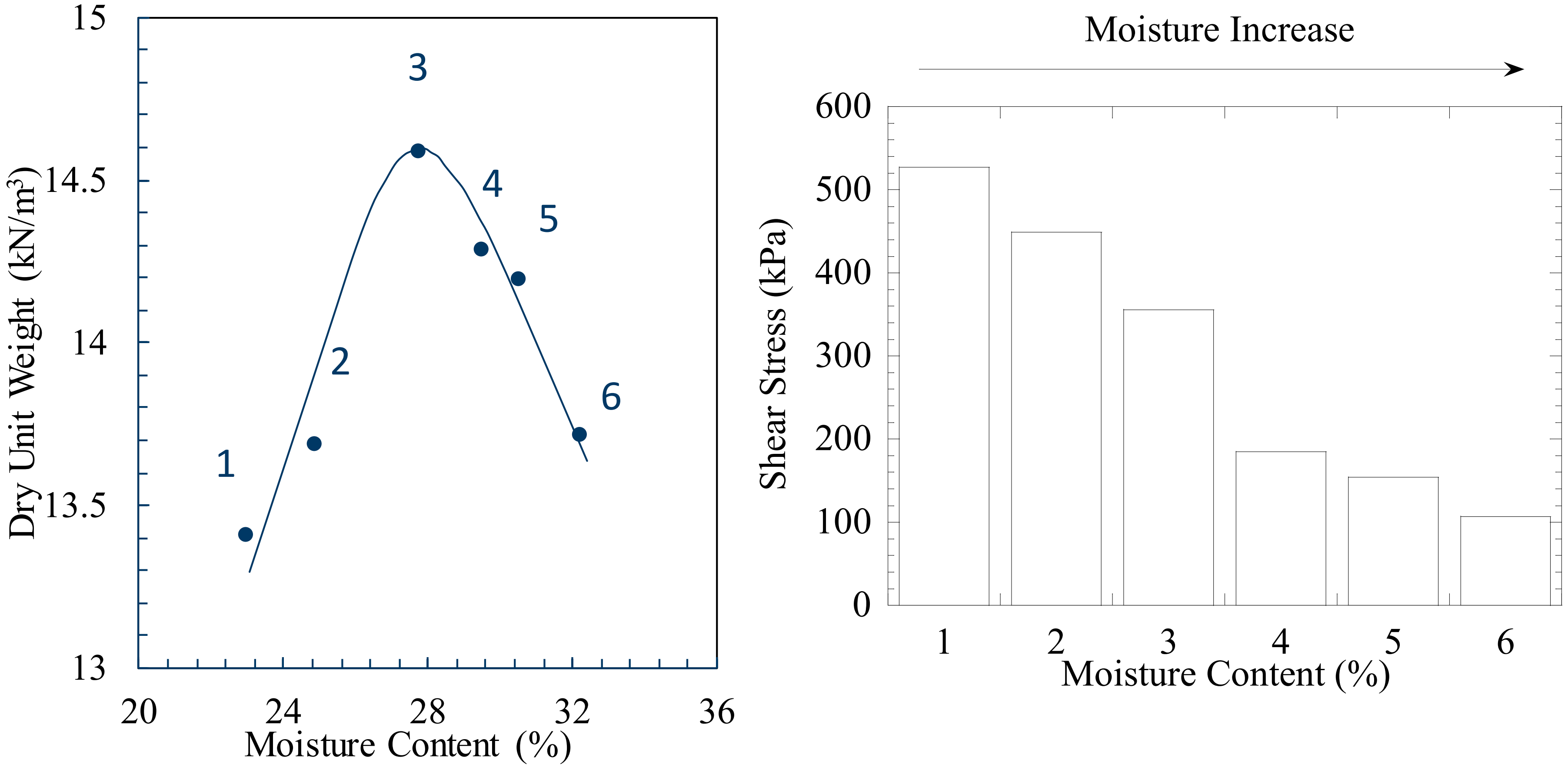
Stress-Strain

and strength



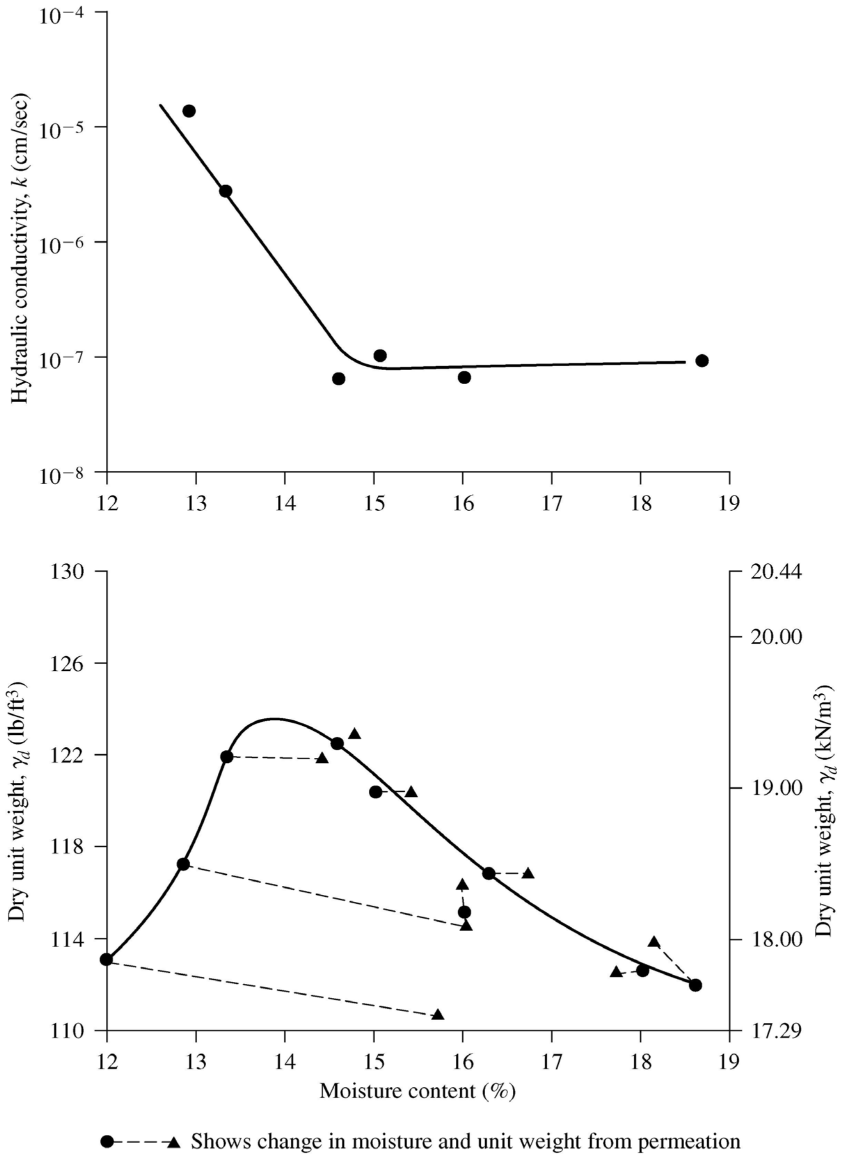
Effect of Moisture on Soil Properties

Stress-Strain and strength



Effect of Compaction on Soil Properties

Permeability



Effect of Compaction on Soil Properties

Strength of clayey soils

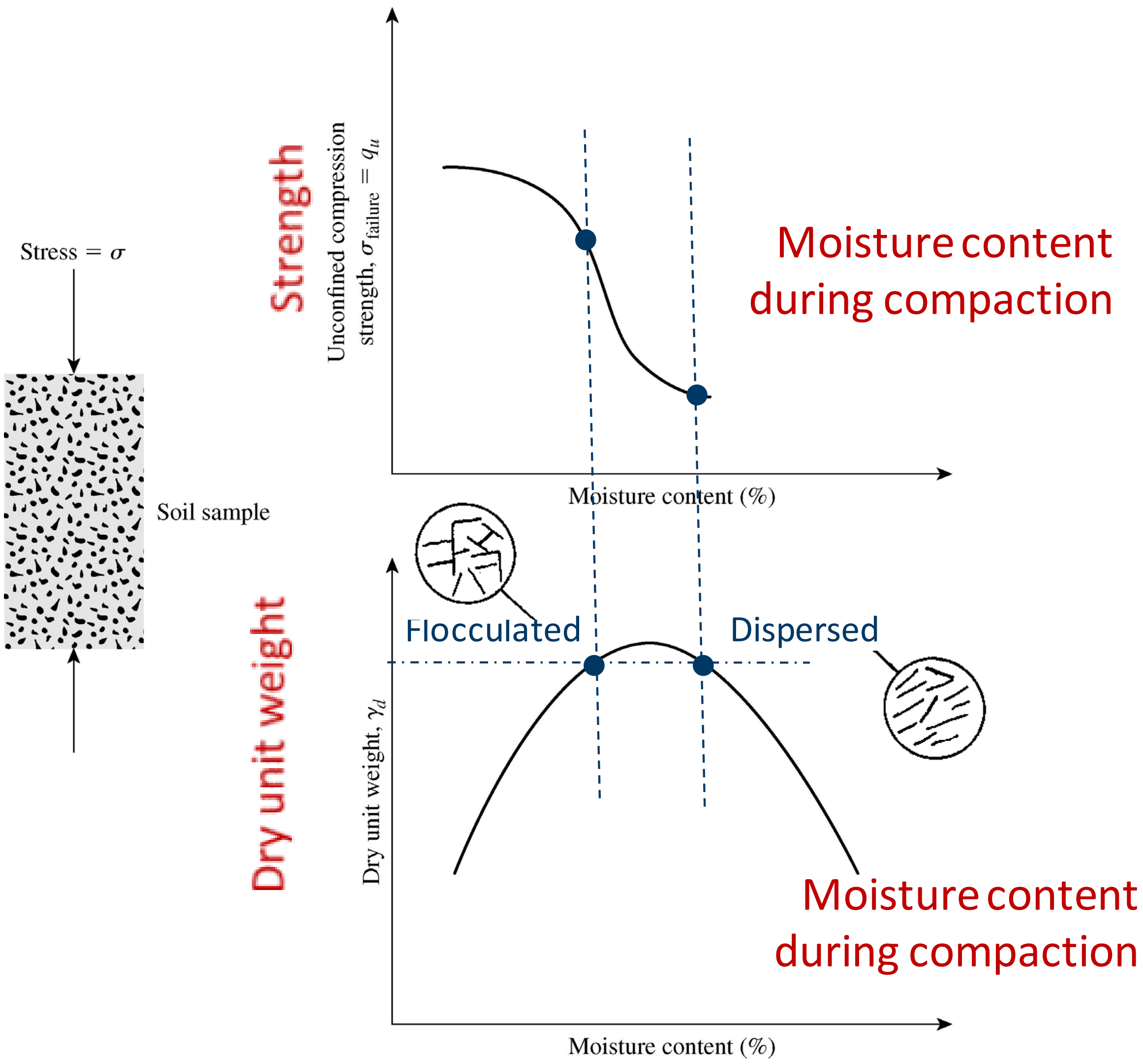
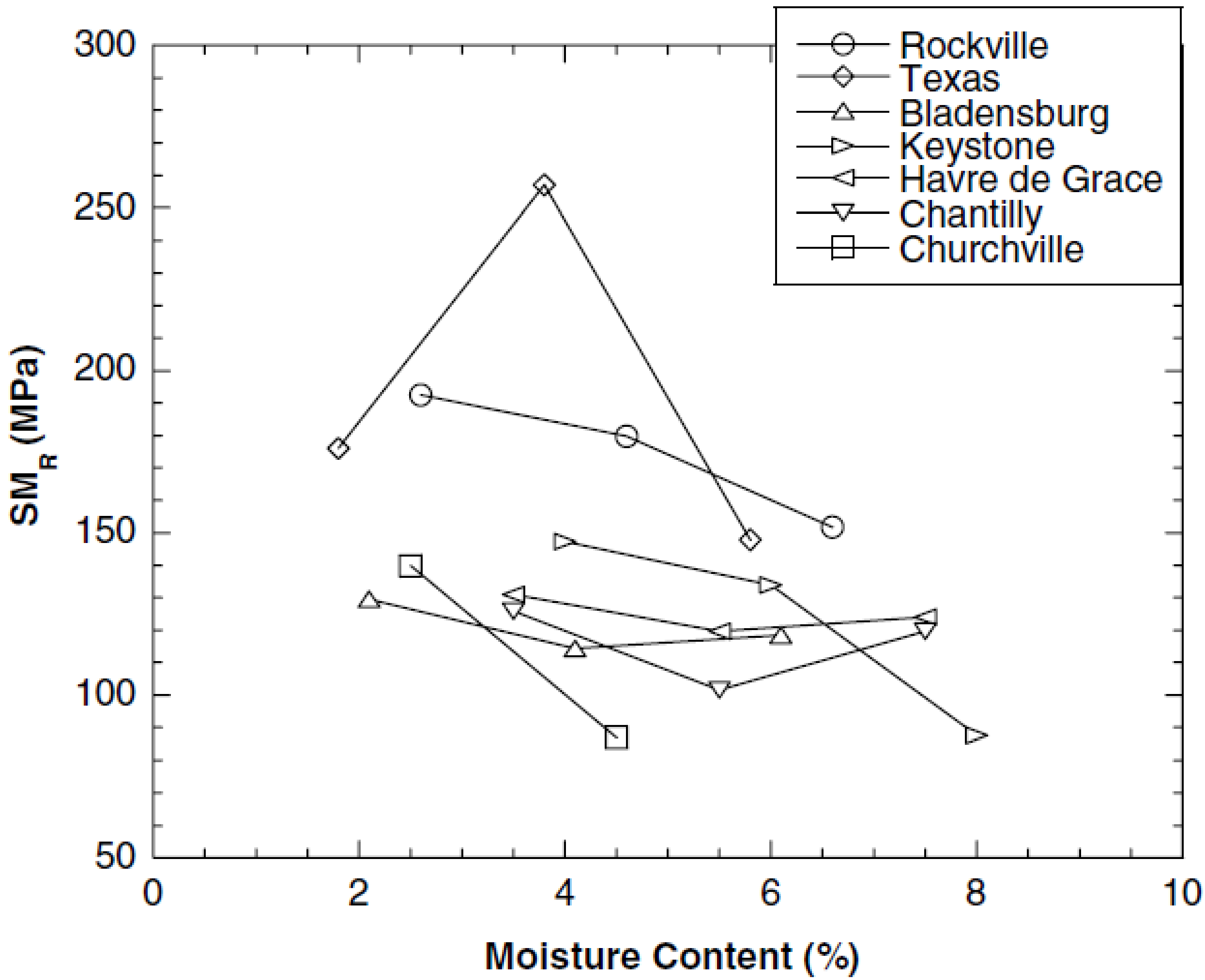


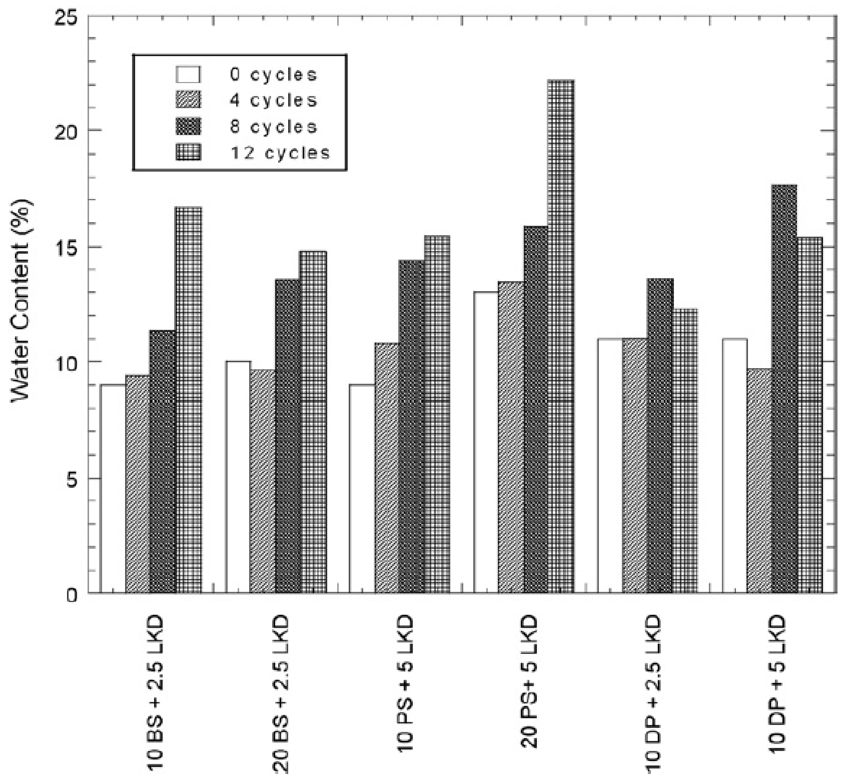
Figure 5.18 Effect of compaction on the strength of clayey soils

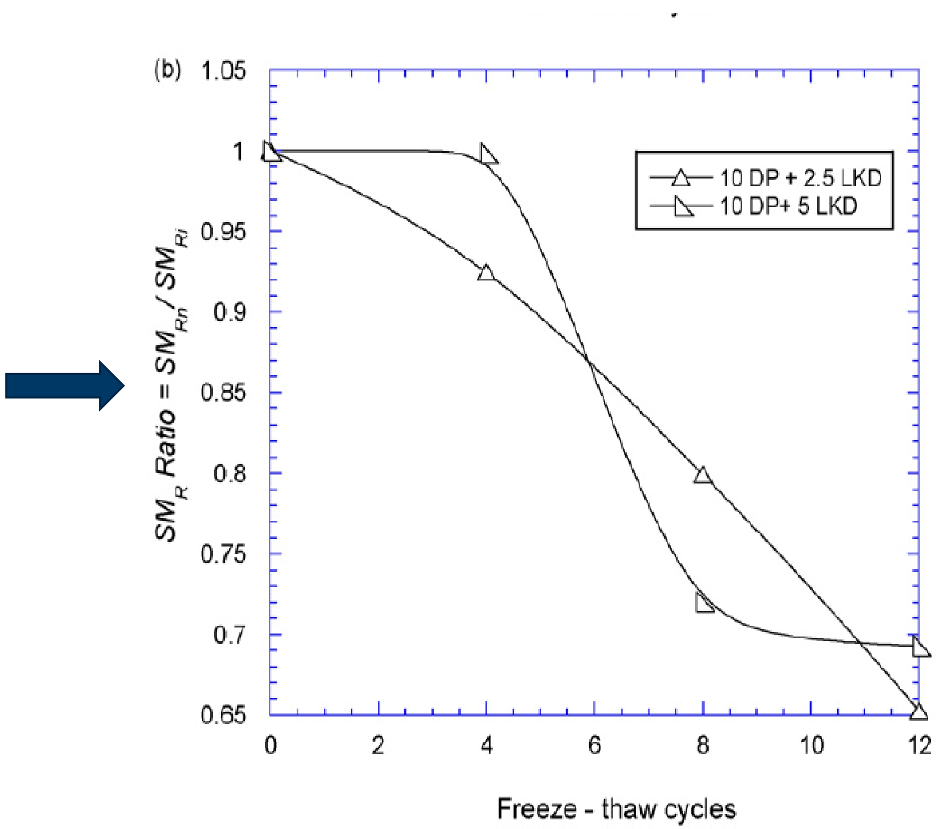
Effect of Moisture Content on Resilient Modulus of Granular Aggregate Base Materials



(Haider et al. 2014)

Effect of 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)

Relationship between Matric Suction and Stiffness Properties of Materials

- Effect of wetting and drying cycles on Maximum shear modulus

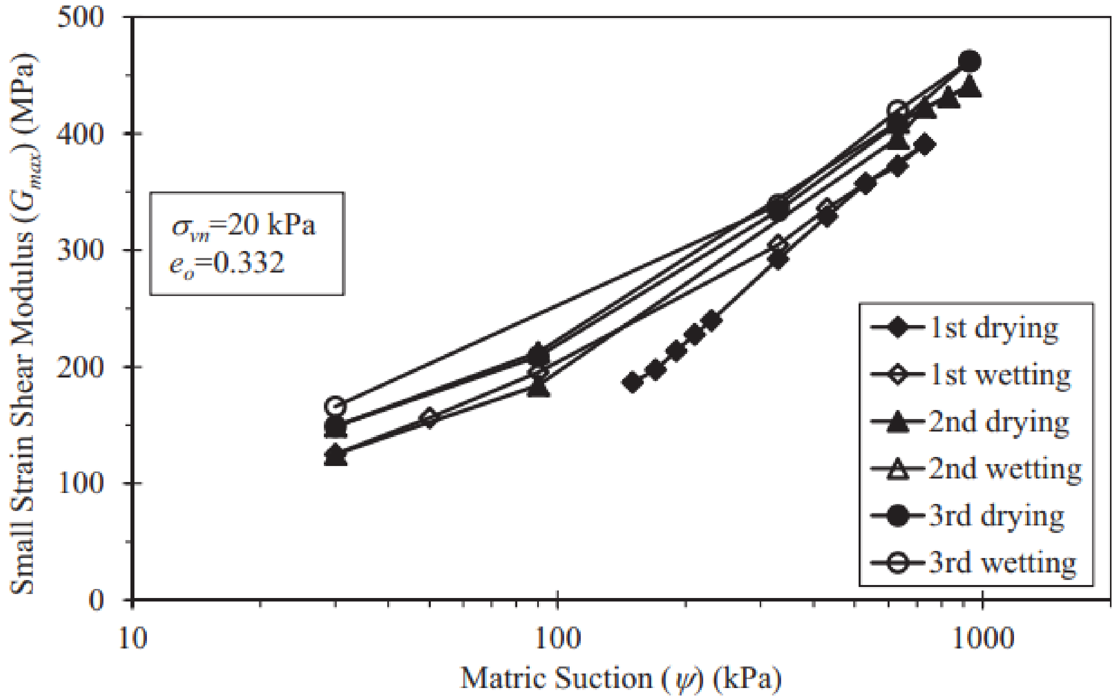
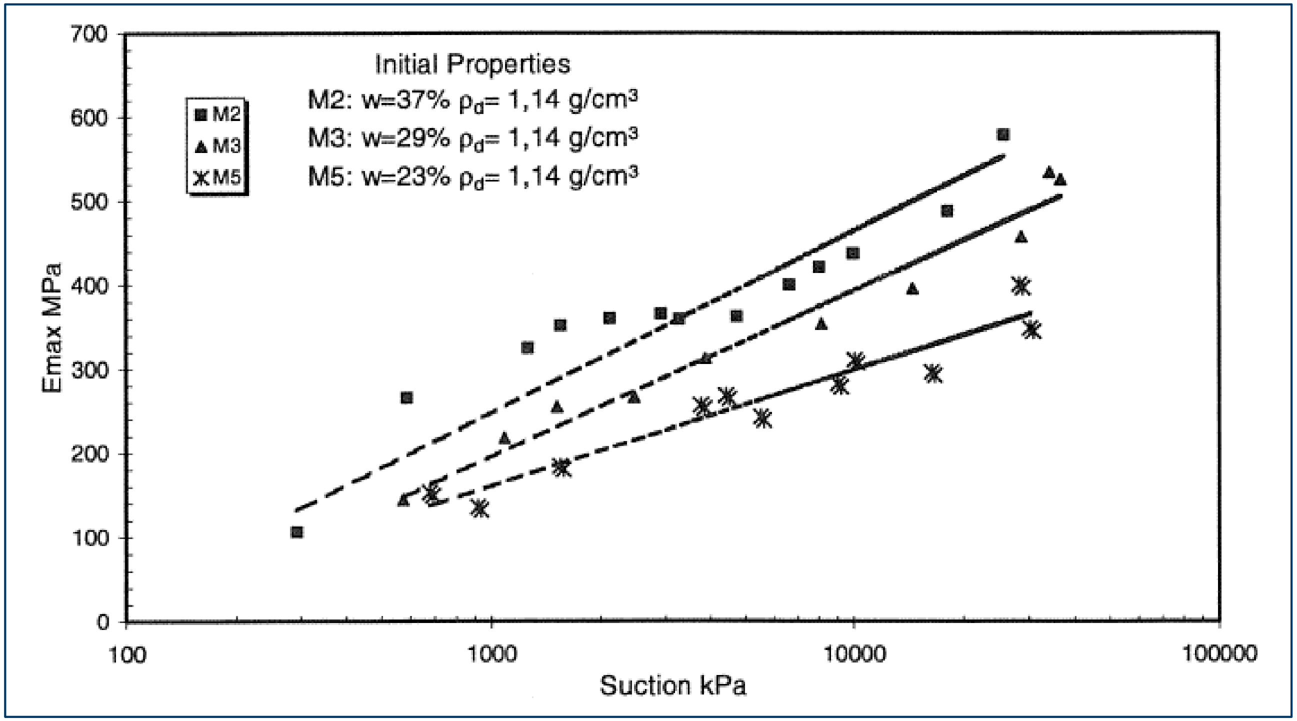


Fig. 11. G_{max}–ψ relationship during the three drying-wetting cycles.

(Ngoc et al., 2019)

Relationship between Matric Suction and Stiffness Properties of Materials

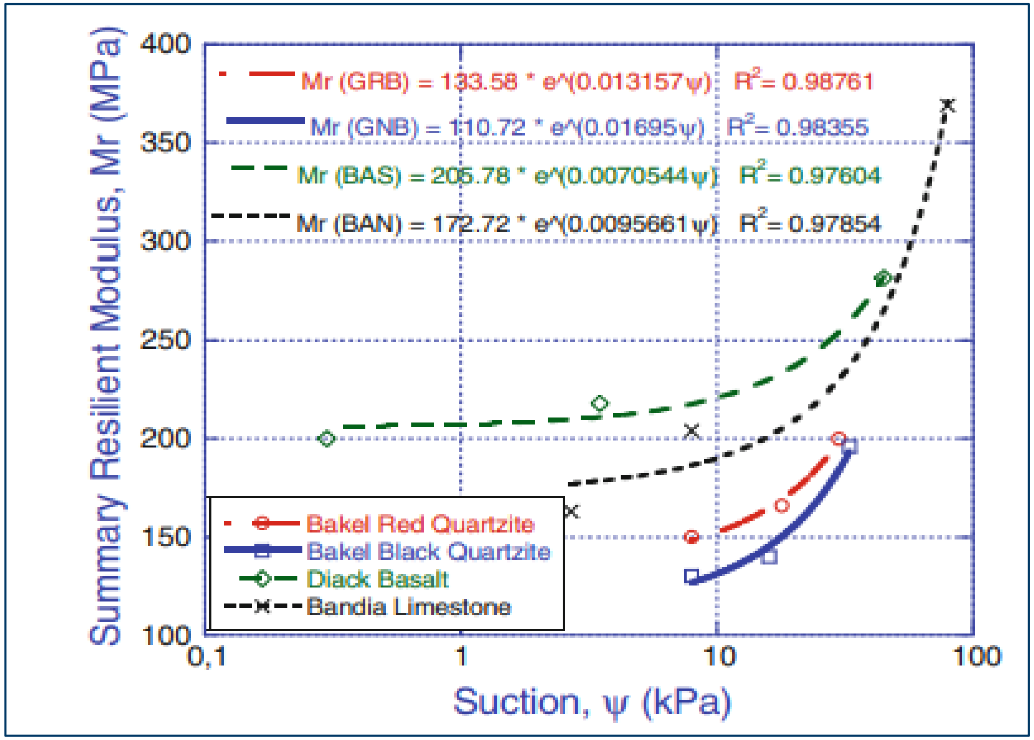
- Relationship between Young's Modulus and Matric Suction



(Mendoza and Colmenares 2006)

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

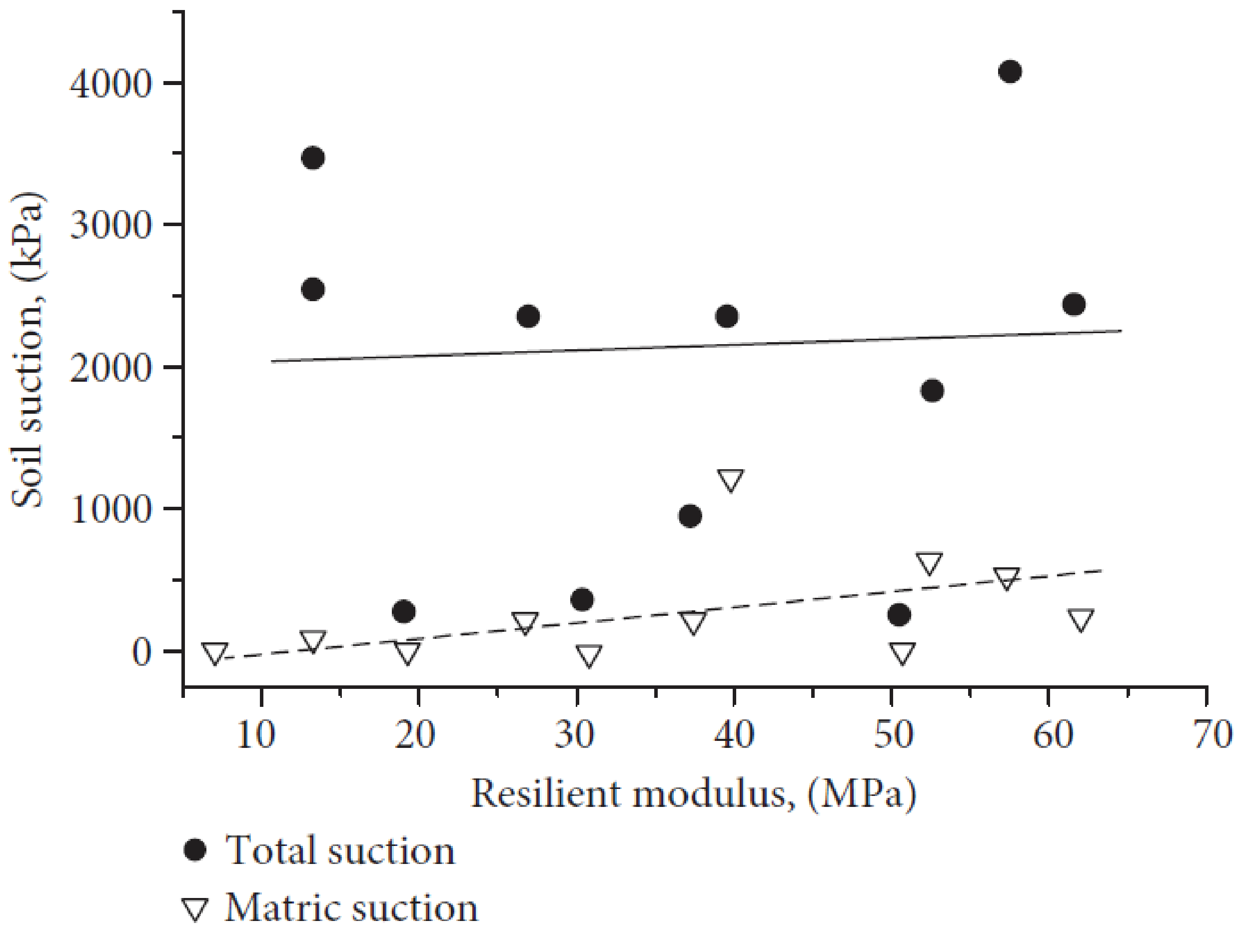
$$M_R = k_1 p_a \left(\frac{\theta_b}{p_a}\right)^{k_2} \left(k_4 + \frac{\tau_{oct}}{p_a}\right)^{k_3} + \alpha_1 \psi^{\beta_1}$$

Khoury et al., 2009

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

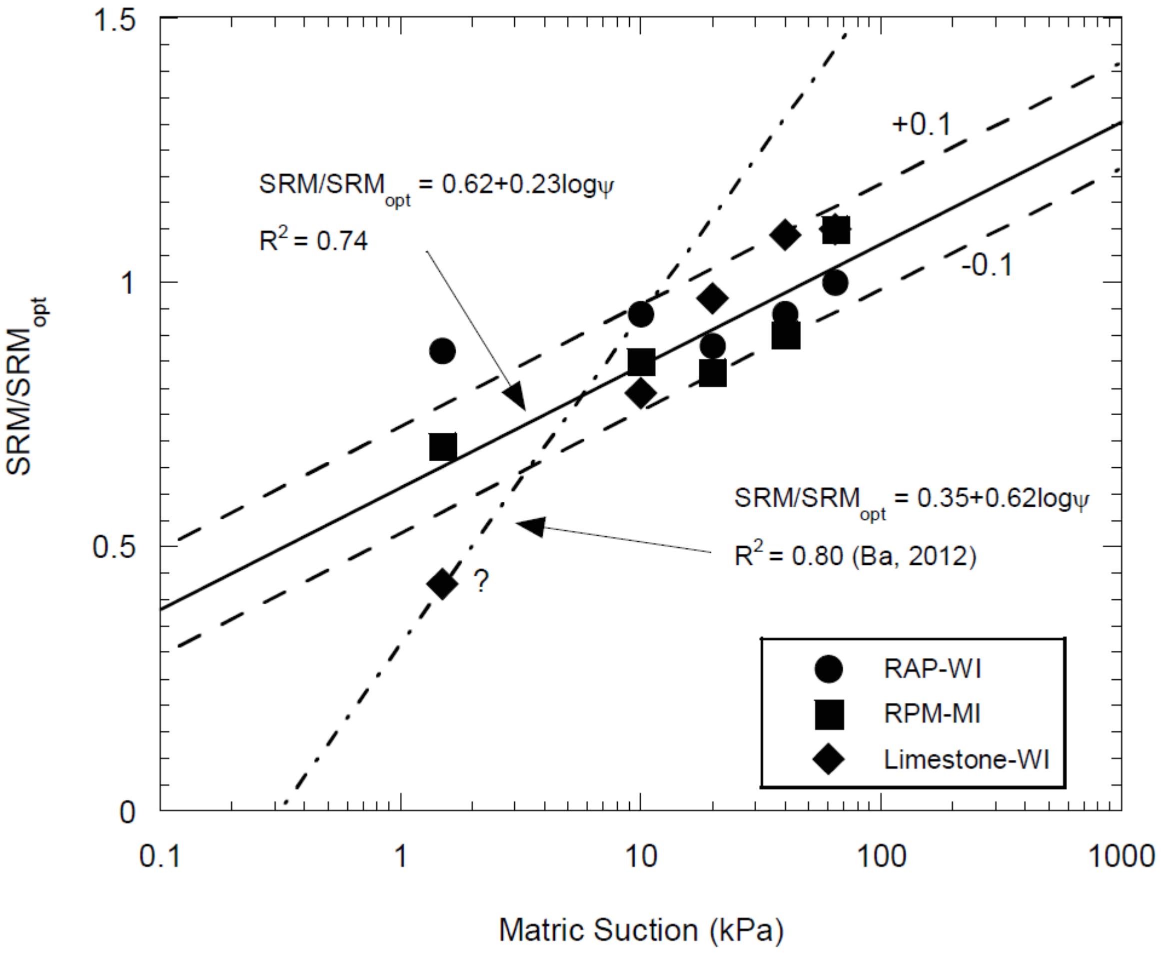
Lytton, 1995

Matric Suction - Modulus



(Chu 2020)

Matric Suction - Modulus



(Nokkaew et al. 2013)

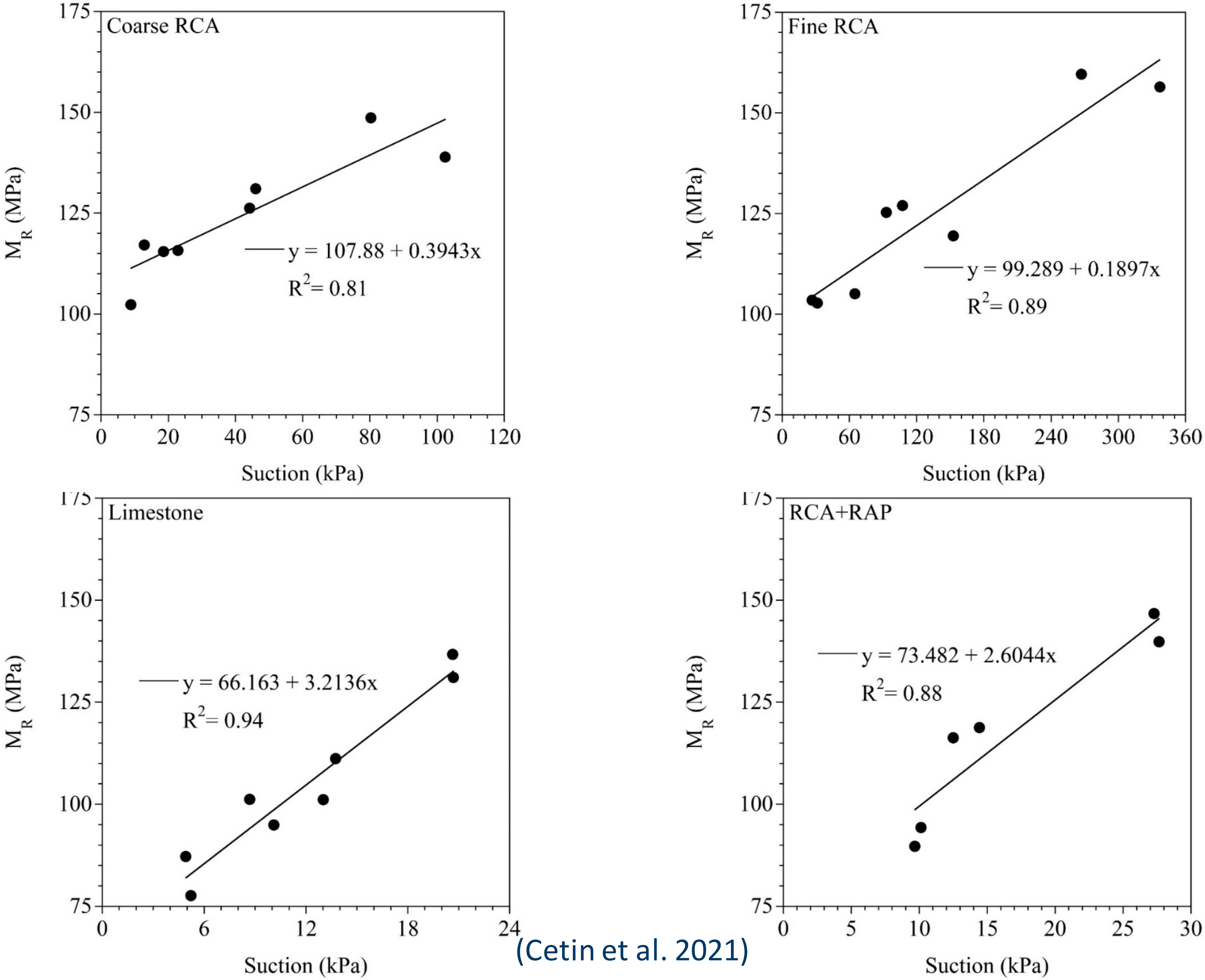
Determining Pavement Design Criteria for Recycled Aggregate Base and Large Stone Subbase

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

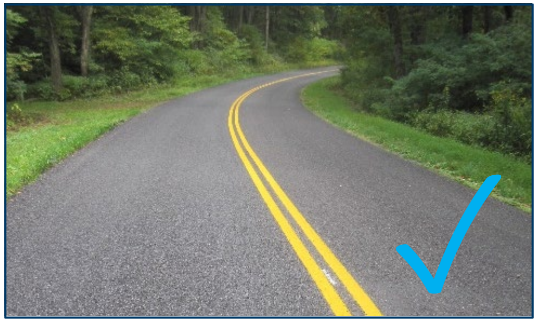


(Cetin et al. 2021)

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!

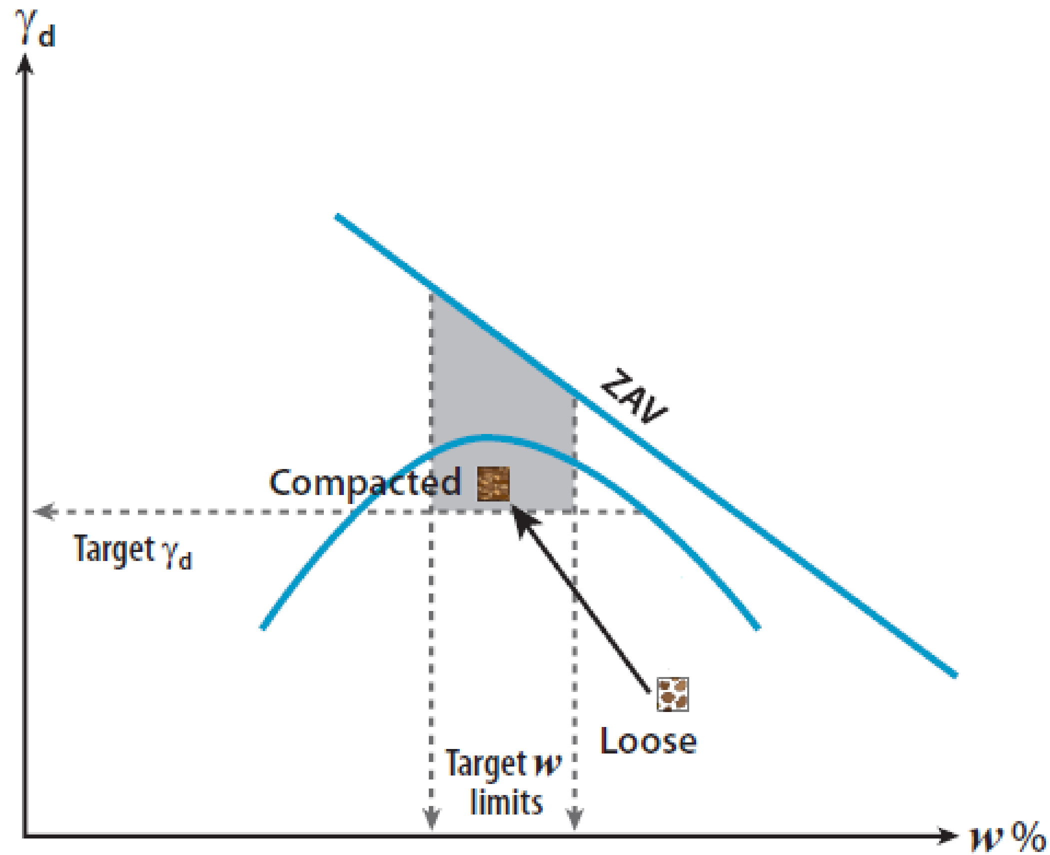
Influence of moisture content on compaction quality for geomaterials

TRB Webinar: Improving Pavement Geomaterial Performance with Unsaturated Soil Mechanics

August 3, 2021

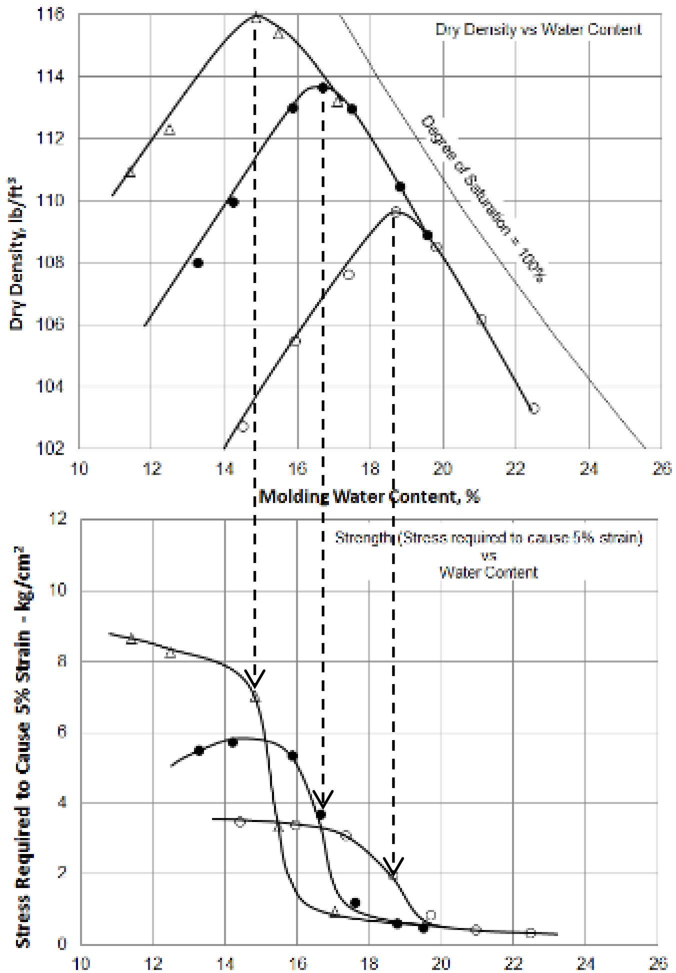
David J. White, Ph.D., P.E.
President and CEO
Ingios Geotechnics, inc.
david.white@ingios.com

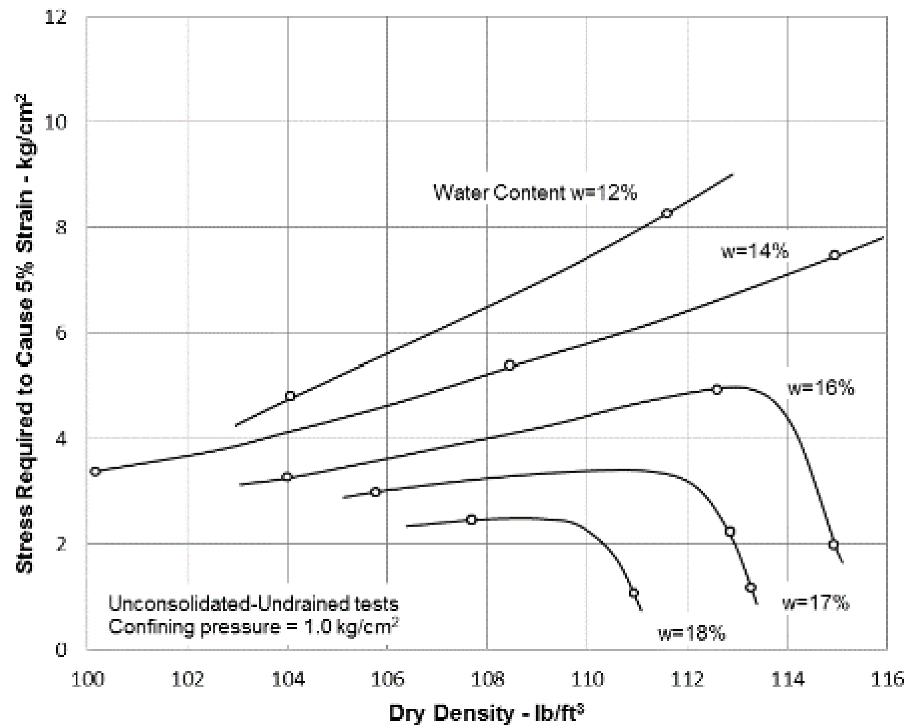
In practice, specifications for earthwork are fixated on Proctor compaction test results for QC/QA.



Relationship between moisture content and density of geomaterial
(from White et al. 2010)

An important consideration for compacted materials is moisture content-strength-modulus relationship.





Seed et al.1960

Moisture content affects volume change as a function of overburden stresses.

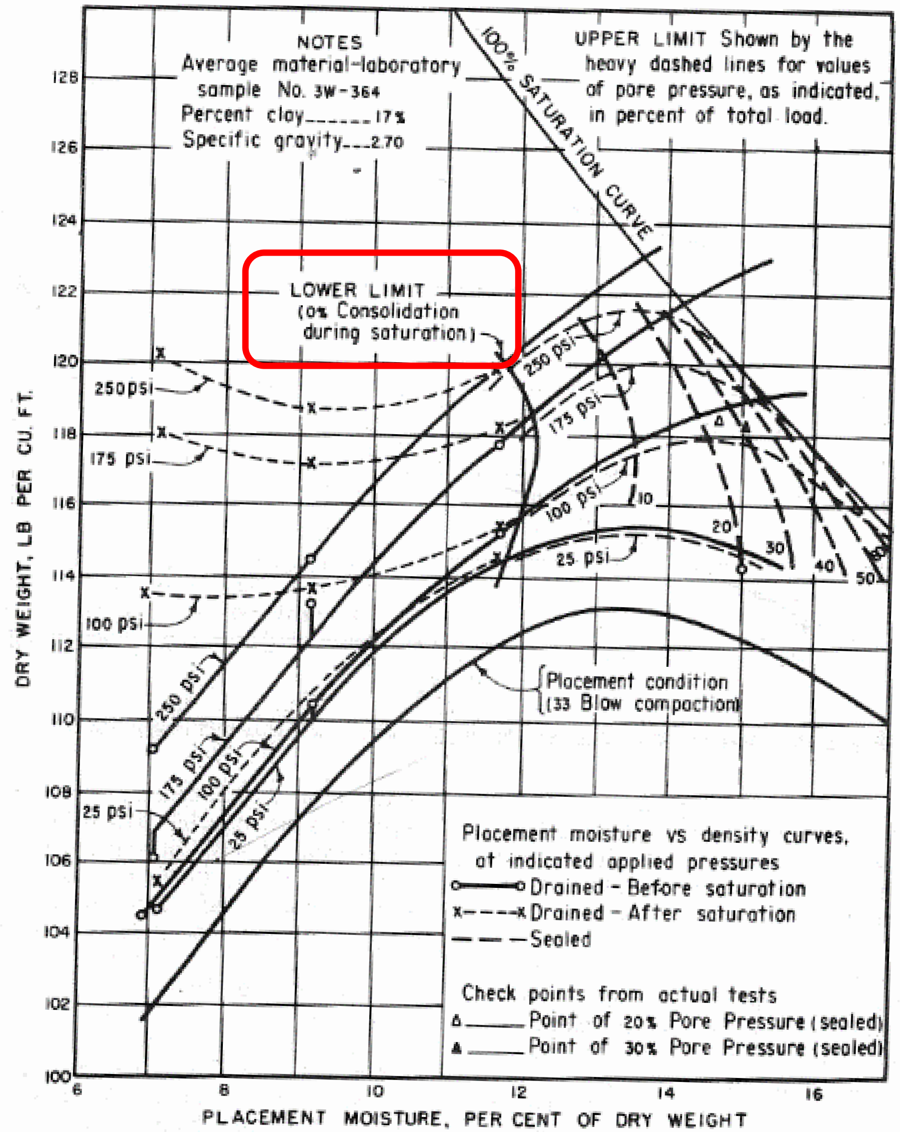


Fig. 8.16 Placement moisture control. (*After Holtz, 1948.*)

Holtz (1948)

Compaction energy and moisture content change density ~10% and strength/modulus ~500%.

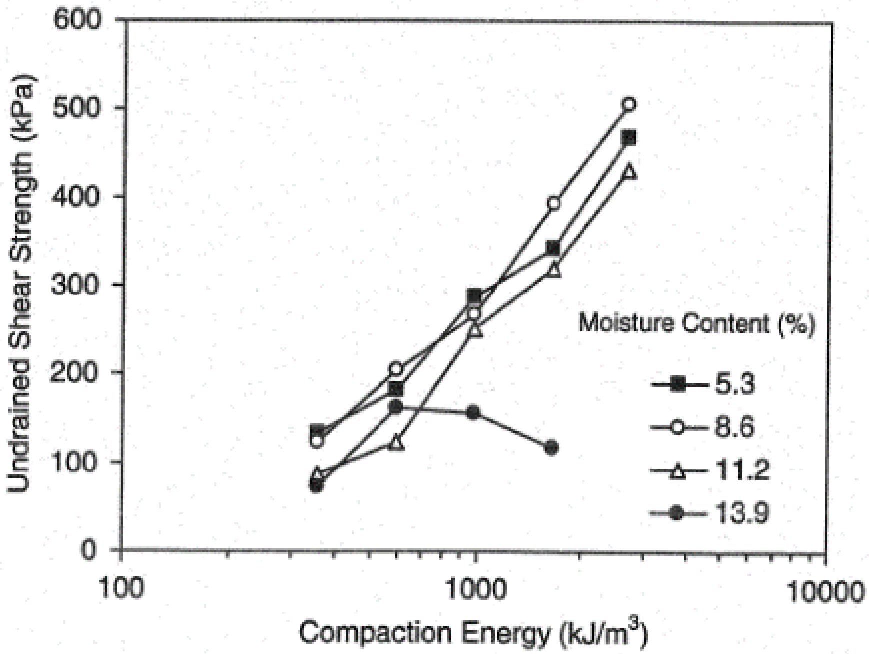


FIGURE 6 Semilogarithmic relationship between undrained shear strength and compaction energy as a function of water content.

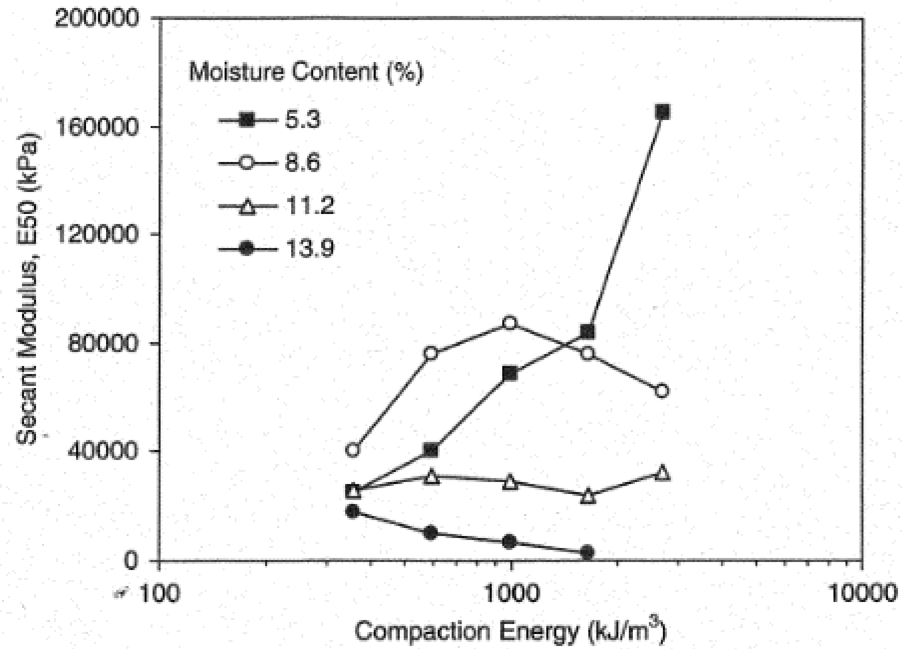
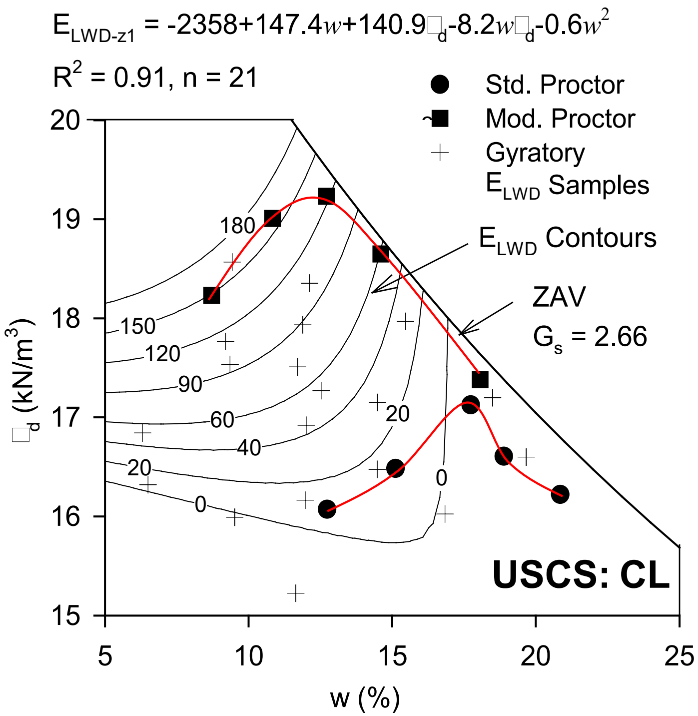


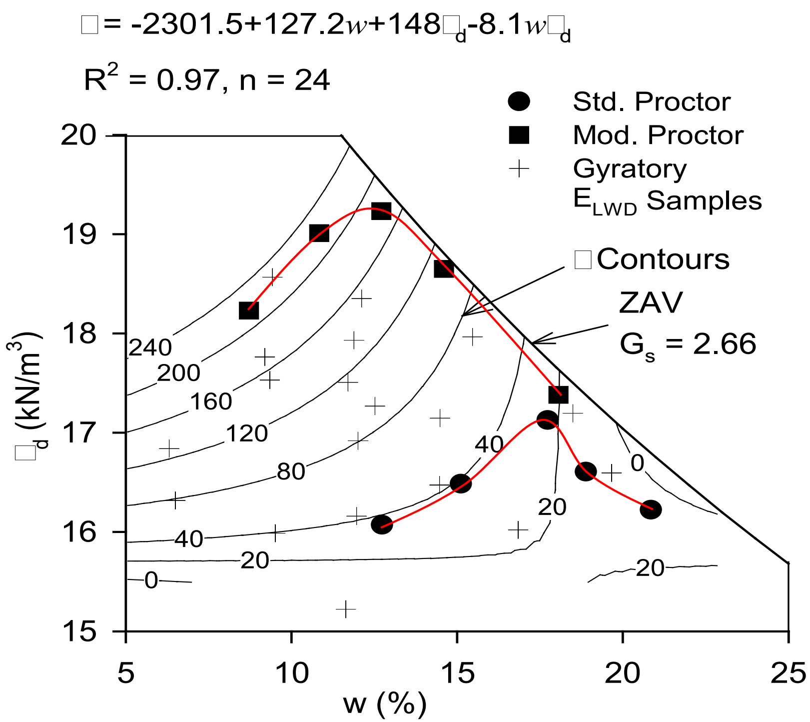
FIGURE 7 Semilogarithmic relationship between secant modulus and compaction energy as function of water content.

(White et al. 2005)

Isobars overlain on M-D plots show changes in strength and stiffness.



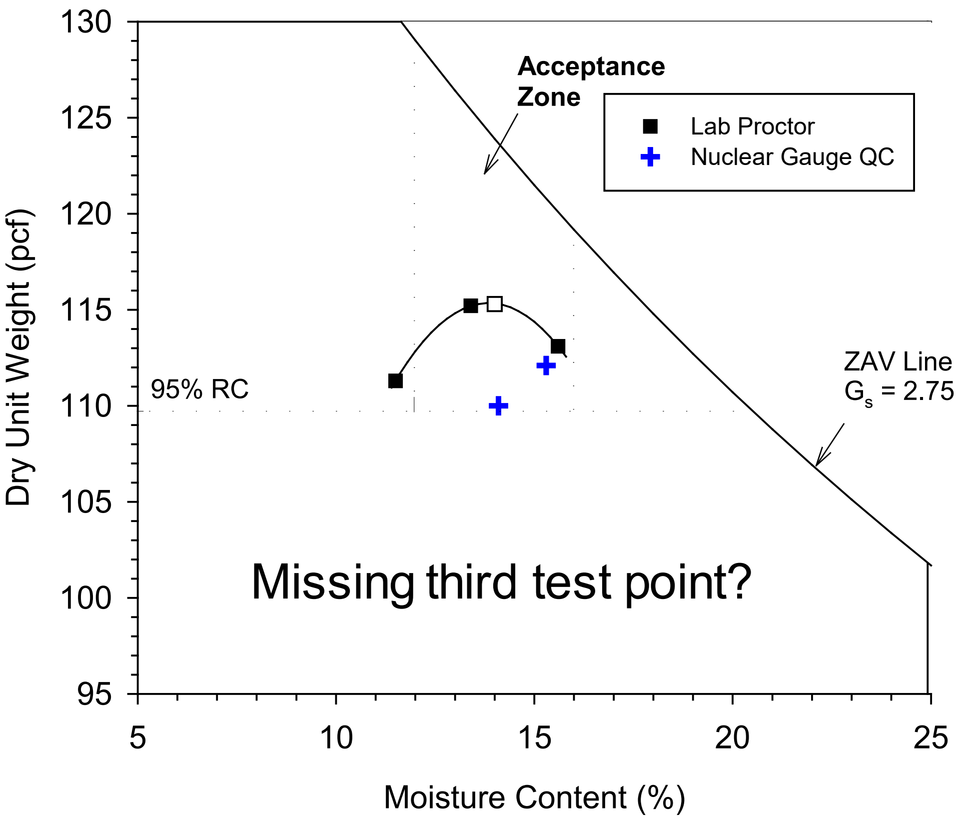
Elastic Modulus



Shear Strength

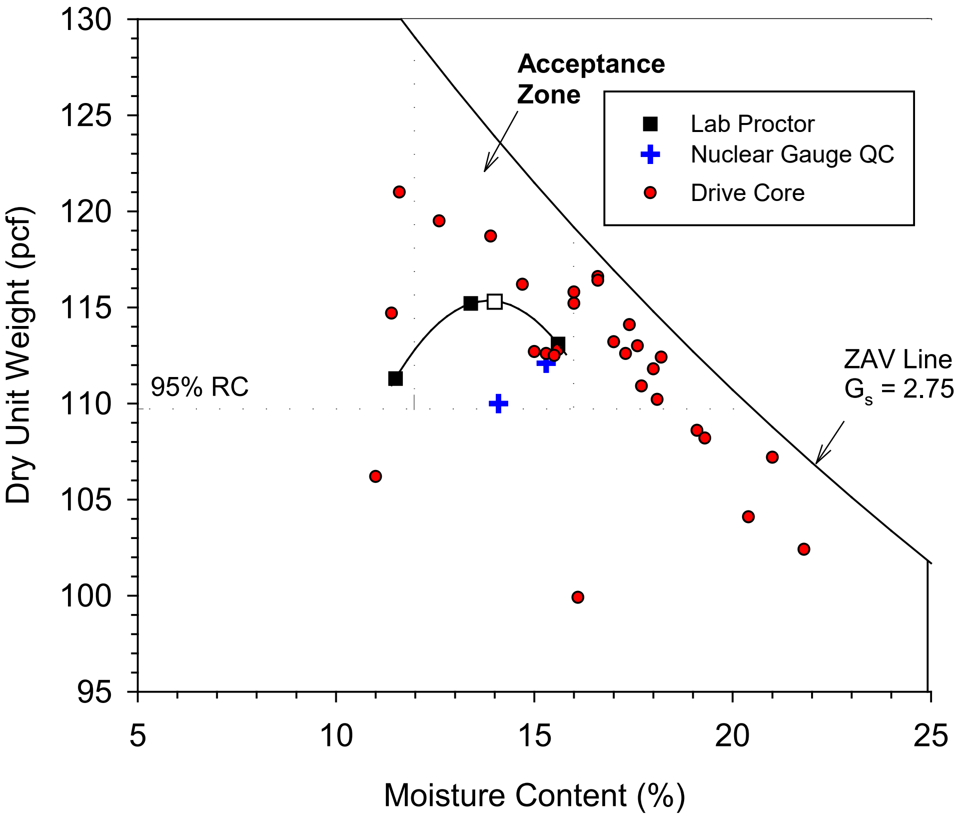
White et al. (2009)

Traditional (limited) density-based specifications indicate bias during QC testing.



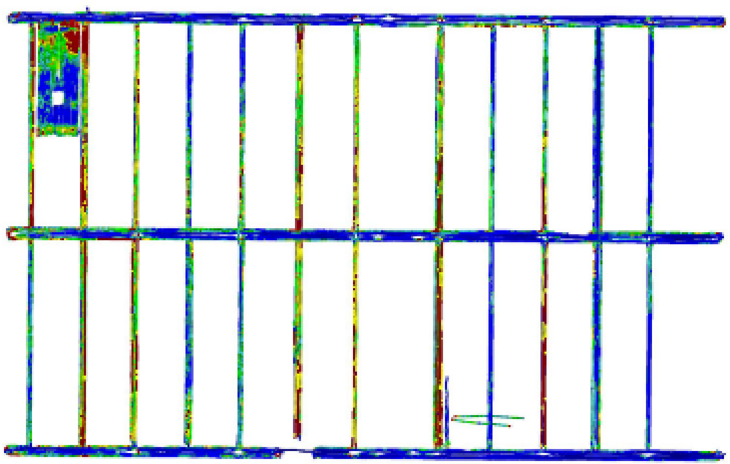
White et al. 2013

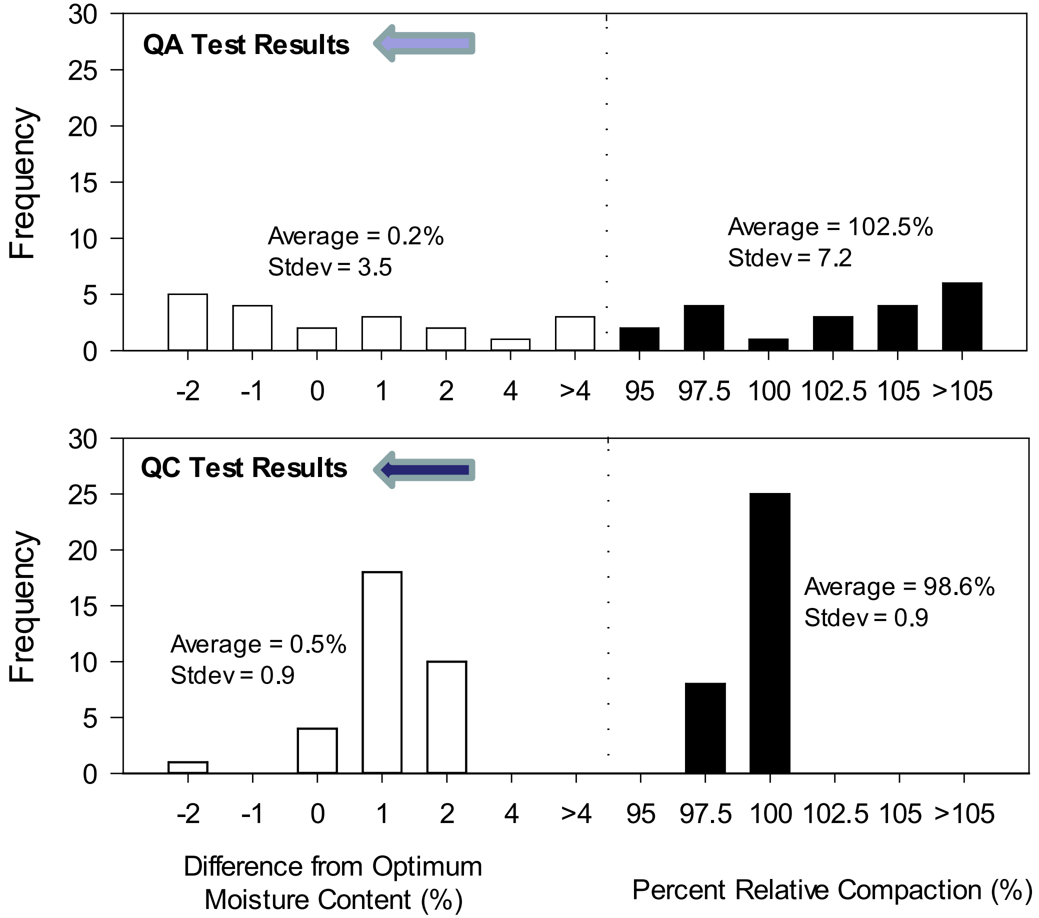
Closer examination shows variability not captured with traditional testing.



White et al. 2013

QC/QA nuclear testing showed lack of reproducibility and did not capture the wide range in stiffness values measured.





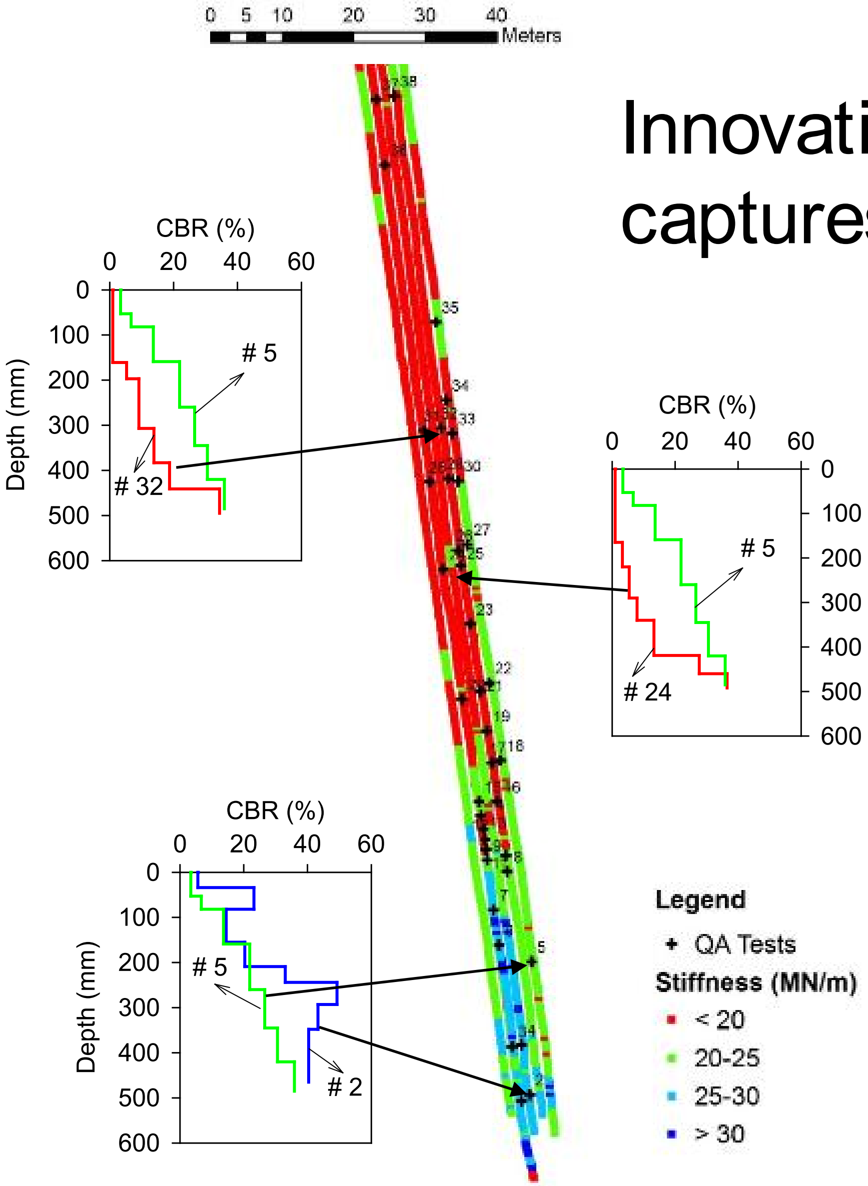
Source: White, D.J., Becker, P., Vennapusa, P., Dunn, M., and White, C. (2013). “Soil Stiffness Assessment of Stabilized Pavement Foundations.” *Transportation Research Record, Journal of Transportation Research Board*, 2235, 99-109.

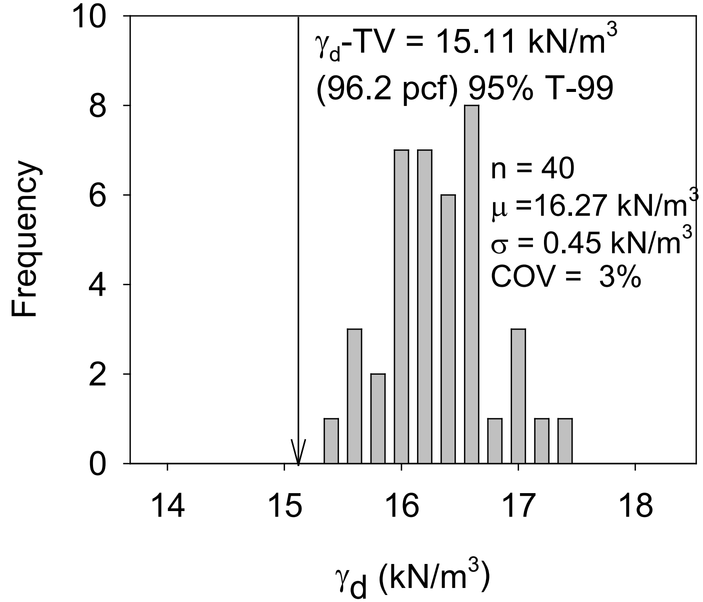
Acknowledgment of problems is difficult…

— they are an essential part of experimentation and a prerequisite for innovation. So don’t worry. —

(Harvard Business Review, 2014)

Innovation: Geospatial mapping captures the “weak” spots.



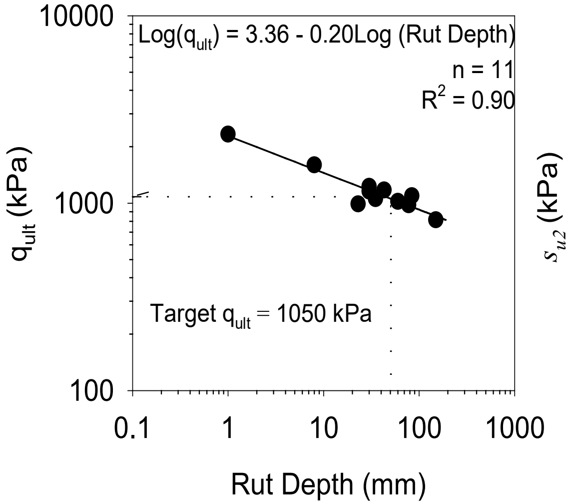


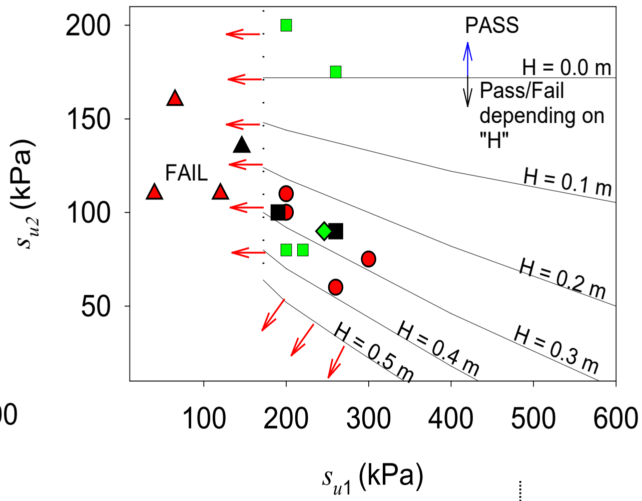
Source: NCHRP 676 Report

—The primary problem is not so much to determine the average conditions, as it is to make reasonably certain that possibly the most unfavorable conditions are known over a given area that may give rise to soft spots.—

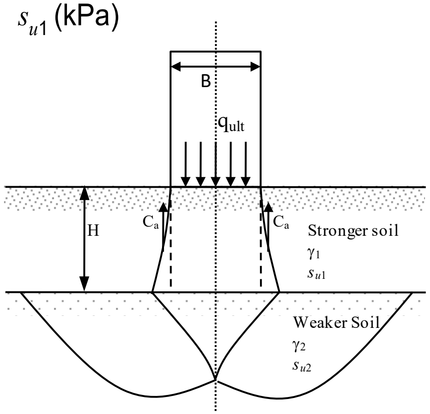
Donald M. Burmister (1948).

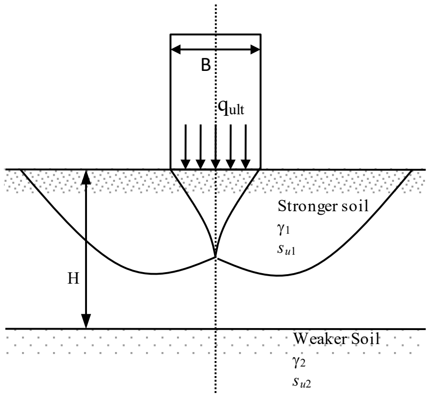
“Weaker” underlying layers contribute to rutting on surface.





- TH60 Fail (Points 2, 3, and 8)
- TH60 Pass (Points 1, 4, 6, 7, 10, and 11)
- TH60 Pass (Points 5,9) q_{ult} < target q_{ult} (1050 kPa)
- TH 14 Fail (Points 1, 2, and 4)
- TH 14 Pass (Point 5)
- TH60 Pass (Point 3) q_{ult} < target q_{ult} (1050 kPa)

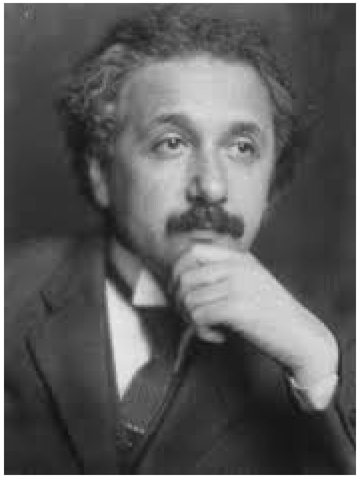




Source: White, D.J., Vennapusa, P., Gieselman, H., Johanson, L., and Siekmeier, J. (2009). “Alternatives to heavy test rolling for cohesive subgrade assessment,” *8th Intl. Conf. on the Bearing Capactiy of Roads, Railways, and Airfields (BCR²A’09)*, June 29 – July 2, Champaign, Illinois.

— Always make things as simple as possible, but not simpler —

Albert Einstein

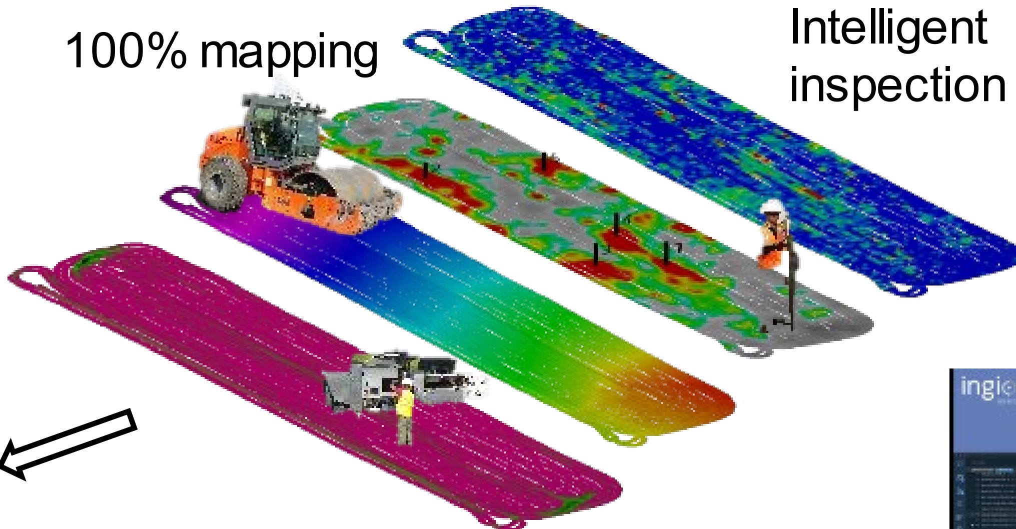


Geospatial mapping technology is here and a game changer!

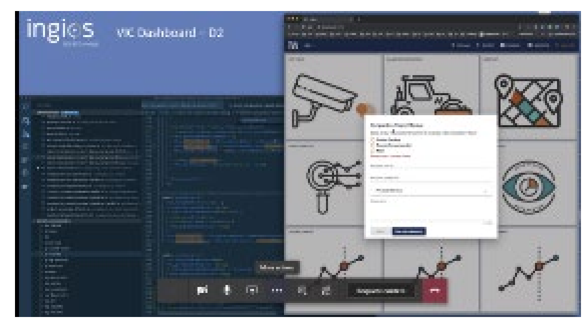
100% mapping

Intelligent inspection

Mobile real-time data

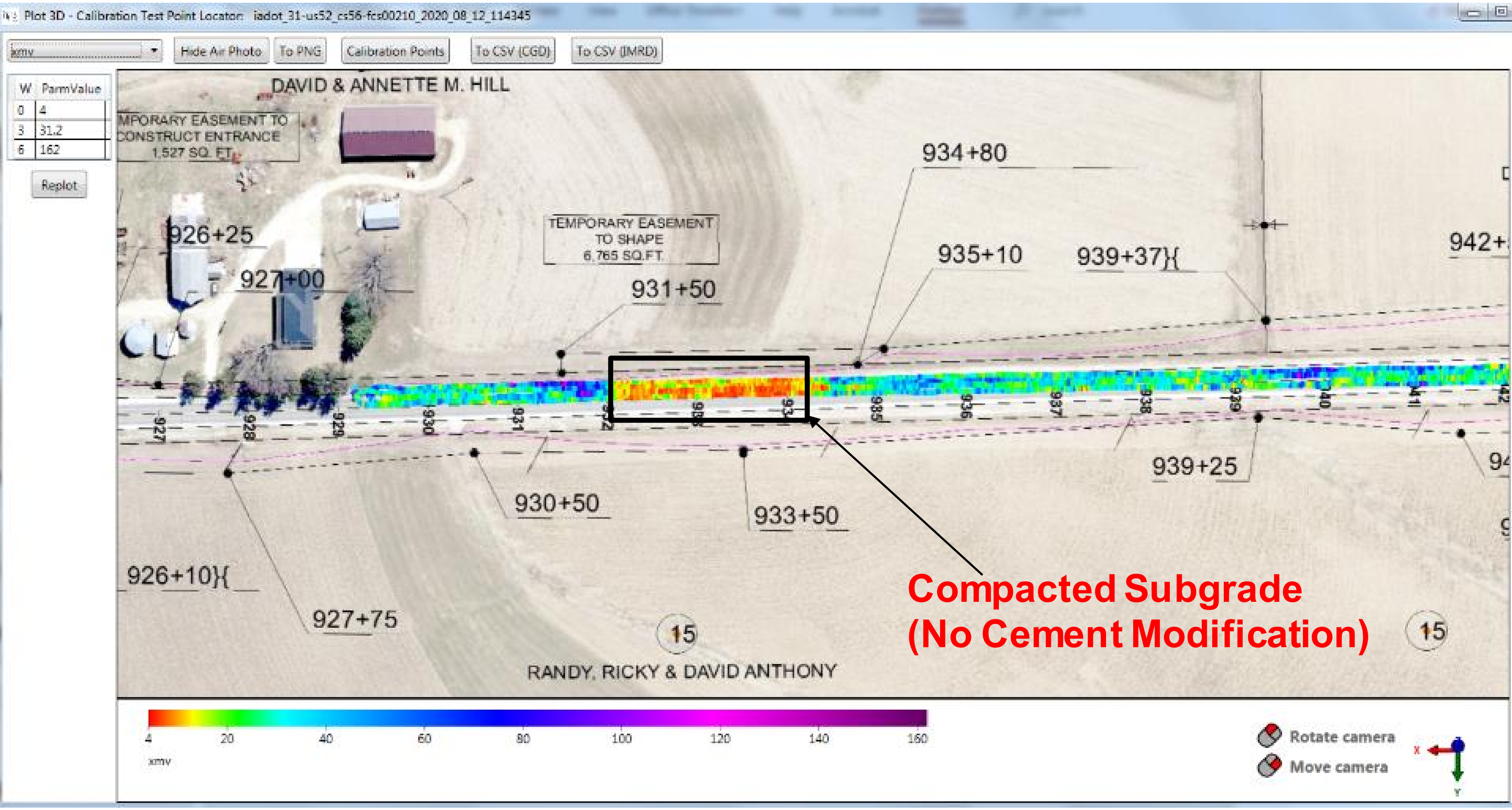


Could based computing and real-time analytics

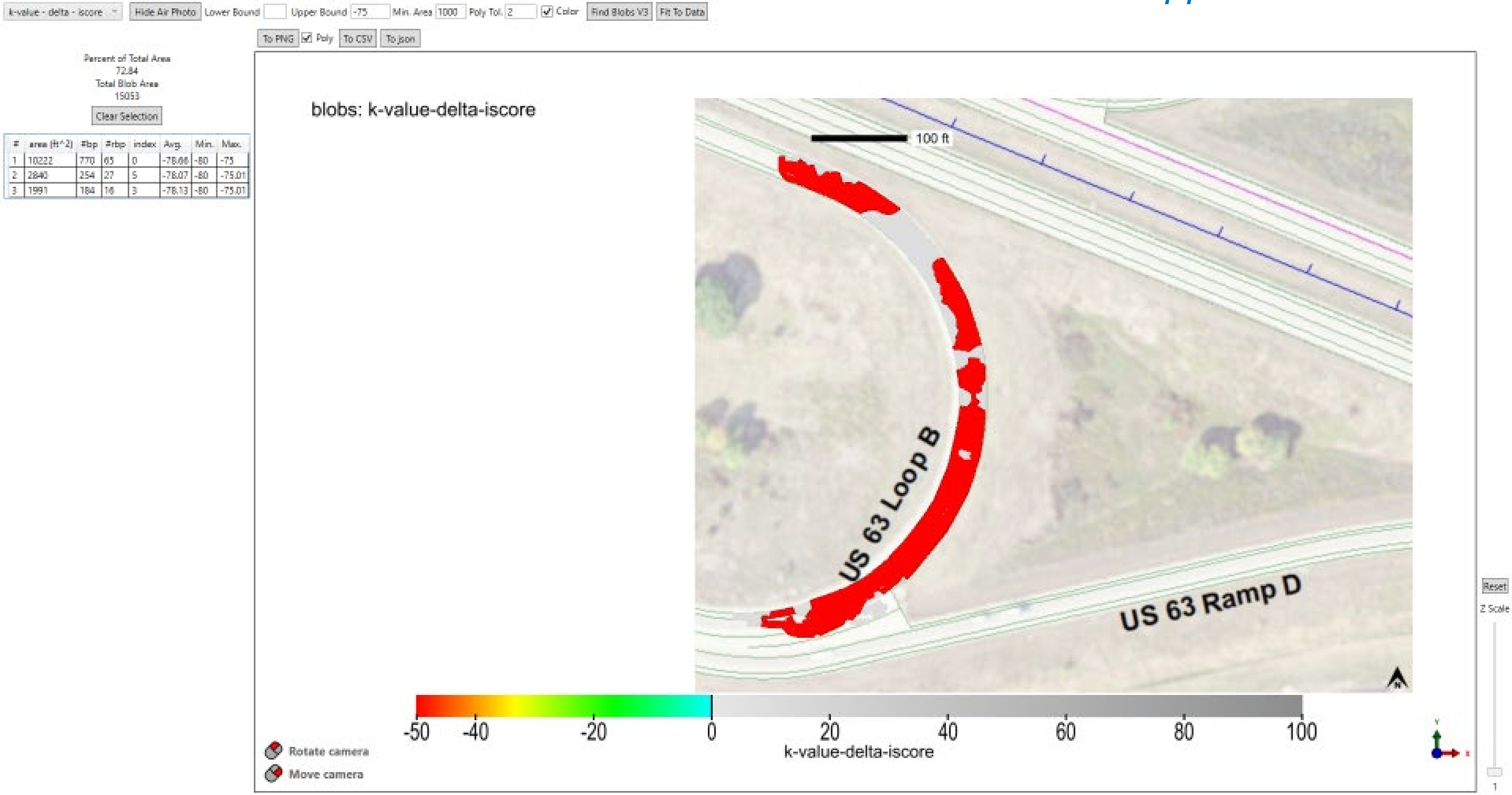


Stress-dependent modulus measurement

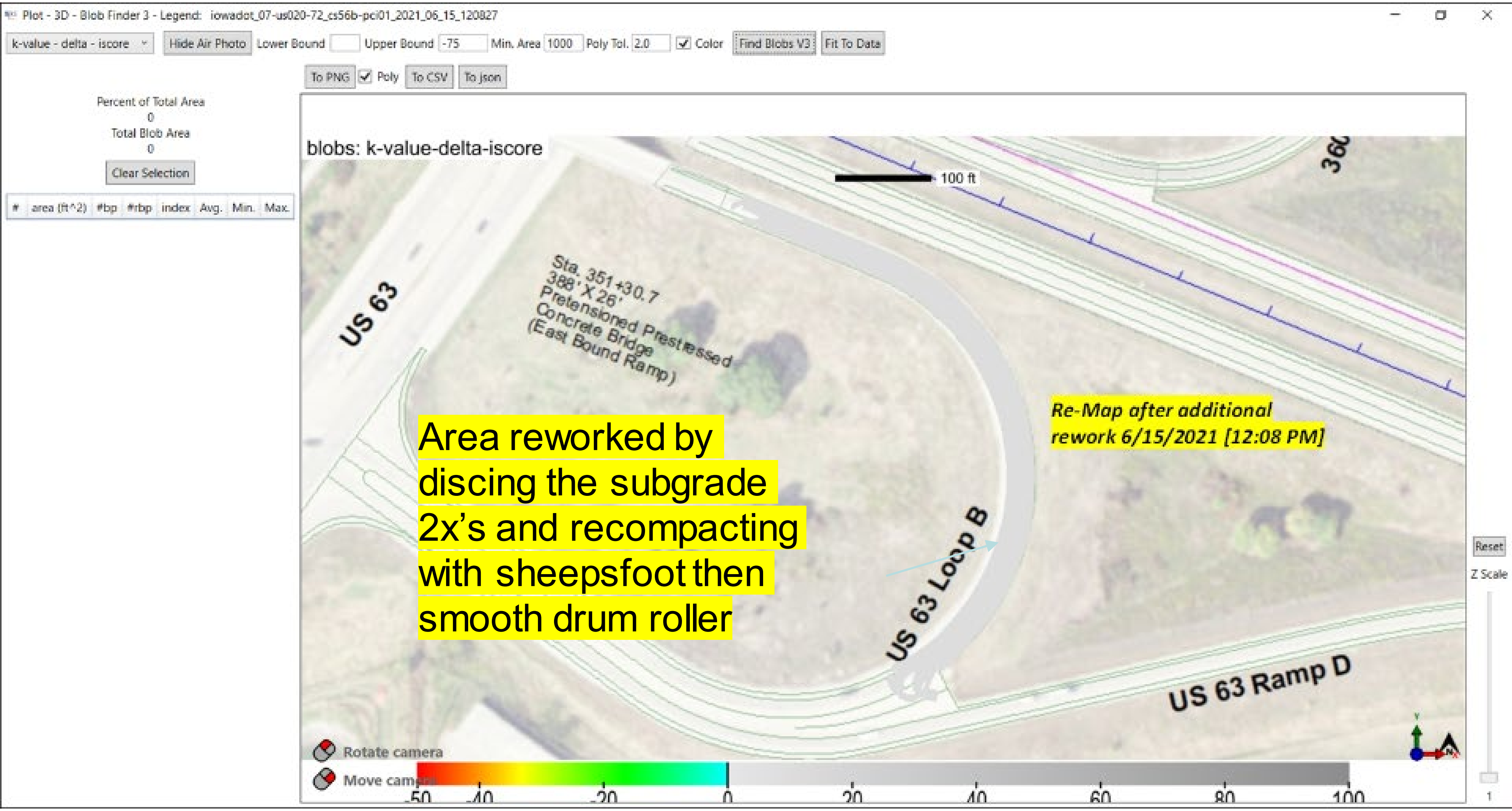
Dubuque County, US52 (08/12/2020) – Cement Modified Subgrade



Entire map area needed to be re-worked and remapped

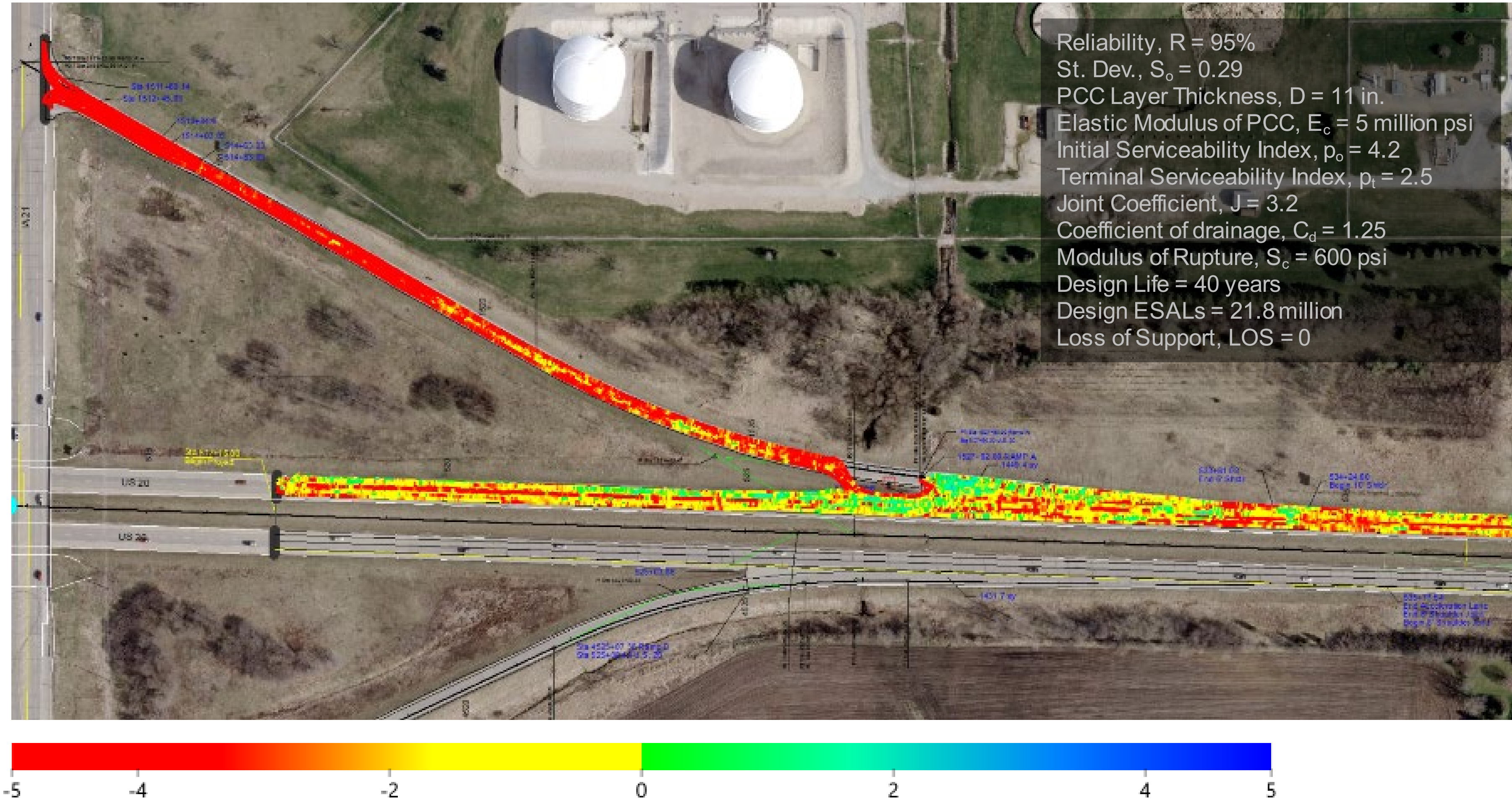


Would this area have been reworked/improved with traditional spot testing?

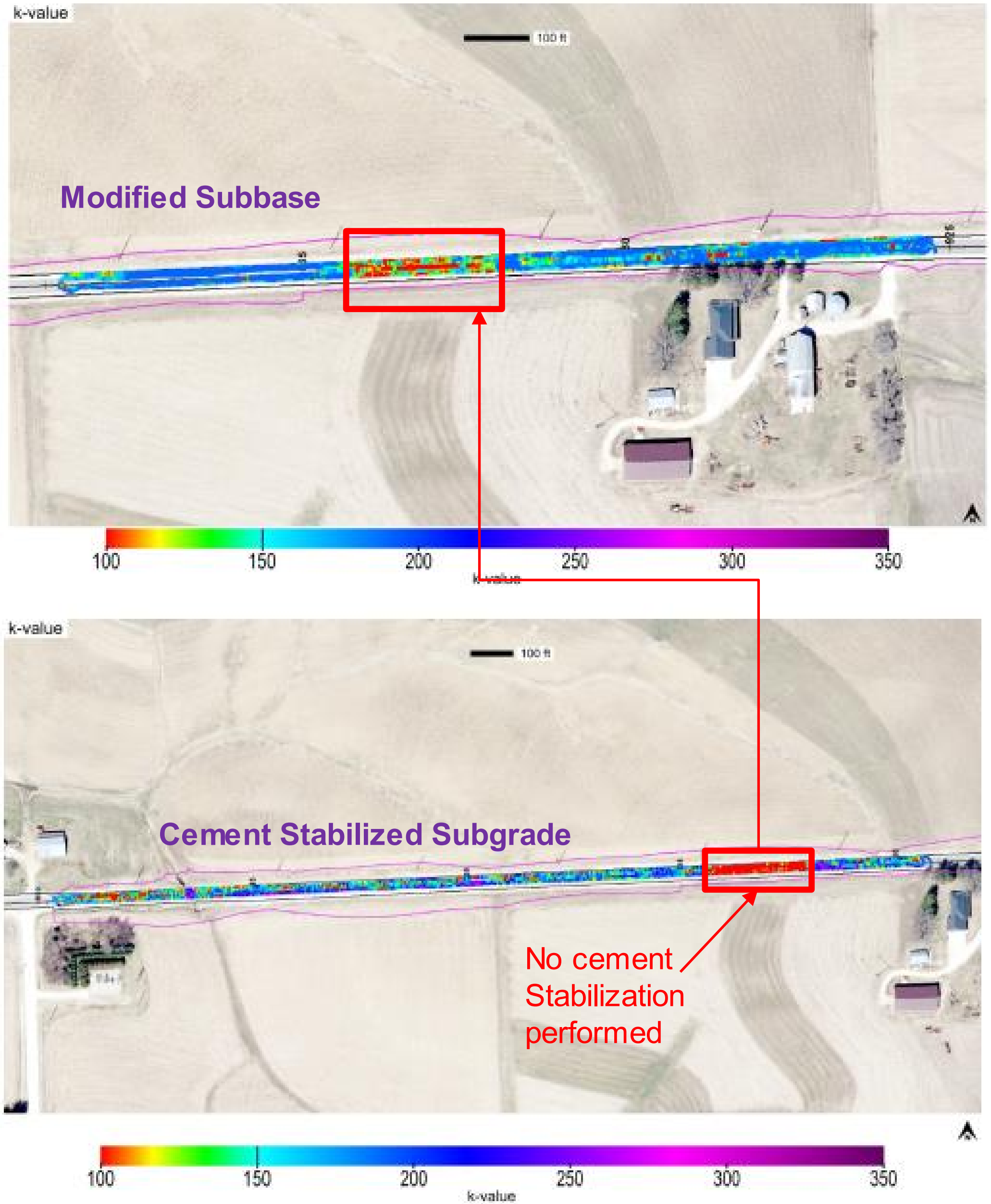


Blackhawk County, US20 (09/05/2019) – Modified Subbase

Delta Design Life Map 1

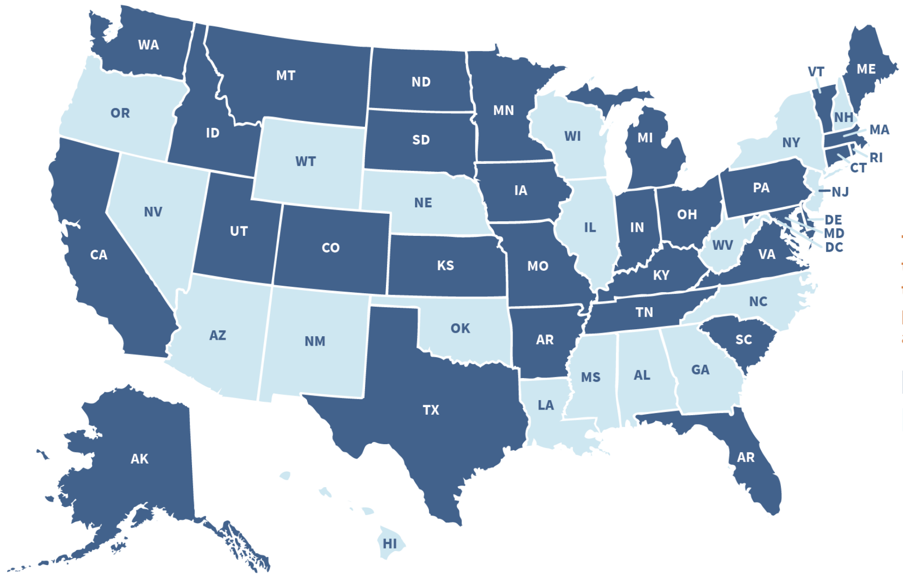


Design Life – delta (No LOS)



"Weak" layers in the underlying subgrade reflect on the overlying subgrade.

National DOT Survey Findings | February 2021



The survey was administered to all 50 state DOTs, the DC DOT, the Puerto Rico DOT, and various positions within AASHTO, TRB, and FHWA.

- Responded
- No Response

Of the 31 responding DOT agencies...

97% want more effective quality acceptance (QA) for pavement foundation construction.

94% want data reports to support field process control during foundation layer construction.

94% want to field verify the engineering properties used in pavement design of the various foundation layers.

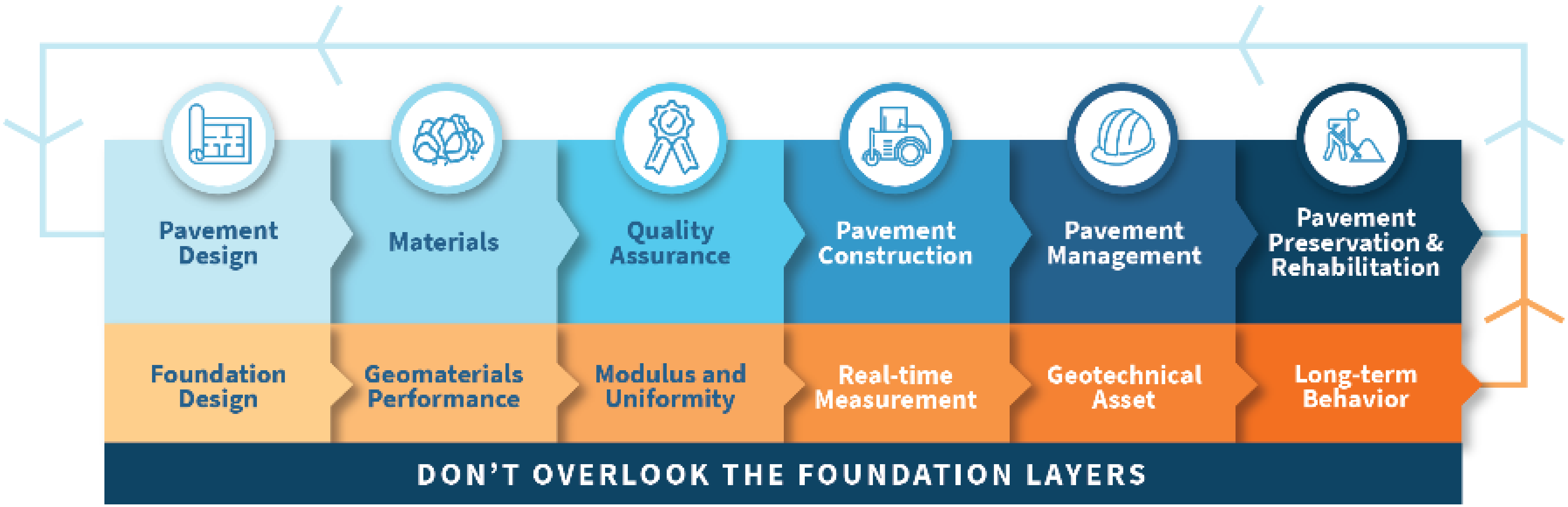
100% are interested in learning more of Iowa DOT's AID implementation efforts to bring improved solutions to pavement foundation layers.

97% want real-time QA data to determine if design and specification requirements are being achieved.

3% **Only 3% of DOT agencies have a quality acceptance parameter that directly measures pavement design requirements.**

Source: *National DOT Survey Findings and Results: Accelerated Innovation Deployment (AID) Demonstration Project: Increasing Pavement Performance through Pavement Foundation Design Modulus Verification and Construction Quality Monitoring Interim Report February 26, 2021.*

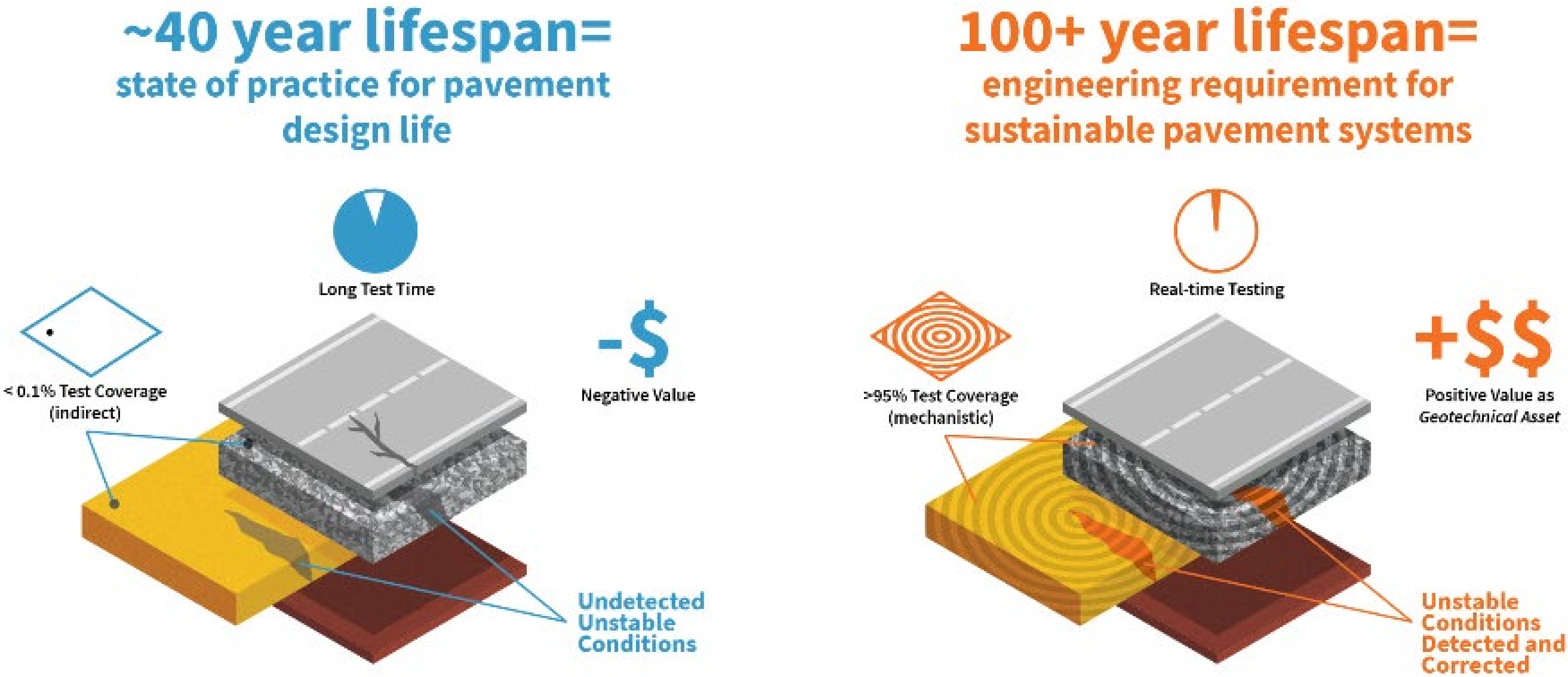
Sustainable Pavement Systems



Foundations are Critical to Performance *and* to Achieving Sustainable Pavements

The foundation layer is largely ignored in modern day road construction techniques. This results in shorter project life-spans and expensive maintenance and repair cycles in the millions of dollars. 95% of these defectsvcan be detected and remediated in real-time during the initial construction process.

Improved pavement foundations extend pavement life and decrease project costs over time.



Thank you!

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Other TRB events for you

- *August 25*: Best Practices for Unsurfaced Road Evaluation and Rating
- *August 26*: Use and Design of Low-Density Cellular Concrete

https://www.nationalacademies.org/trb/events

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