IOWA STATE UNIVERSITY

Center for Earthworks Engineering Research

Improving the Foundation Layers for Concrete Pavements TPF-5(183)

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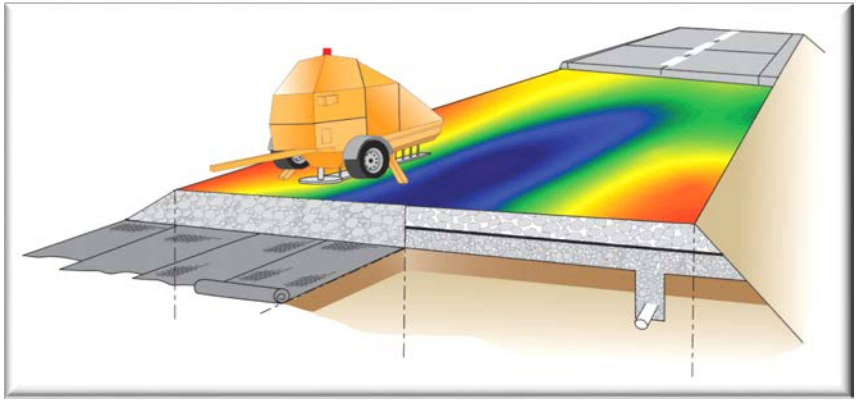


CENTER FOR CEER EARTHWORKS ENGINEERING RESEARCH

ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

National Concrete Pavement Technology Center

CP Tech Center

The University of Nottingham

Acknowledgements

- Transportation Pooled Fund Program TPF-5(183) CA, IA, MI, PA, WI
- FHWA Cooperative Agreement No. DTFH 61-06-H-0011
- Iowa Department of Transportation

Phase I – Problem Identification and Economic Analysis

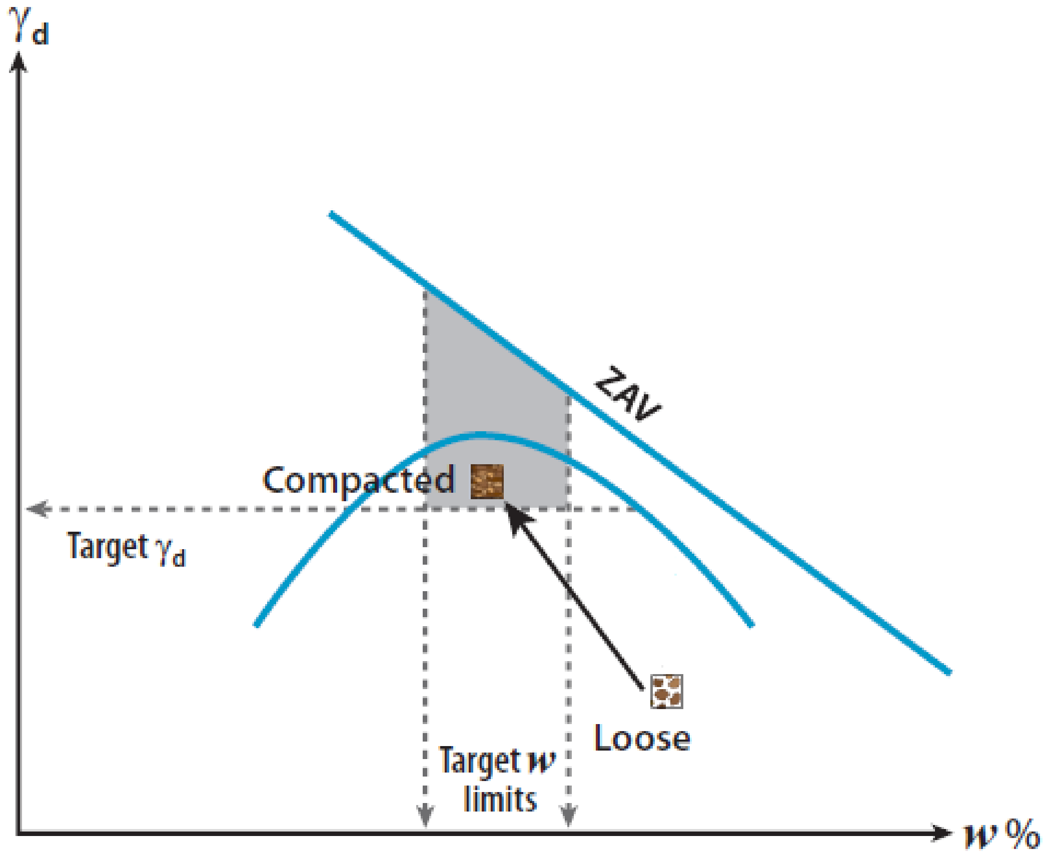
Phase II – Design Parameter Selection and Variability Analysis

Phase III – In-Situ Forensic Investigation and Parameter Characterization

Phase IV –Final Report Preparation

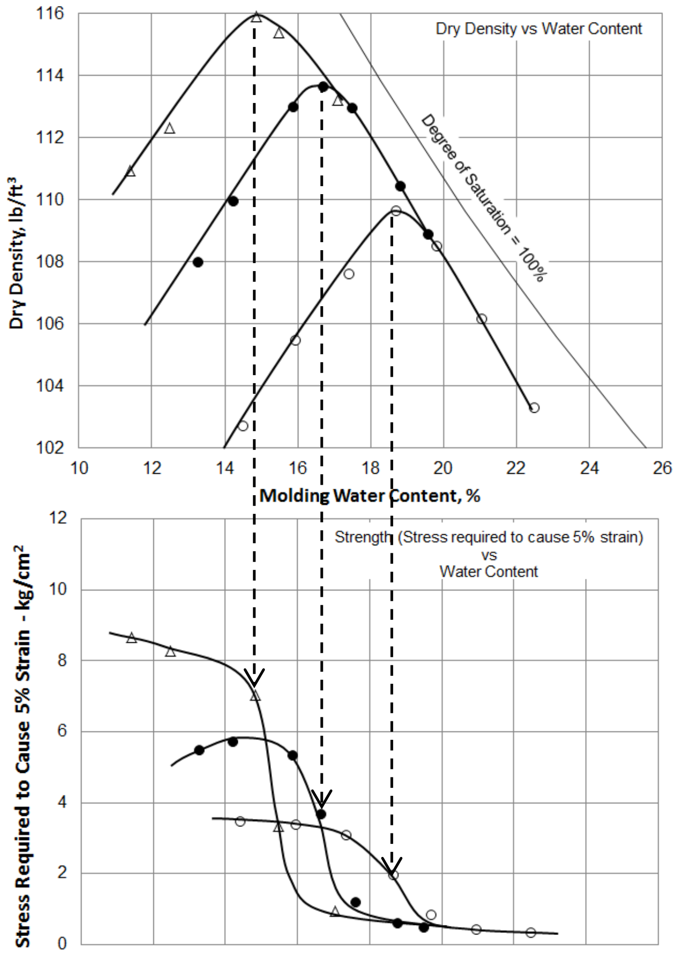
Proper *compaction* is key to achieve stable foundation layers for pavements

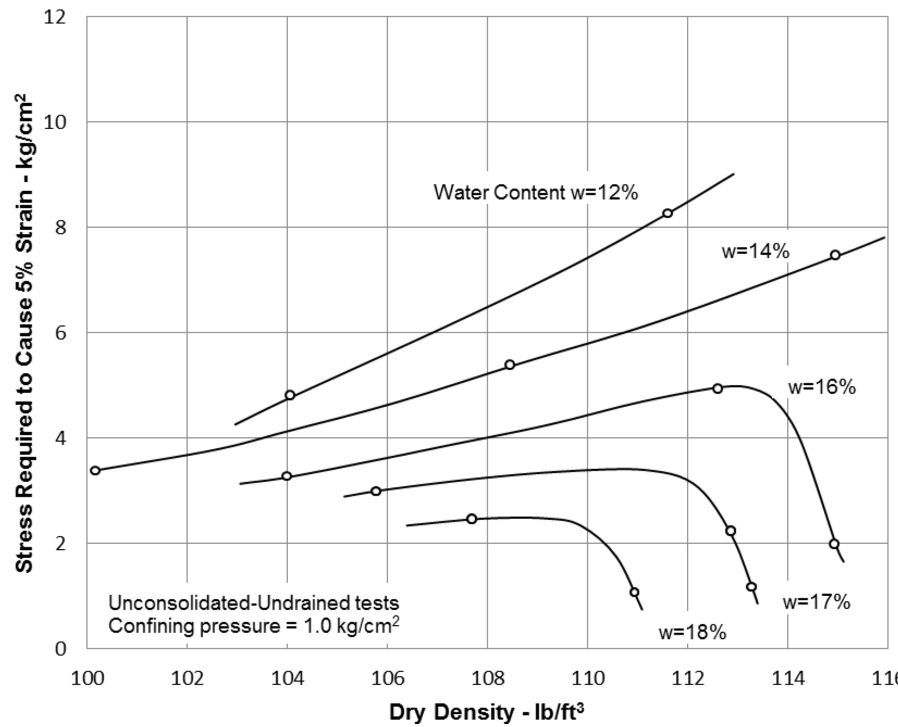
In practice, specifications for earthwork are fixated on Proctor compaction test results for QC/QA.



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

An important consideration for compacted materials is the shear strength/stiffness of the material.





Seed et al.1960

Moisture control limits can be set based on desired volume change characteristics as a function of overburden stresses.

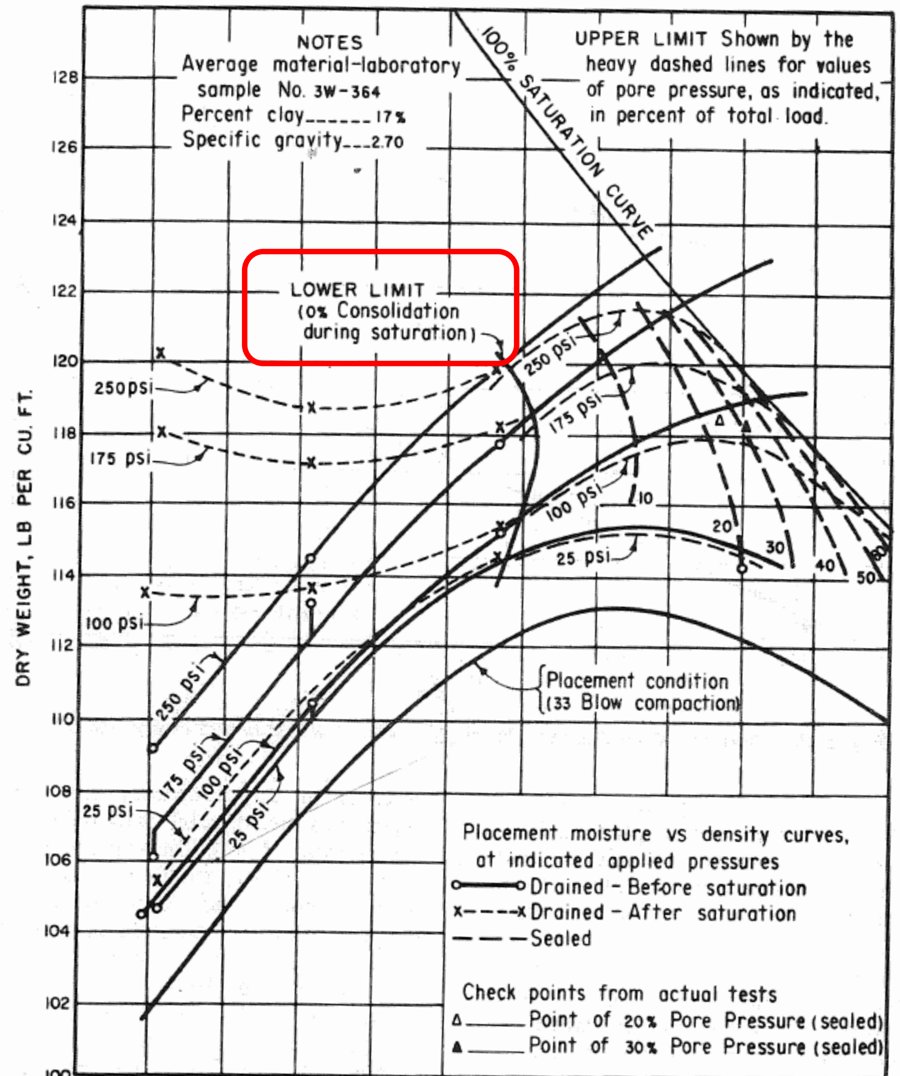


Fig. 8.16 Placement moisture control. (*After Holtz, 1948.*)

Holtz (1948)

Compaction energy and moisture content change density about 10% and strength/stiffness 500%.

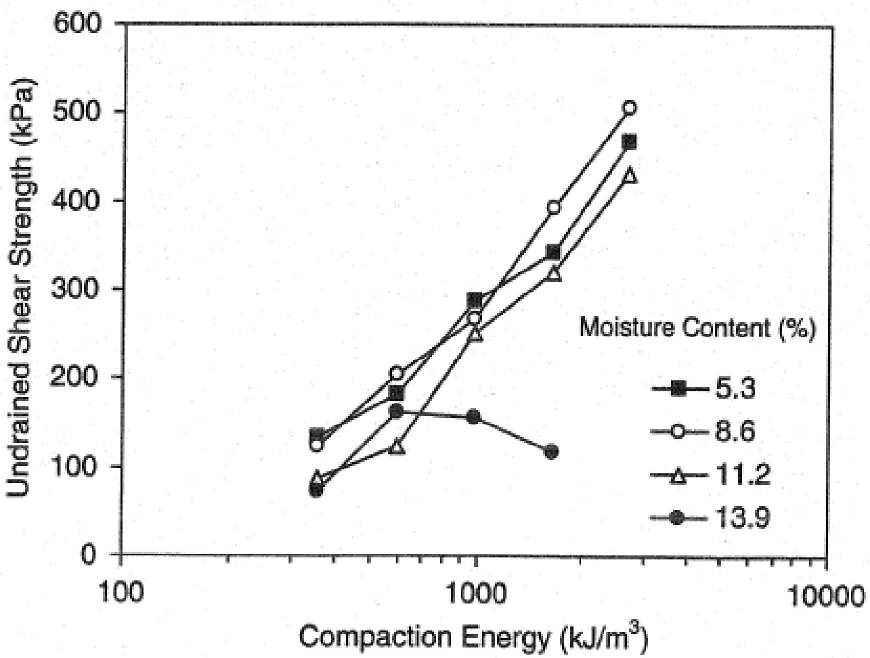


FIGURE 6 Semilogarithmic relationship between undrained shear strength and compaction energy as a function of water content.

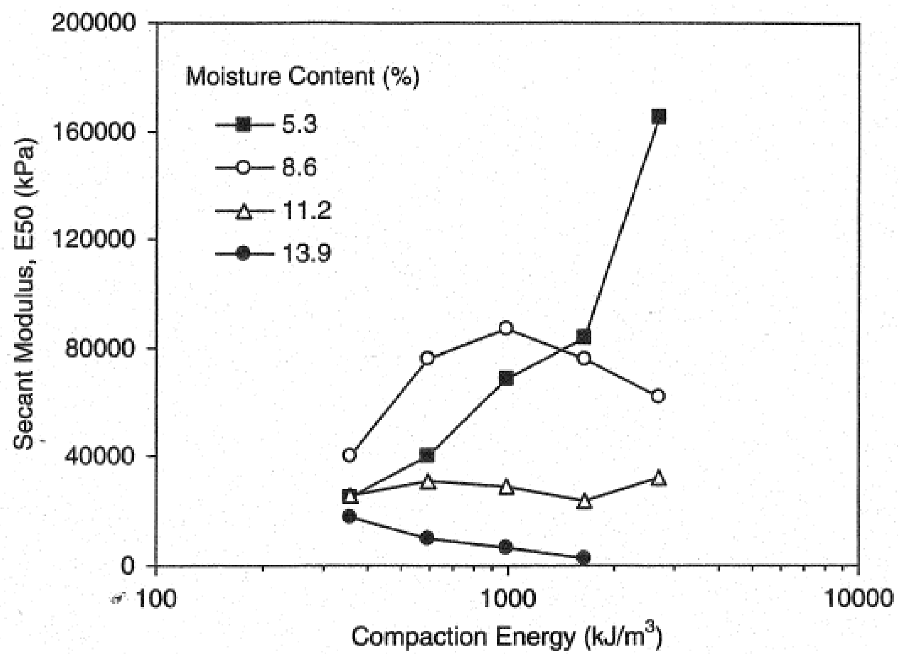
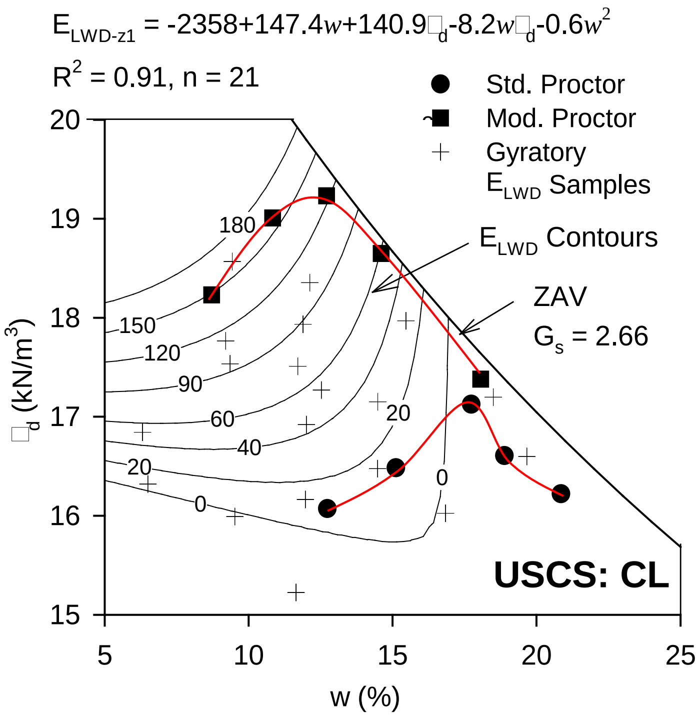


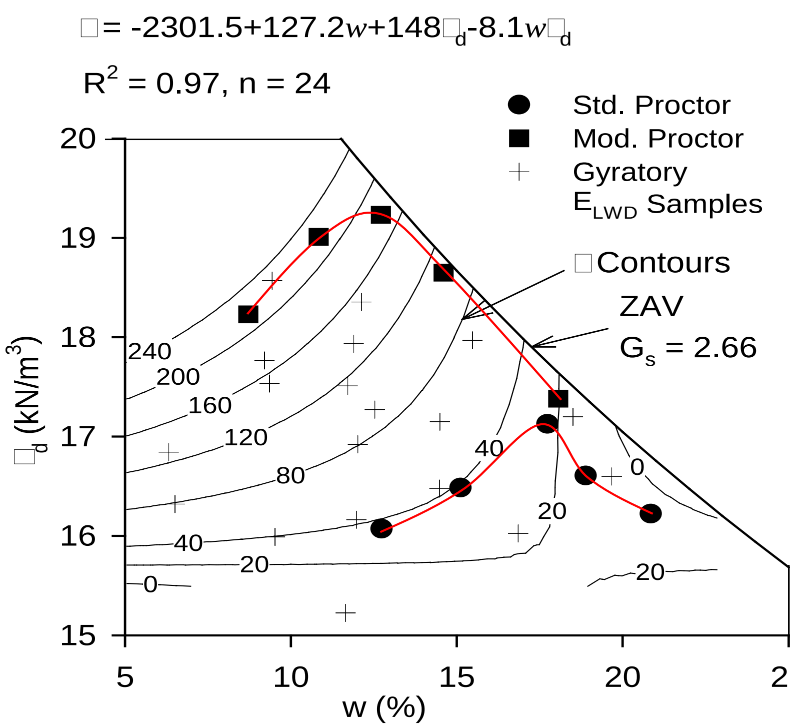
FIGURE 7 Semilogarithmic relationship between secant modulus and compaction energy as function of water content.

(White et al. 2005)

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



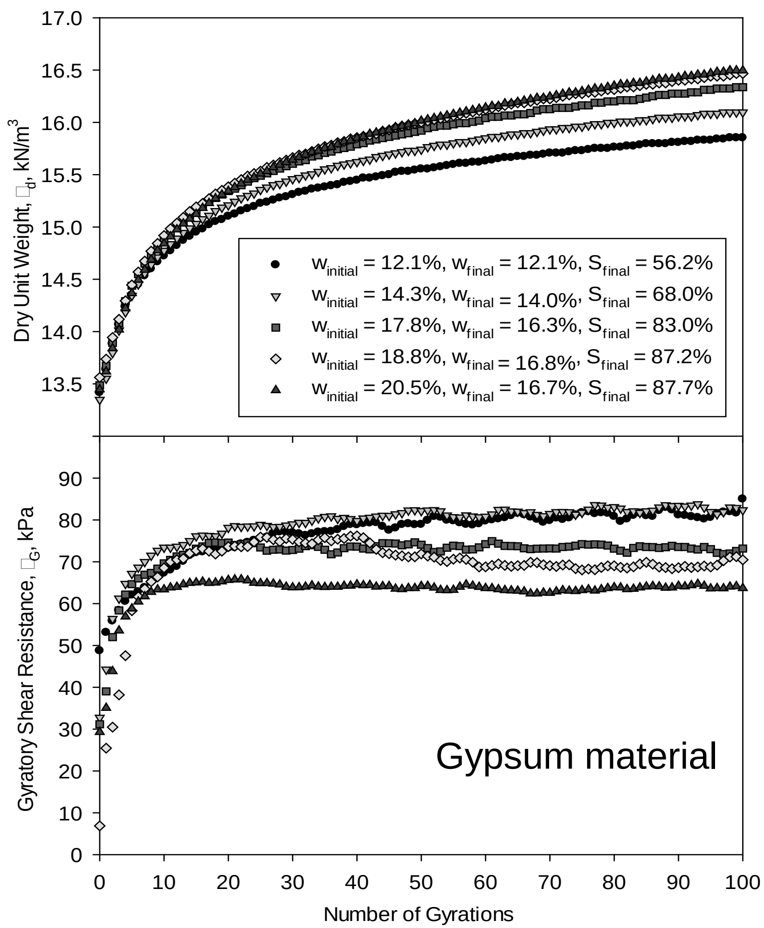
Elastic Modulus

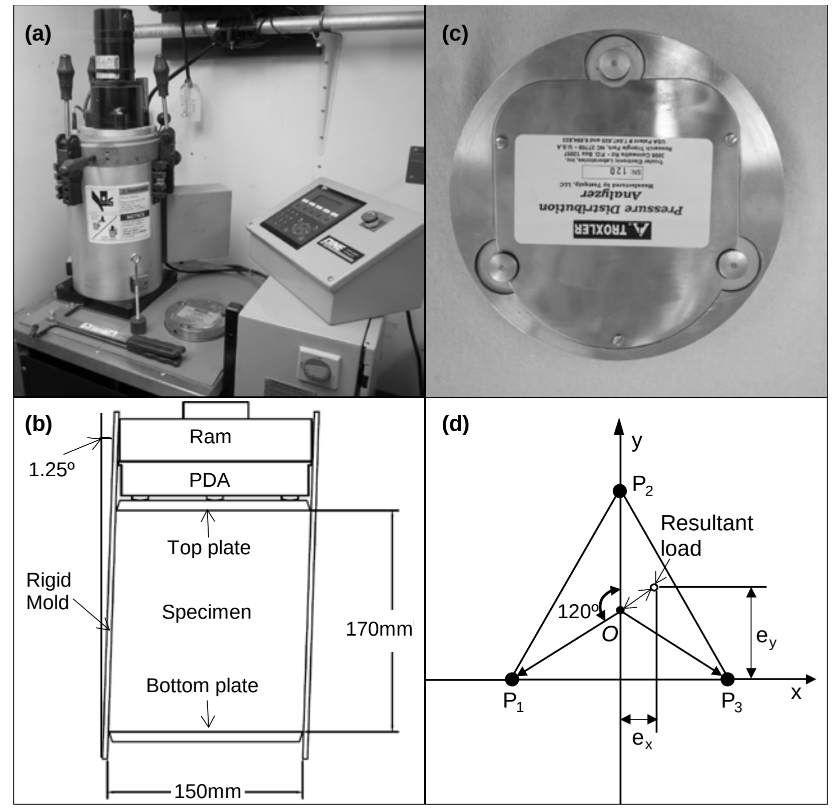


Shear Strength

White et al. (2009)

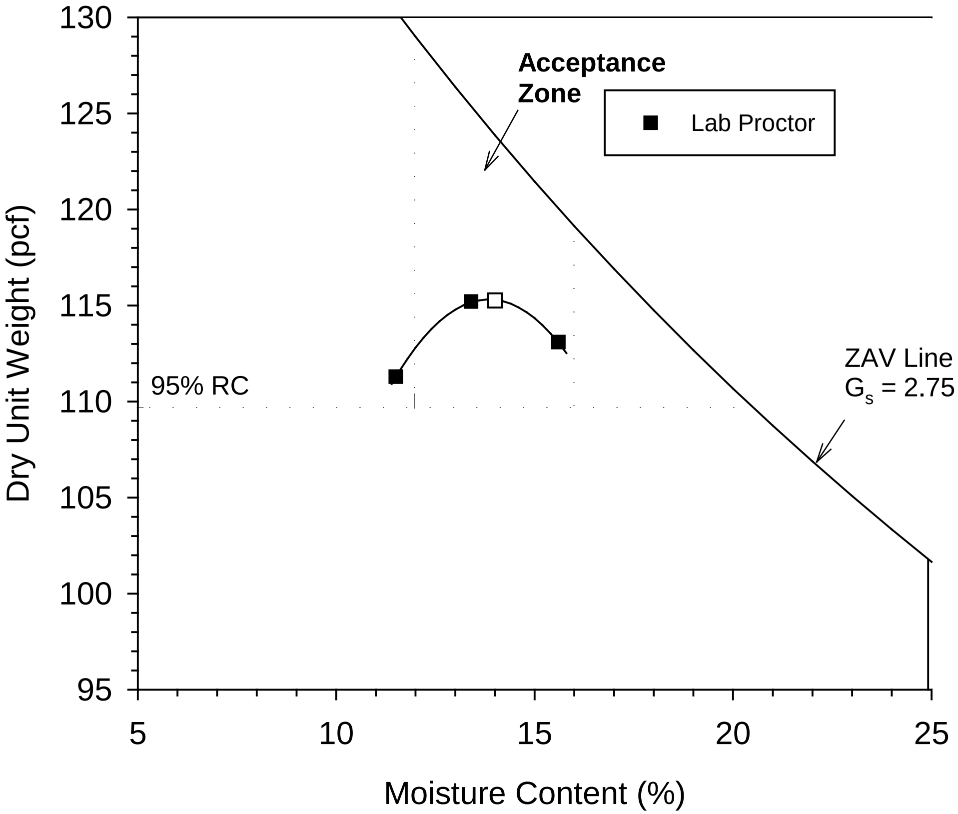
Laboratory gyratory compaction tests can provide moisture-density-shear strength-energy relationships.





Source: Li, C., White, D.J., Vennapusa, P. (2014). "Moisture-Density-Strength-Energy Relationships for Gyratory Compacted Geomaterials." *Geotechnical Testing Journal,* ASTM, (in review).

Traditional density based specifications indicate bias during QC testing.



White et al. 2013

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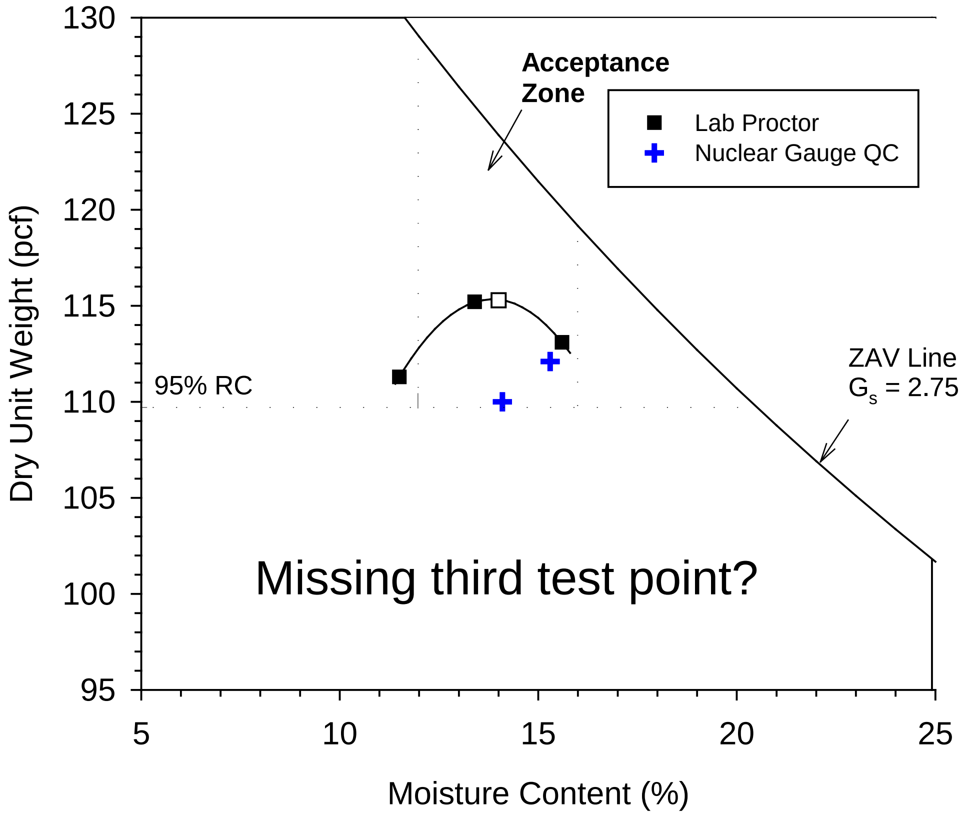
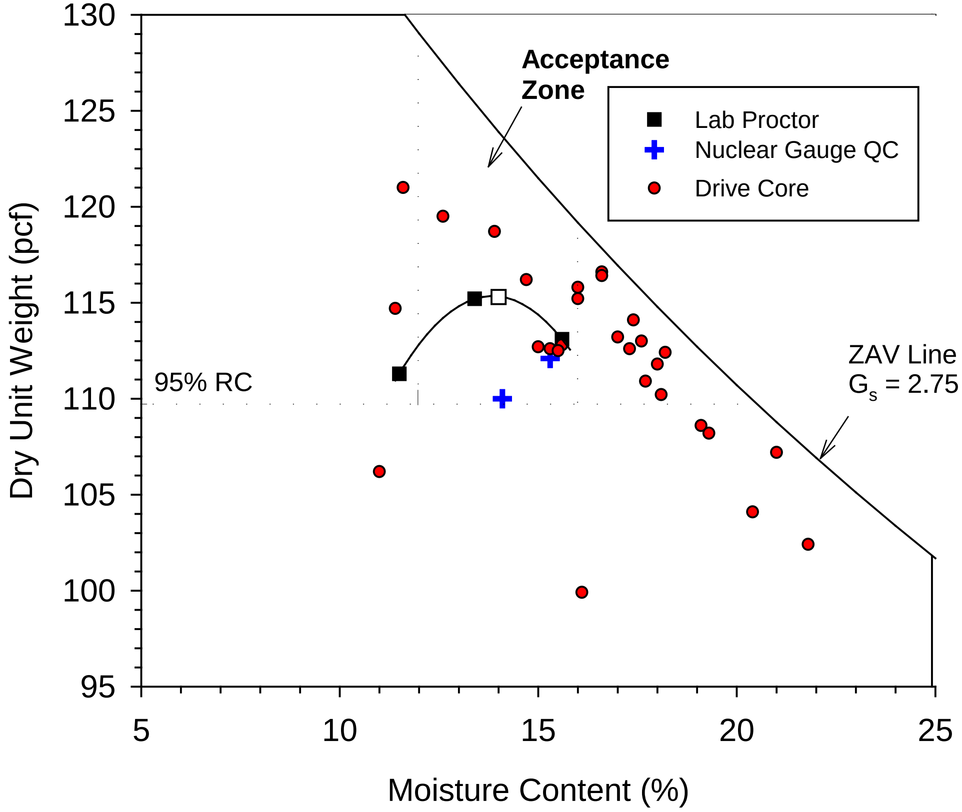


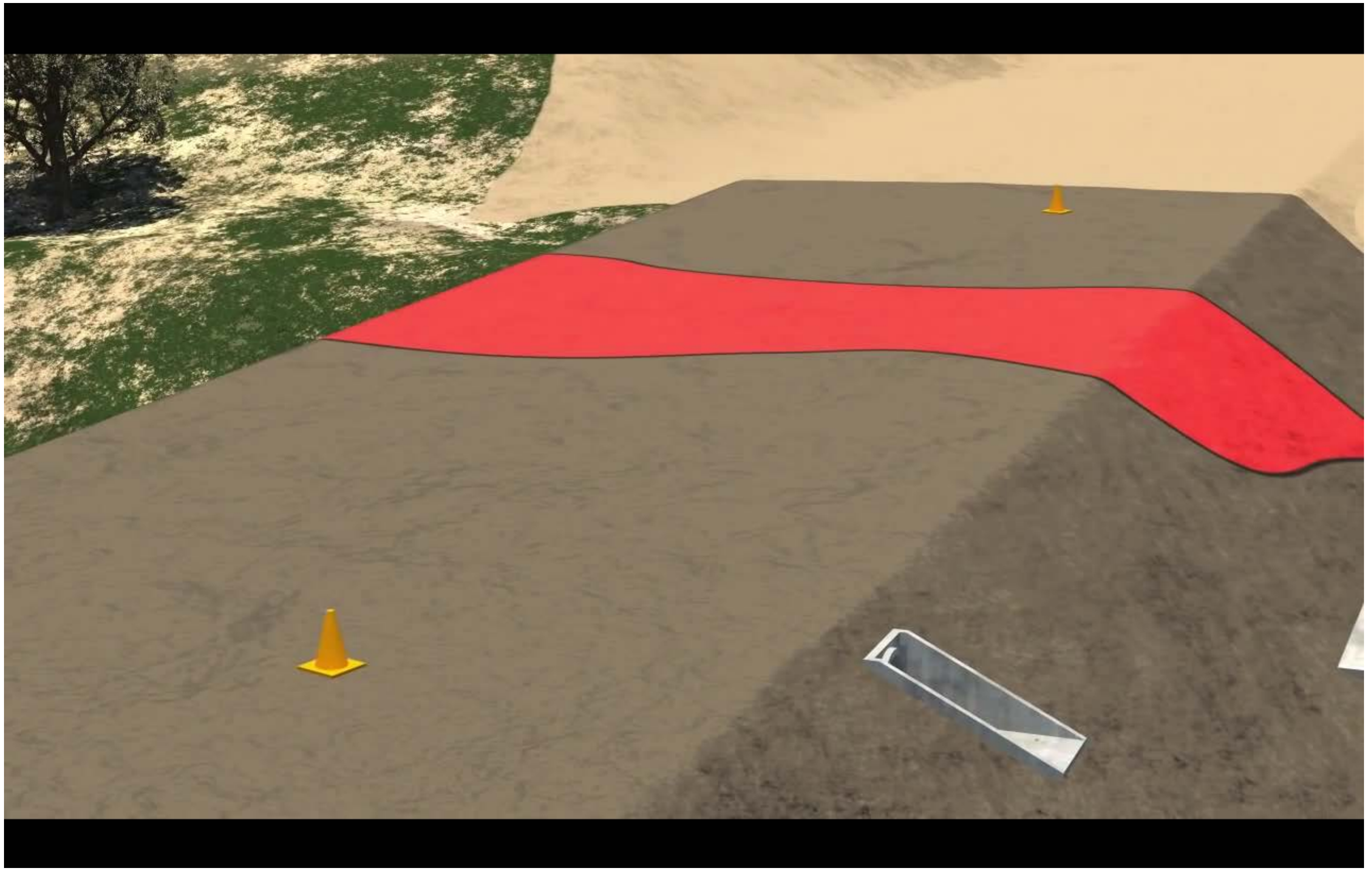
White et al. 2013

Traditional density based specifications indicate bias during QC testing.



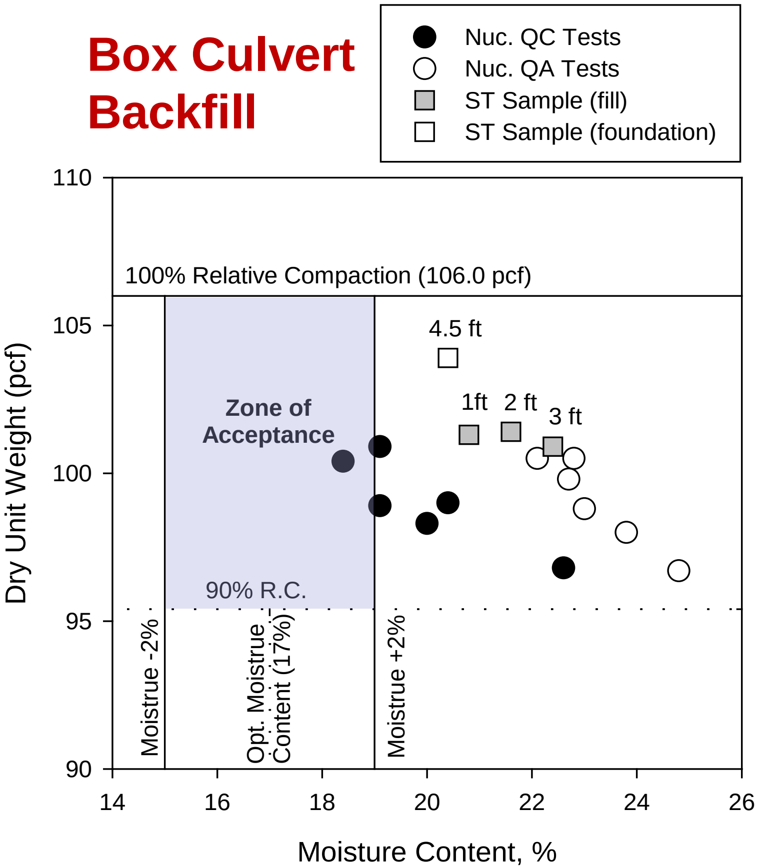
White et al. 2013

Random point testing can be a hit and miss proposition

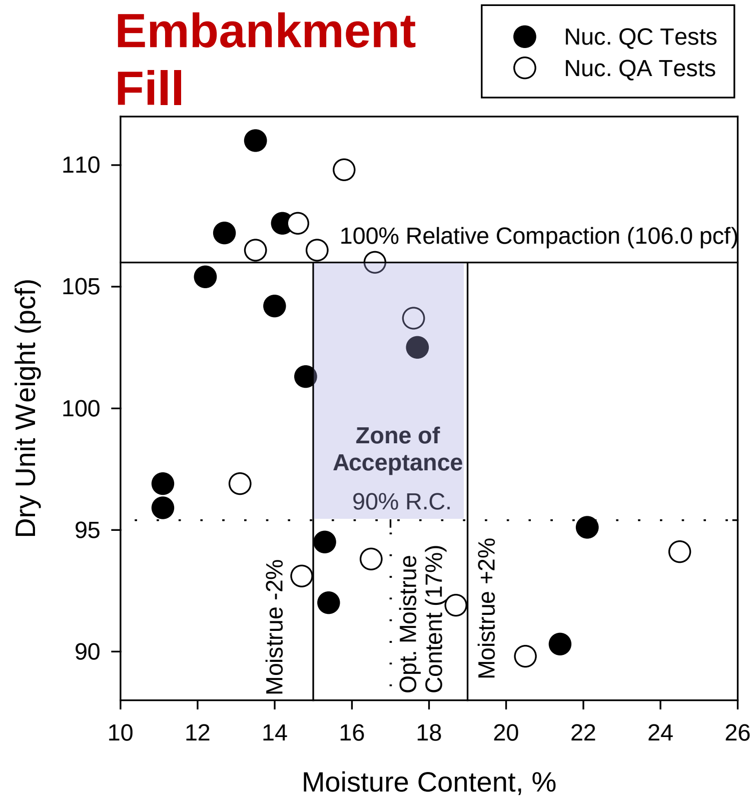


Intelligent Compaction 101 Video – Youtube

Box Culvert Backfill



Embankment Fill

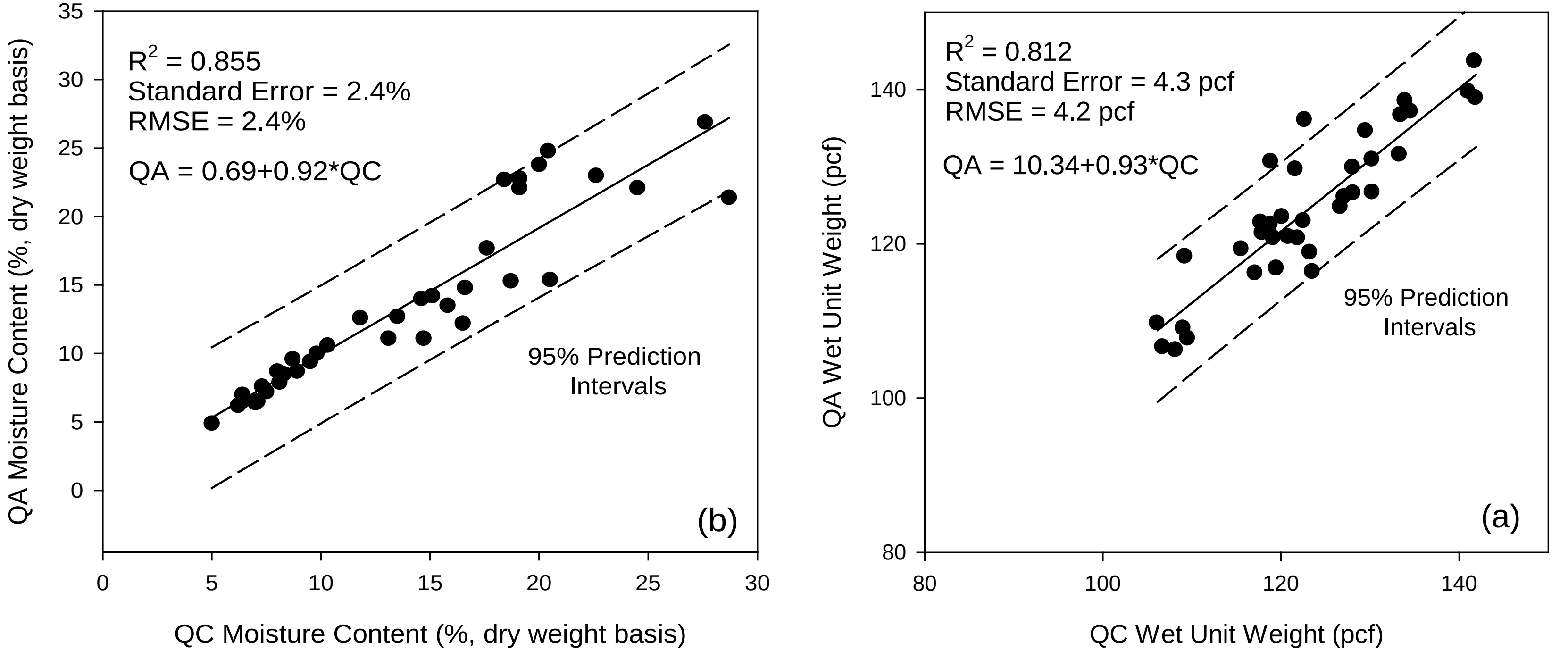


White, D.J., Vennapusa, P. (2013). “Missouri Hwy 141 – Embankment, Box Culvert, and MSE Wall Fill – August 2010.” *Intelligent Compaction Brief,* Technology Transfer for Intelligent Compaction Consortium (TTICC), Transportation Pooled Fund Study Number TPF-5(233), Iowa State University, June, Ames, IA.

— A long habit of not thinking a thing wrong, gives it a superficial appearance of being right, and raises at first a formidable outcry in defense of custom.—

(Paine, 1776).

QC/QA nuclear testing shows lack of reproducibility.

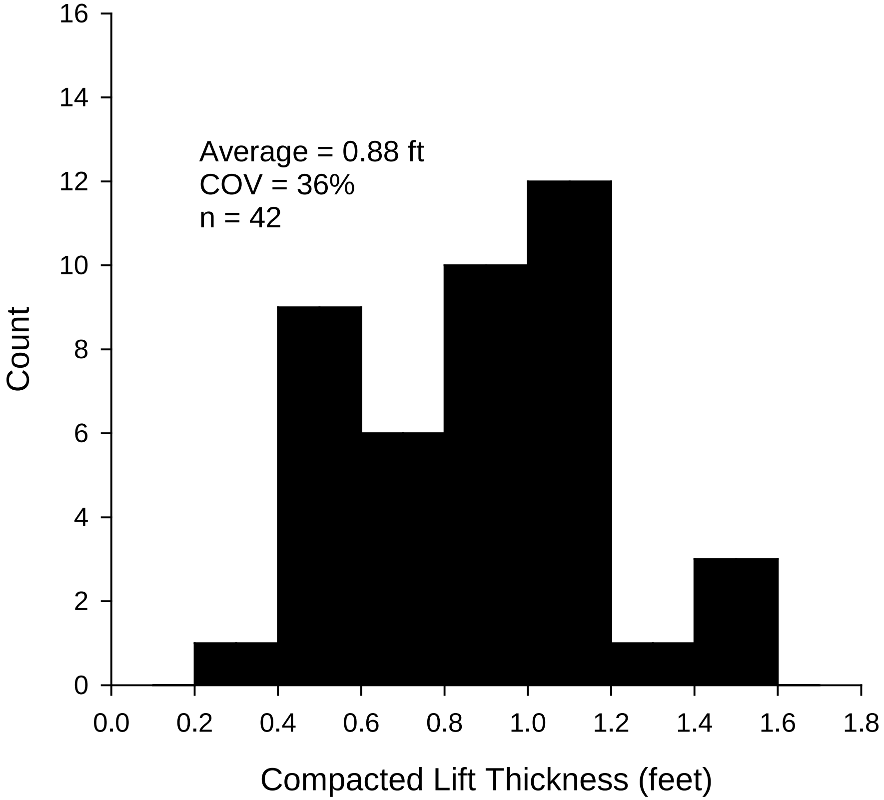


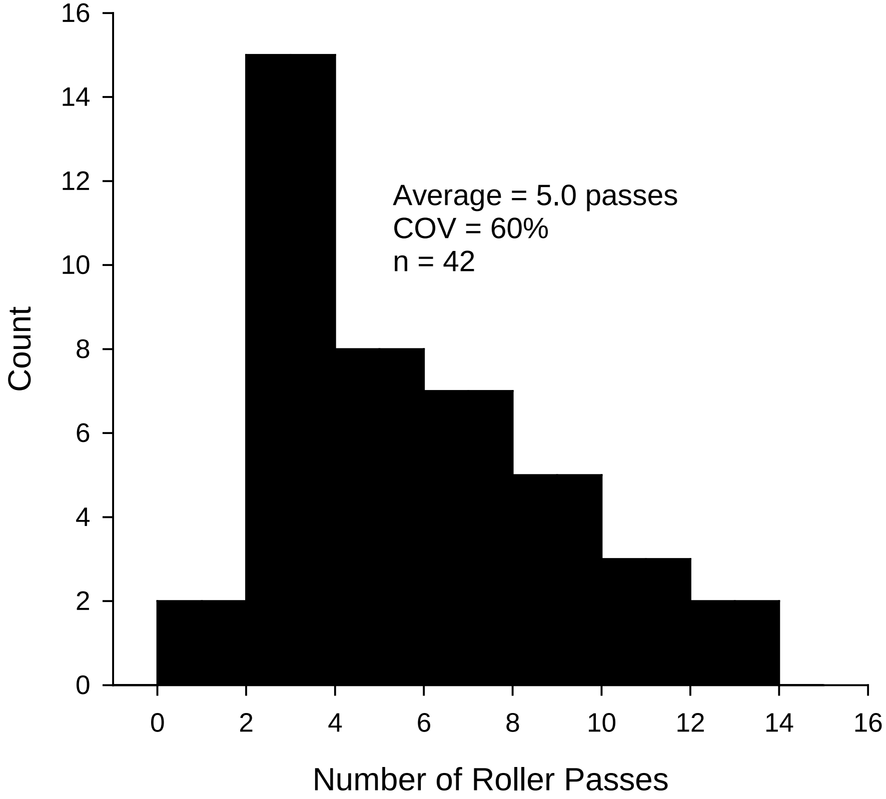
Source: White, D.J., (2013). “Earthwork Performance Specification Integrating Proof Mapping and Alternative In-situ Testing.” *A report from SHRP R07*.

– MoDOT is looking for a technology that both MoDOT and the construction industry can utilize during QC/QA that can provide information with more uniform coverage of compaction data than traditional methods with an outcome being the elimination of nuclear density testing.

(Stone, 2011)

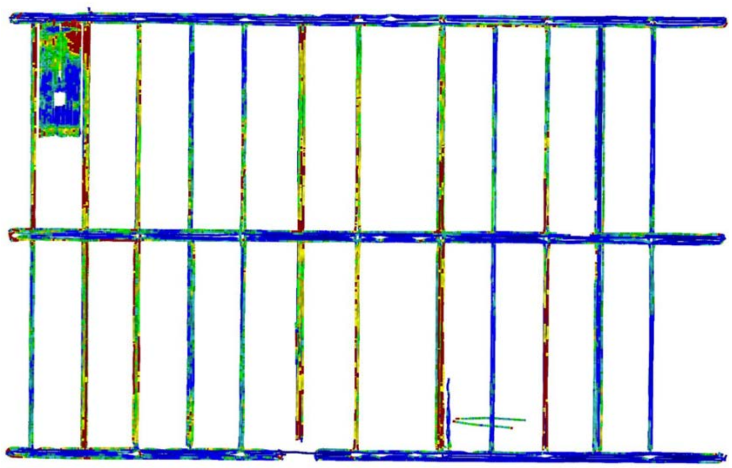
Keeping track of lift thickness and pass coverage is almost impossible.



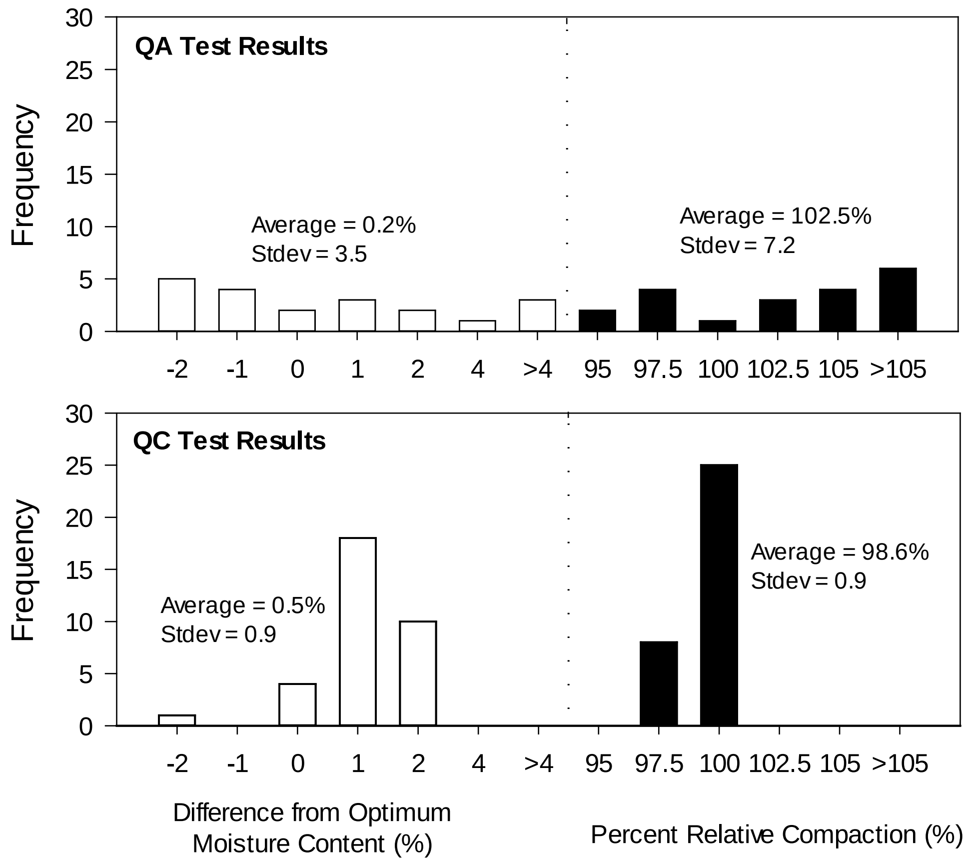


Source: White, D.J., (2013). "Earthwork Performance Specification Integrating Proof Mapping and Alternative In-situ Testing." *A report from SHRP R07*.

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 and mistakes is difficult.

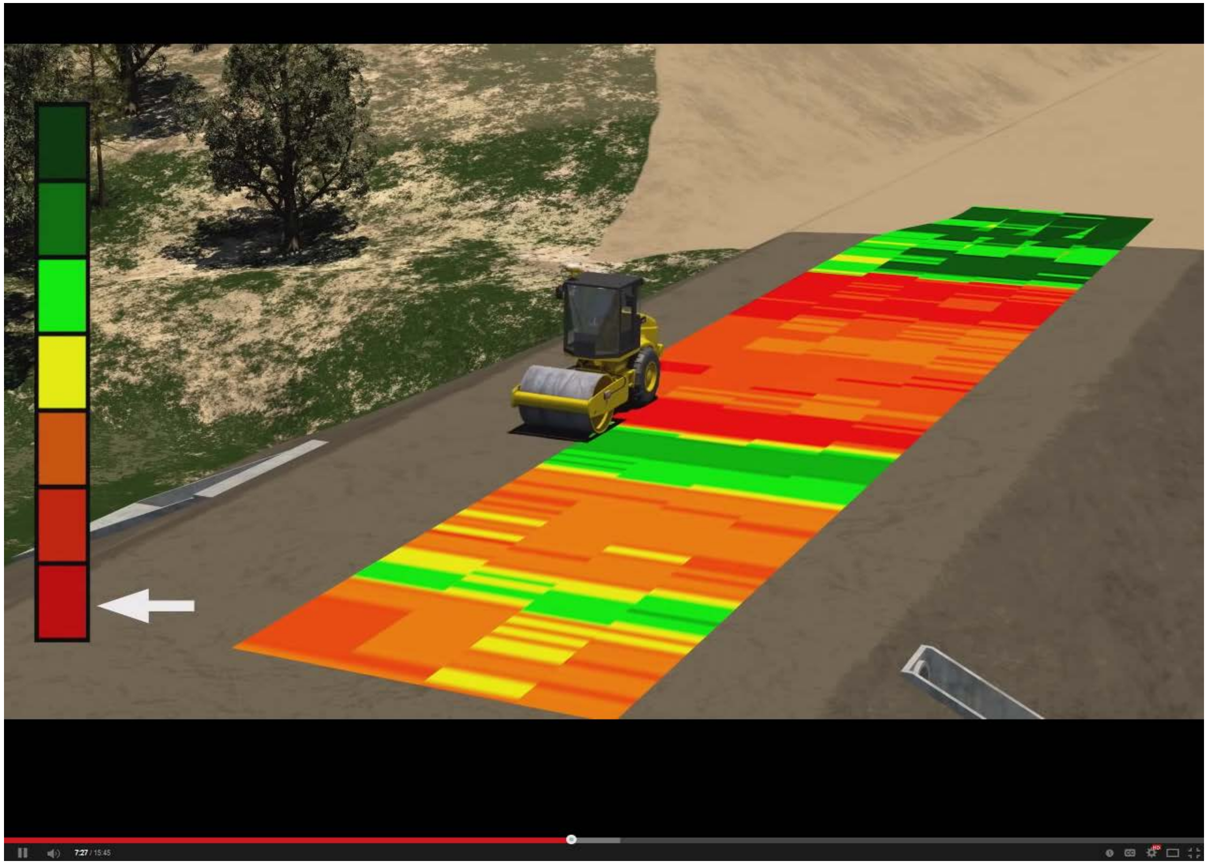
— they are an essential part of experimentation and a prerequisite for innovation. So don’t worry. —

(Harvard Business Review, 2014)

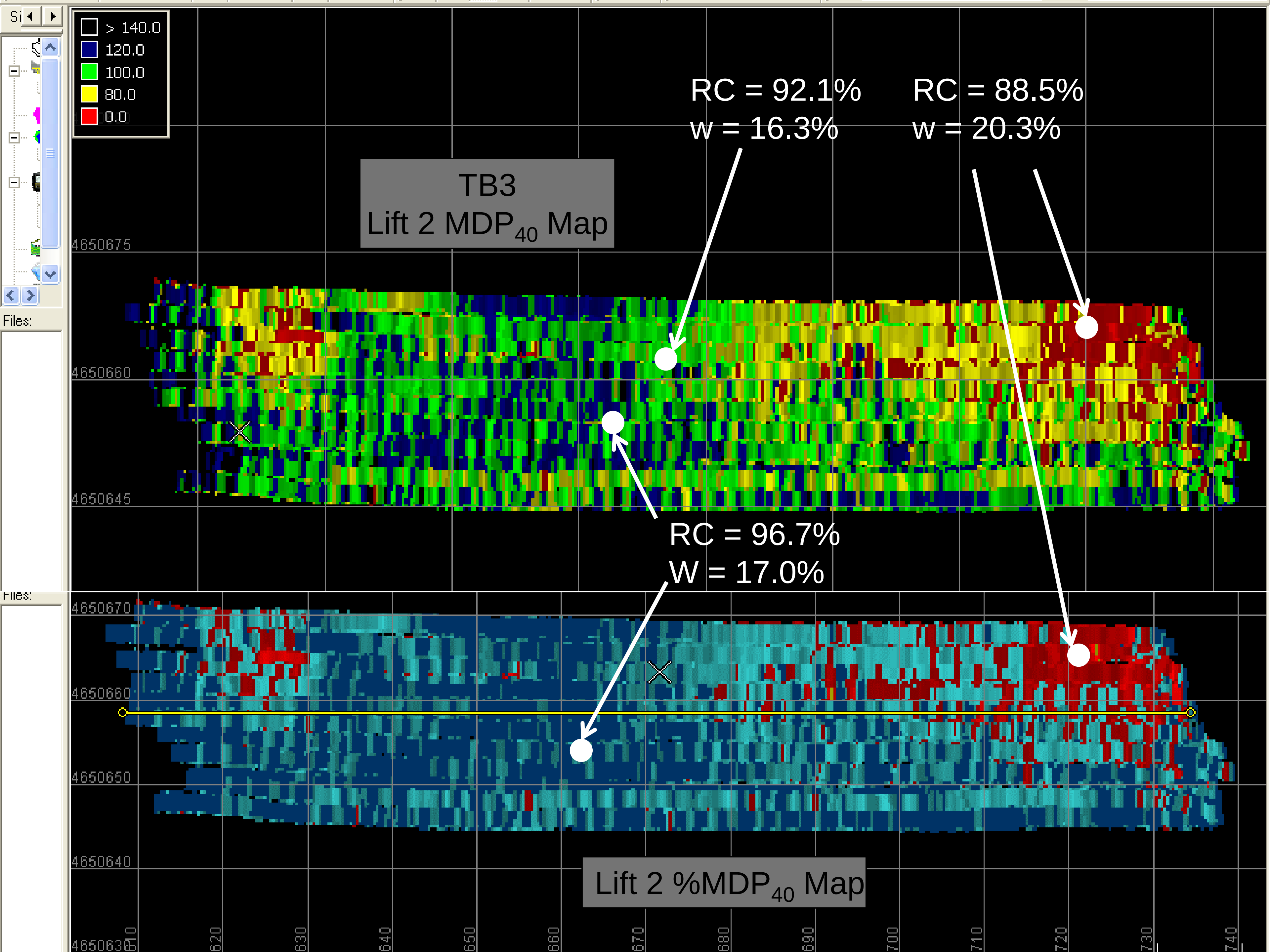
Compaction monitoring technologies can help identify problem areas in real time

Intelligent Compaction 101 Video – Youtube

Compaction monitoring technologies can help identify problem areas in real time



Intelligent Compaction 101 Video – Youtube



> 140.0
120.0
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TB3
Lift 2 MDP40 Map
RC = 92.1%
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RC = 88.5%
w = 20.3%
RC = 96.7%
W = 17.0%
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Lift 2 %MDP40 Map
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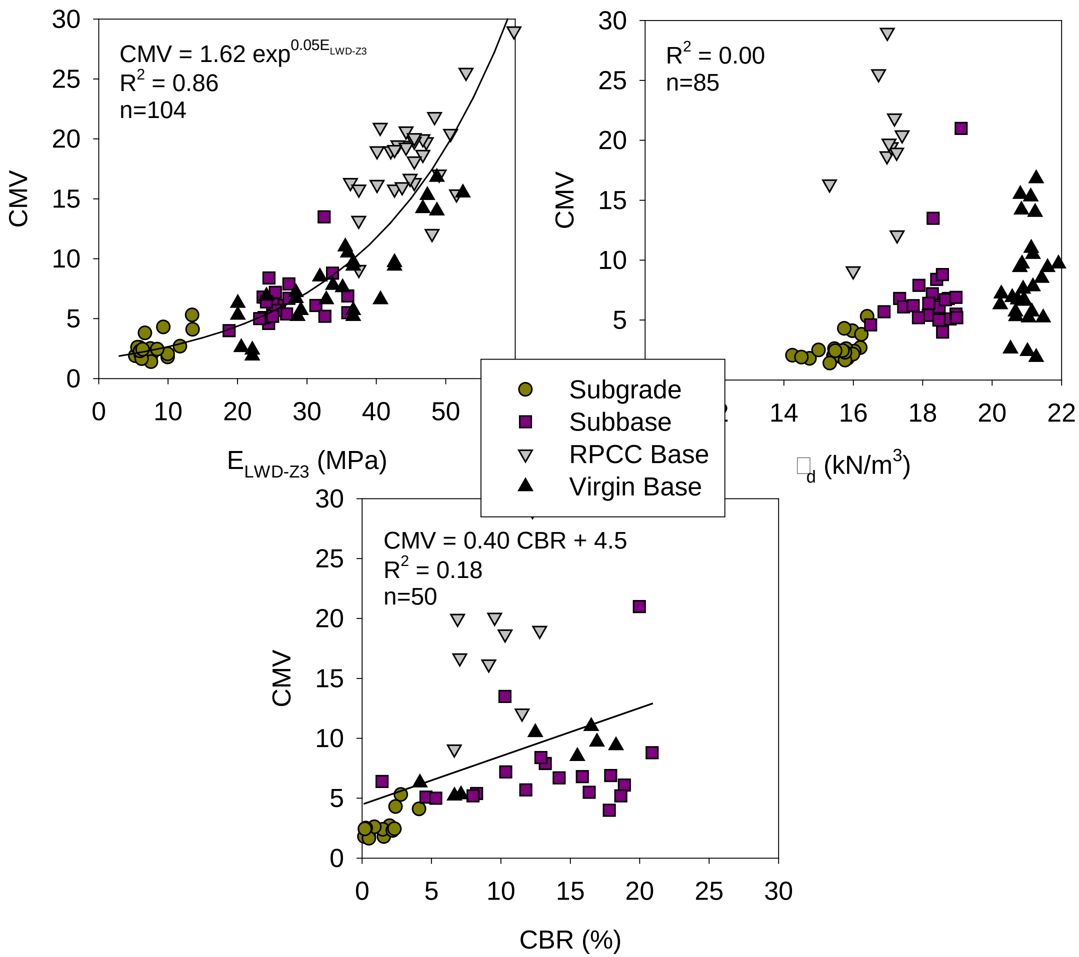
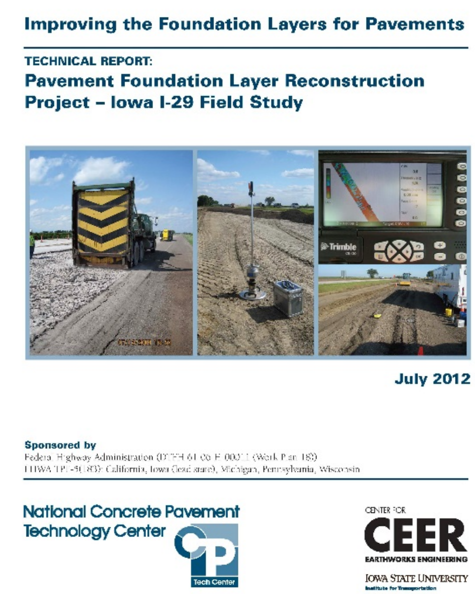
IC measurements correlate better with elastic modulus, than with compaction layer dry unit weight and CBR

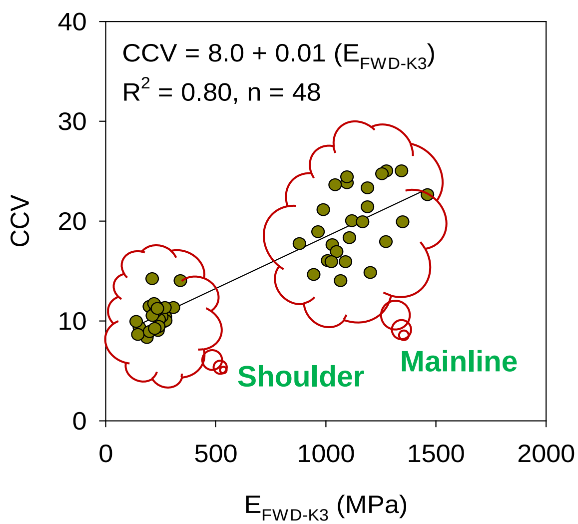


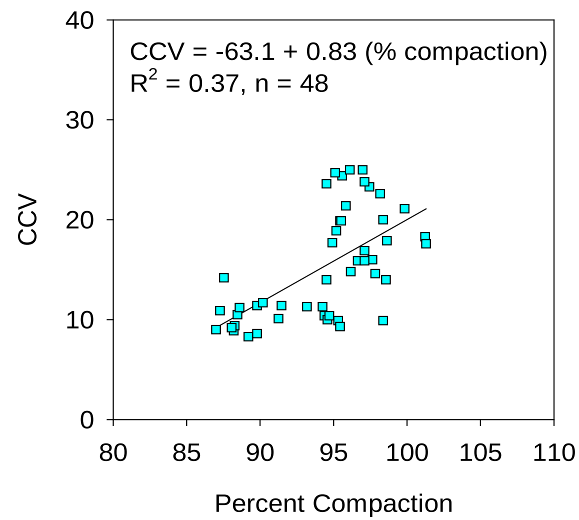


I-29 PF2 Project – White et al. (2014)

IC measurements on HMA also correlated better with FWD modulus values than with density







Stabilization can improve long-term support conditions of pavement foundation layers

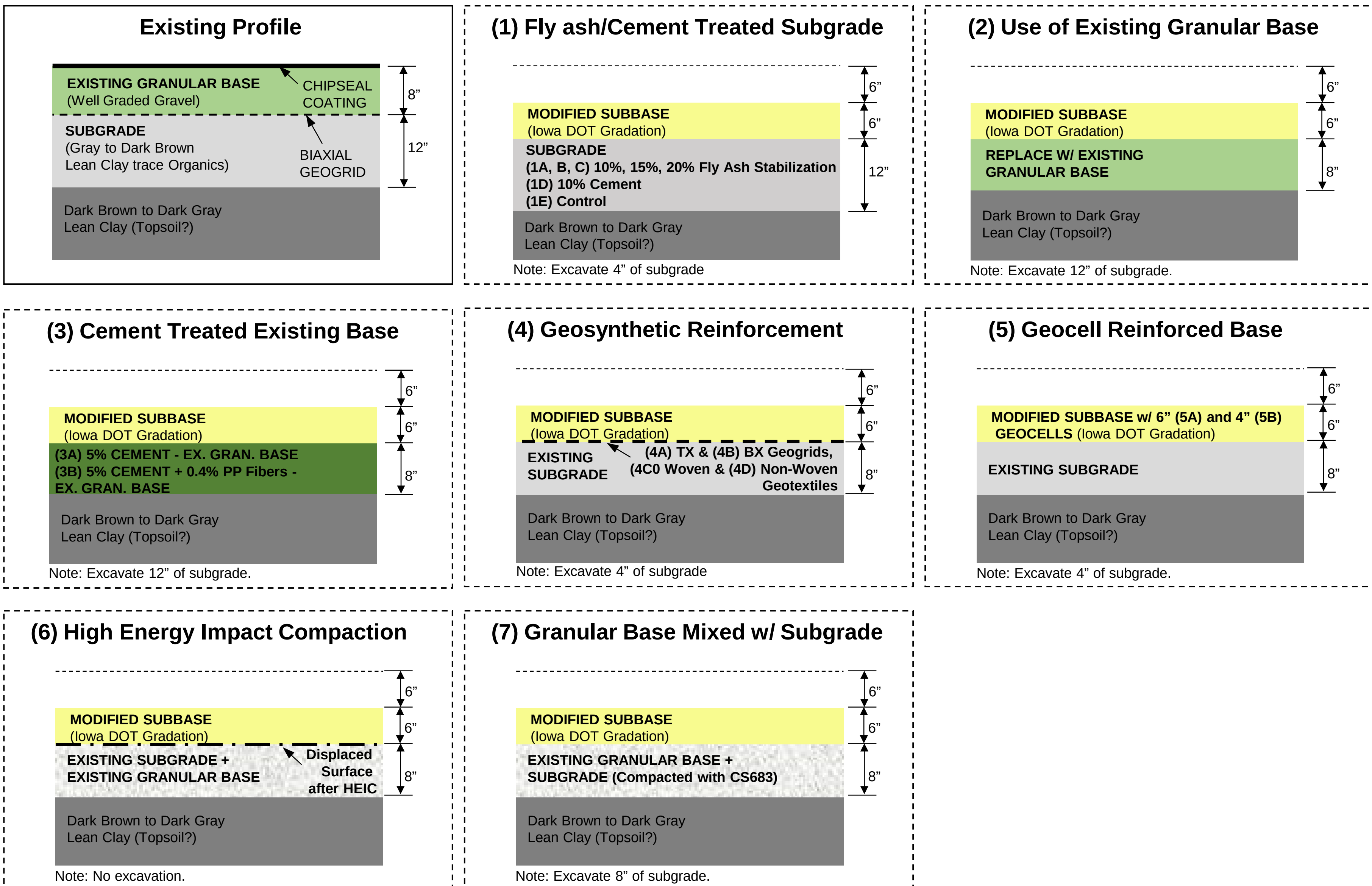
16 different test sections were designed and constructed at Central Iowa Expo Site in Boone, Iowa.

YOUTUBE Videos:

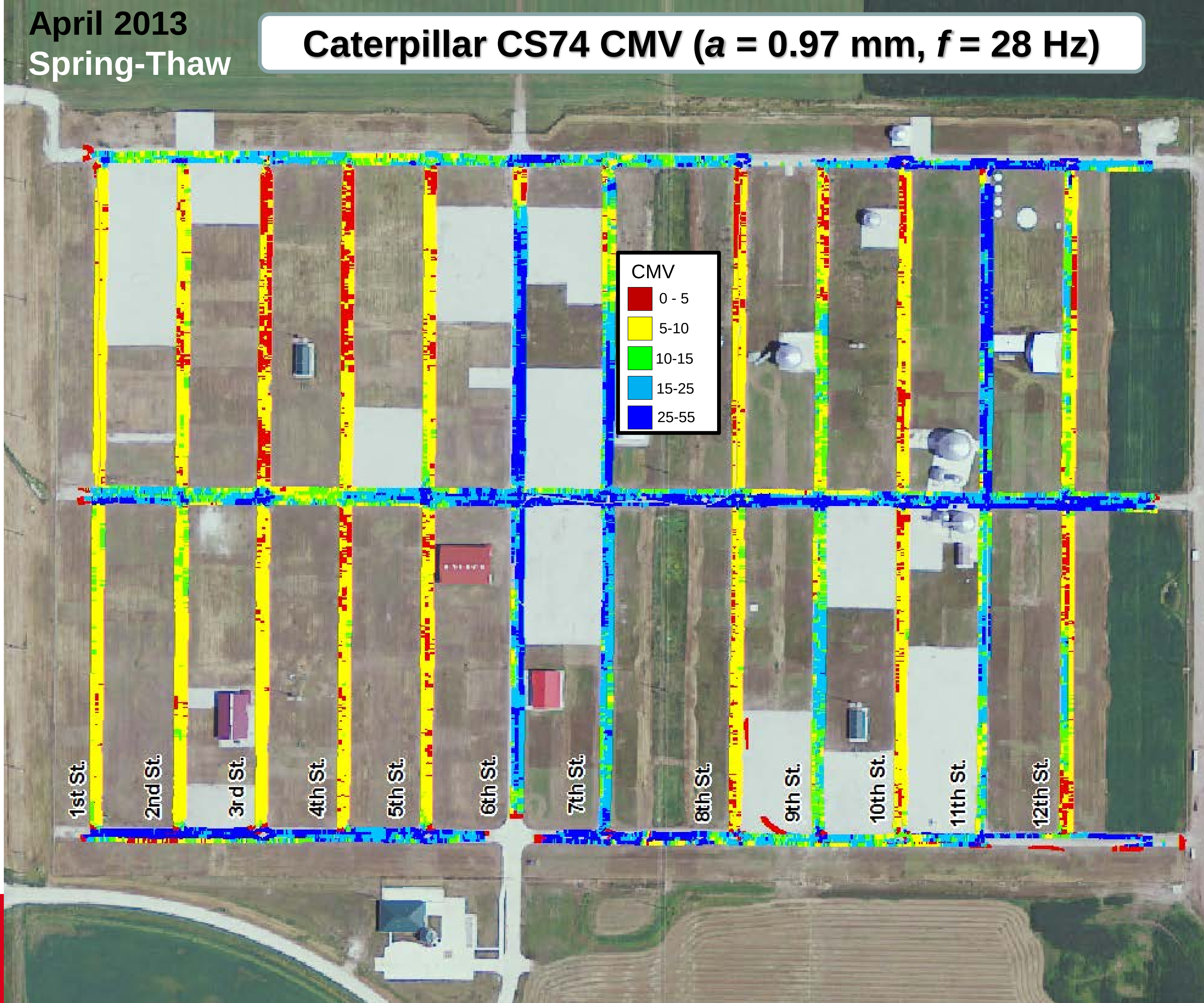
https://www.youtube.com/watch?v=qnq4fmRs6so

https://www.youtube.com/watch?v=Ks8zhj_L8Ys

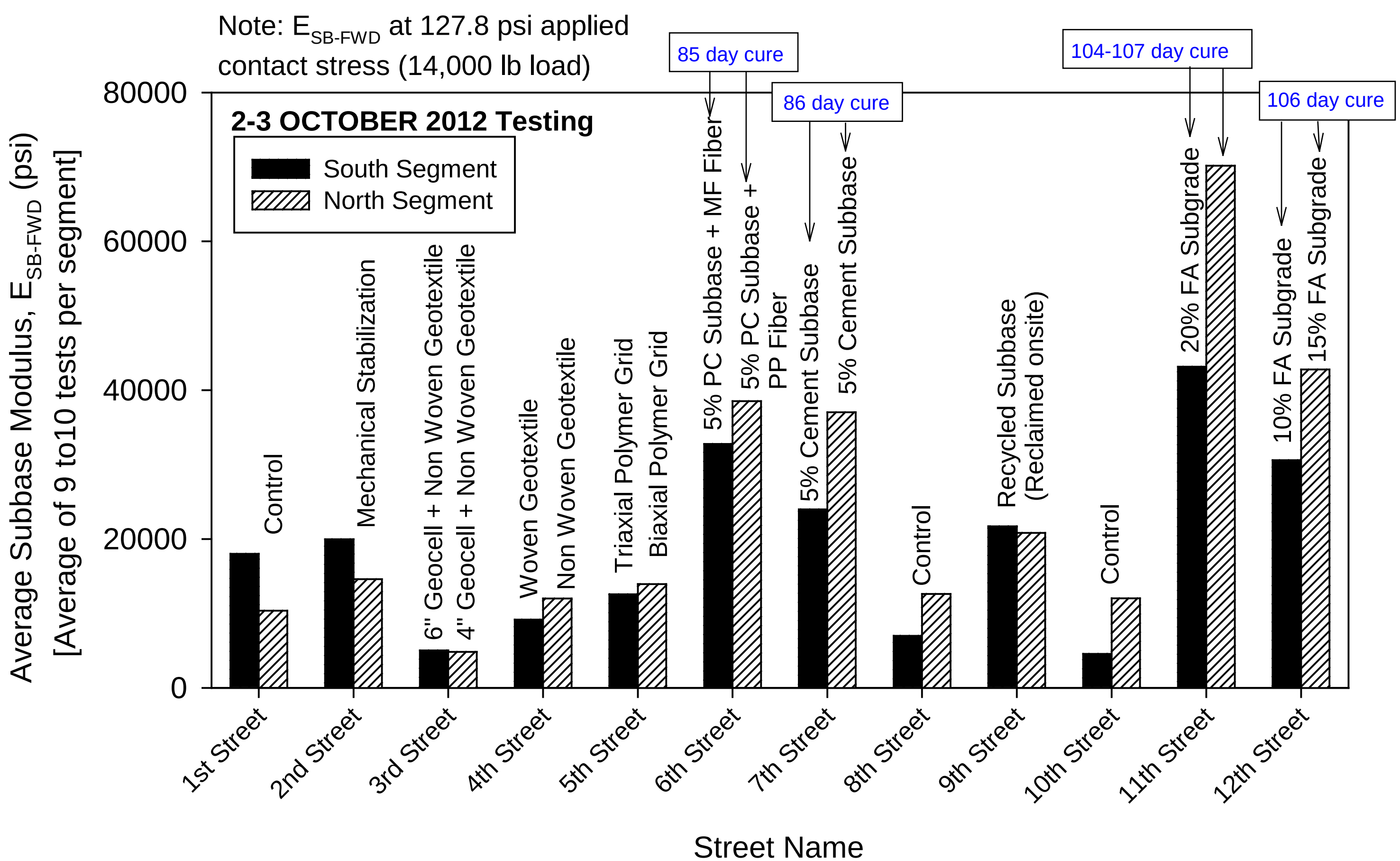
16 different test sections were designed and constructed at Central Iowa Expo Site in Boone, Iowa.



Caterpillar CS74 CMV (a = 0.97 mm, f = 28 Hz)

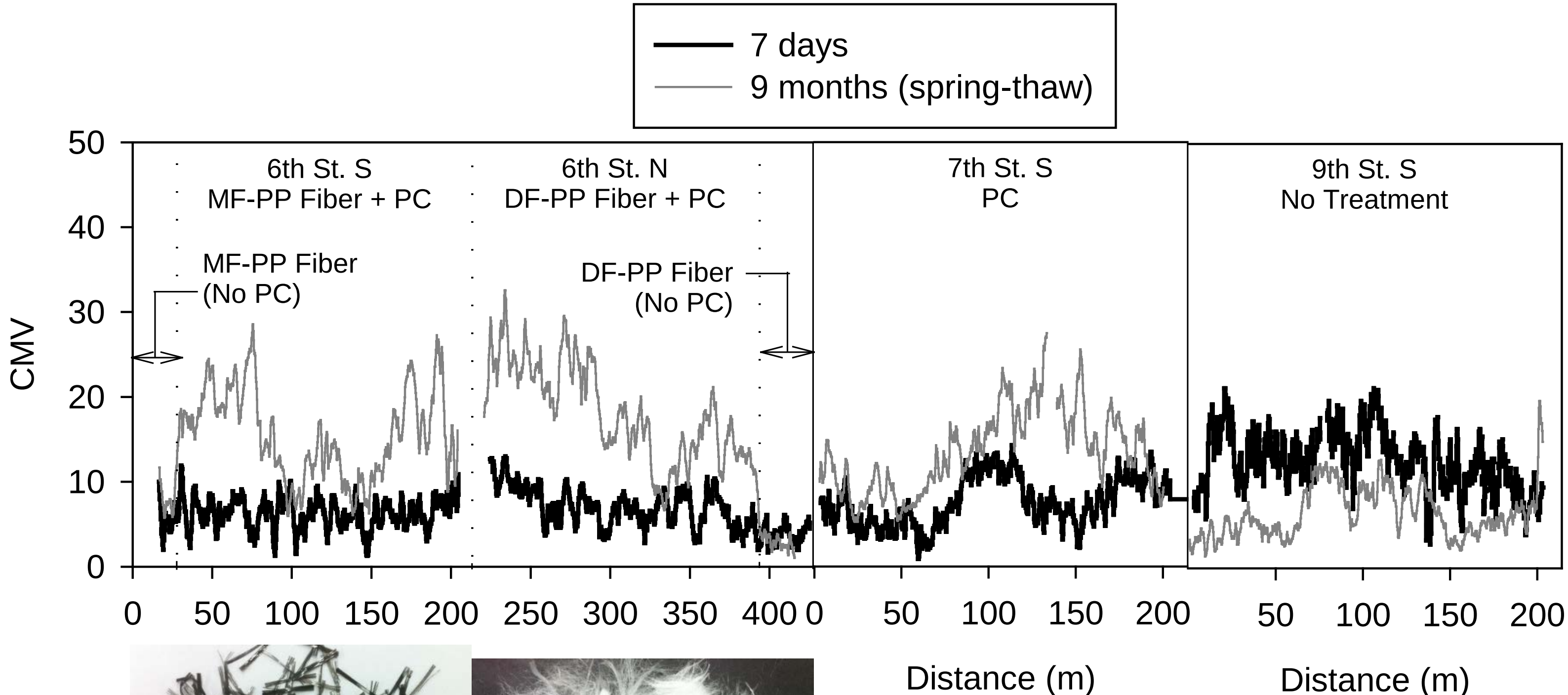


FWD testing showed higher modulus values on cement stabilized sections



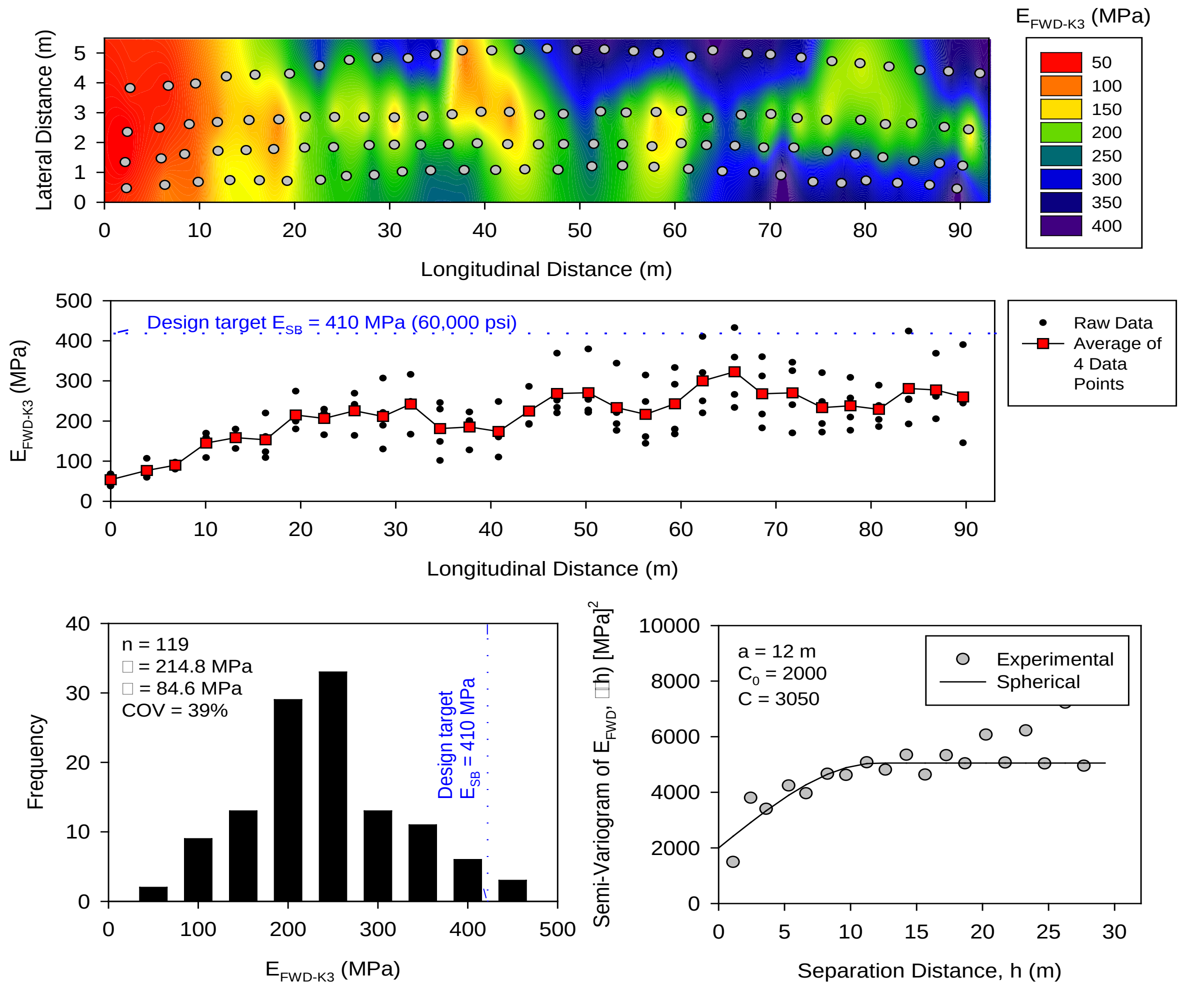
Source: White et al. (2014)

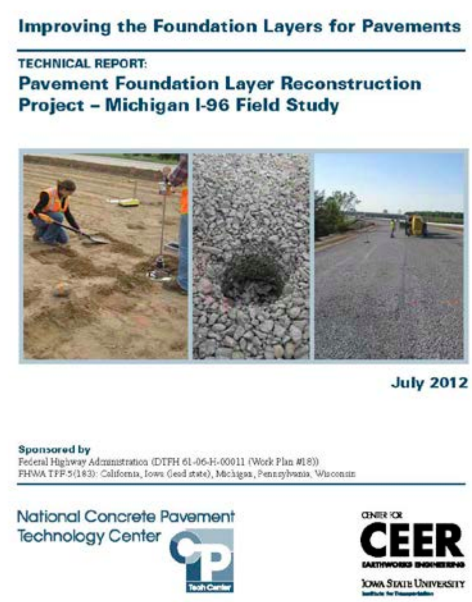
IC data showed higher values during spring-thaw than after construction in areas with PC and PC with fibers



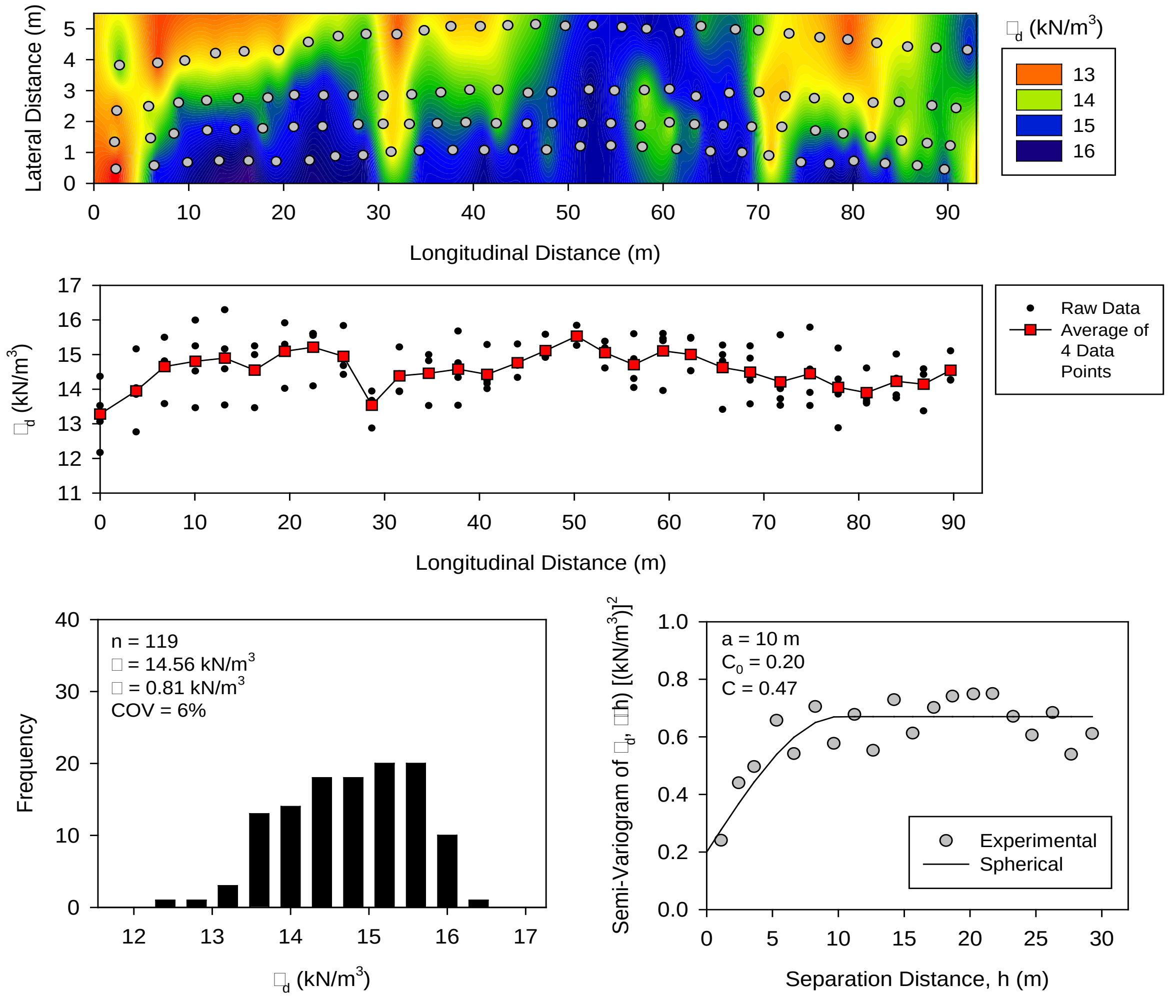
Source: White et al. (2014)

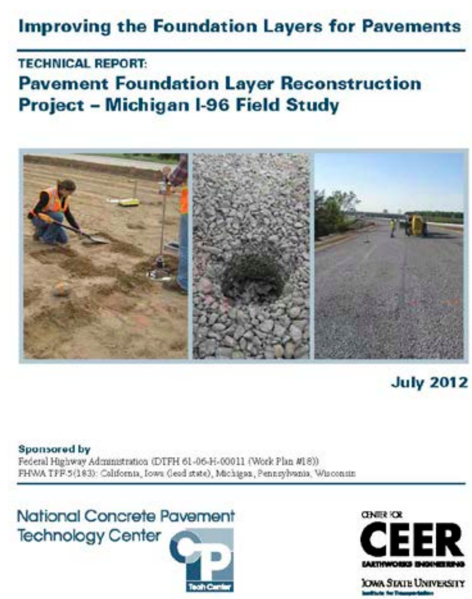
Cement treated base material (with dense-graded aggregate) showed significant spatial variability in modulus

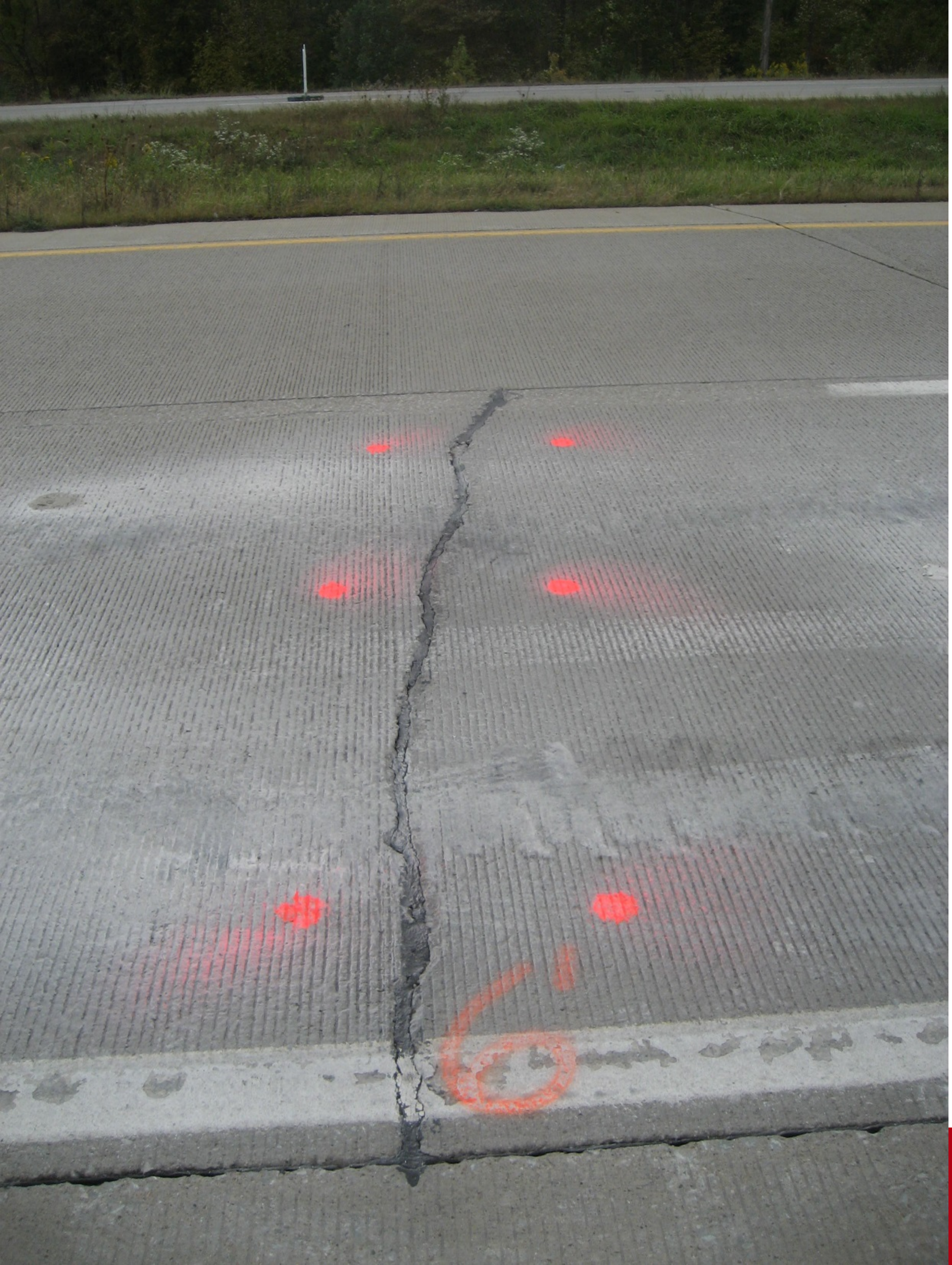




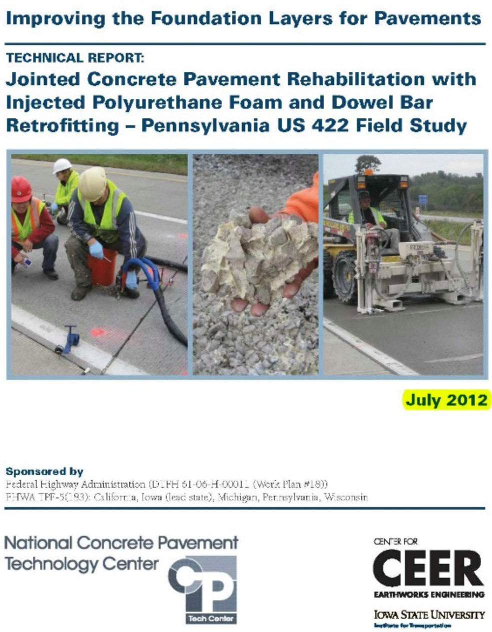
Variability in dry density is low and does not match well with variations in modulus







US422 Pavement Rehabilitation using Injected Polyurethane Foam


Improving the Foundation Layers for Pavements

TECHNICAL REPORT:

Jointed Concrete Pavement Rehabilitation with Injected Polyurethane Foam and Dowel Bar Retrofitting – Pennsylvania US 422 Field Study

July 2012

Sponsored by

Federal Highway Administration (DTFH 61-06-H-00011 (Work Plan #18))

FHWA TPF-5(183): California, Iowa (lead state), Michigan, Pennsylvania, Wisconsin

National Concrete Pavement Technology Center

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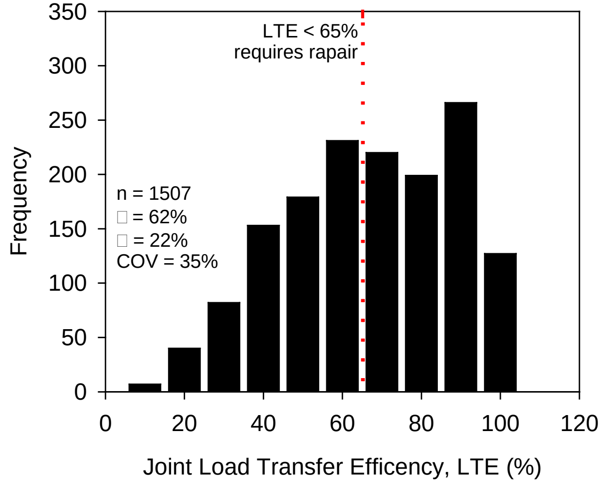
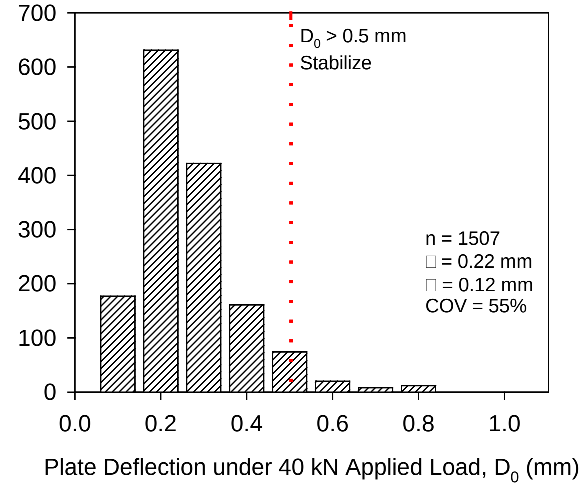
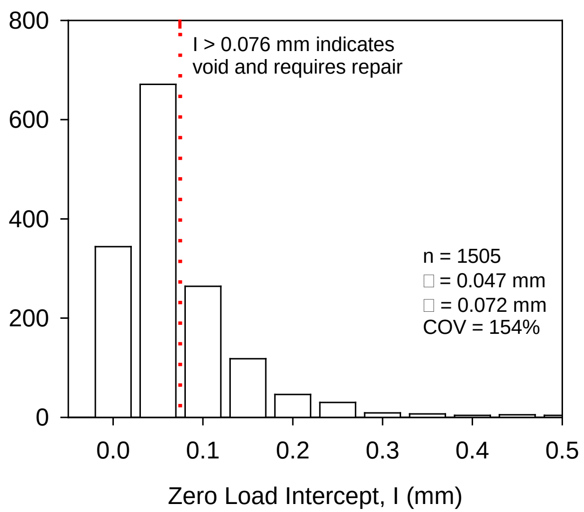
Penn DOT used FWD testing to determine locations for foam stabilization

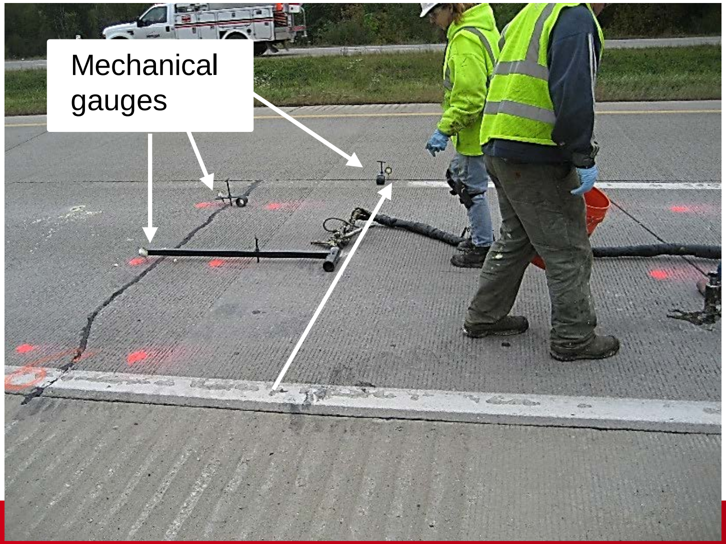


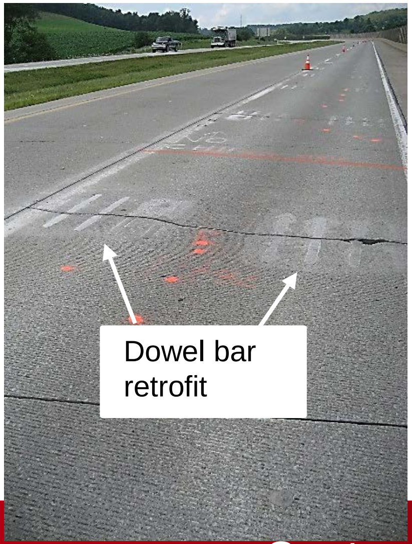




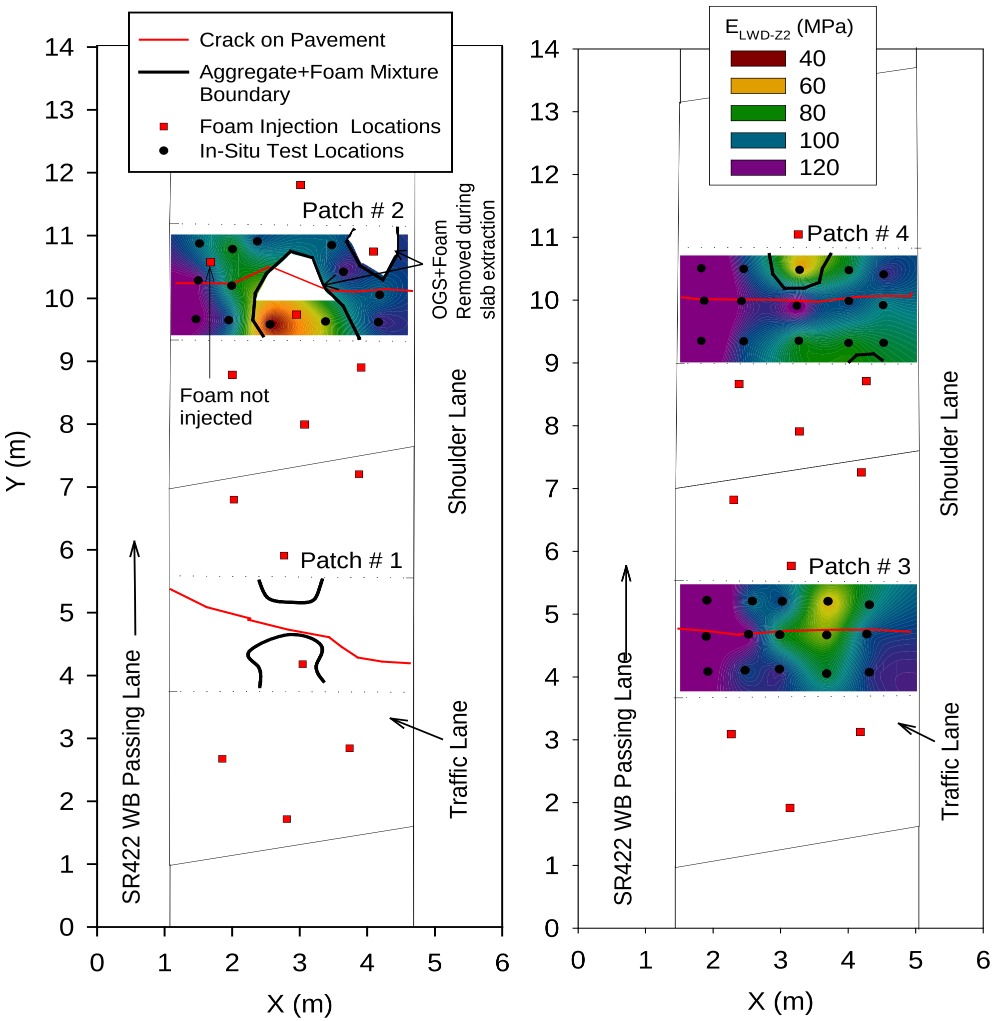
Joints with LTE < 65%, D_0 > 0.5 mm, and I > 0.076 mm require joint patching and stabilization, and all joints with I > 0.076 mm require stabilization only

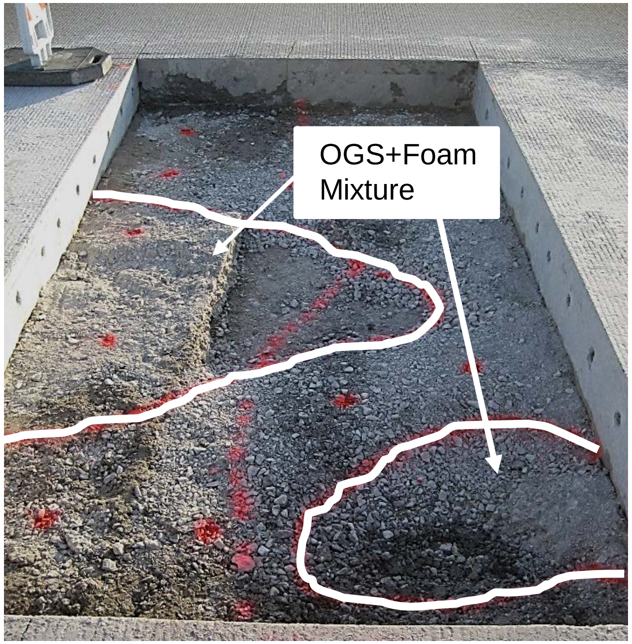
Foam was injected under pressure and pavement lifting was monitored to reduce faulting at cracks



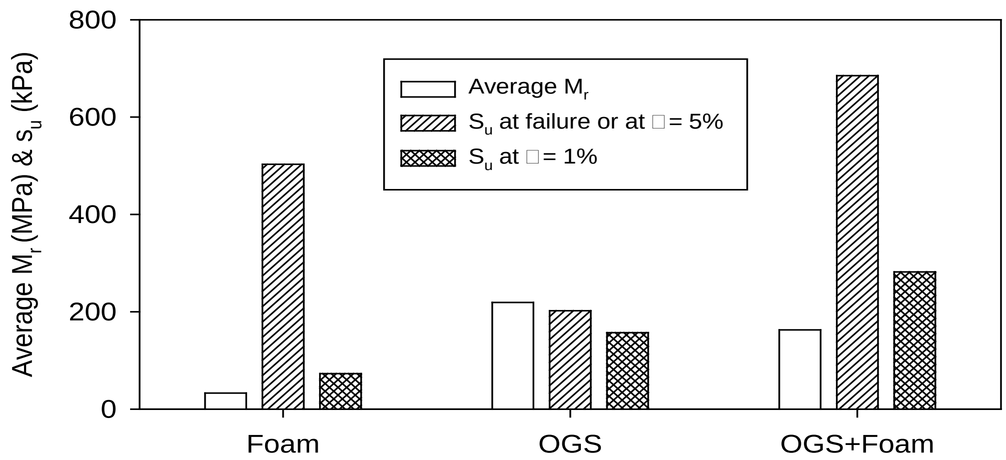


Testing in patching areas showed variable stiffness conditions due to non-uniform foam penetration





Foam stabilized subbase showed high shear strength but lower modulus than unstabilized subbase

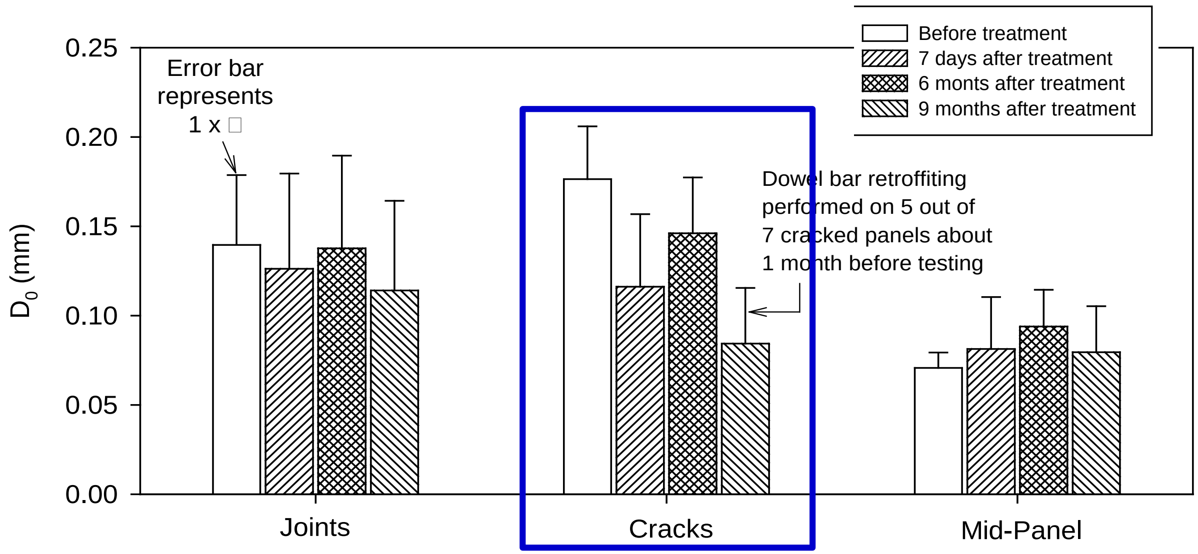


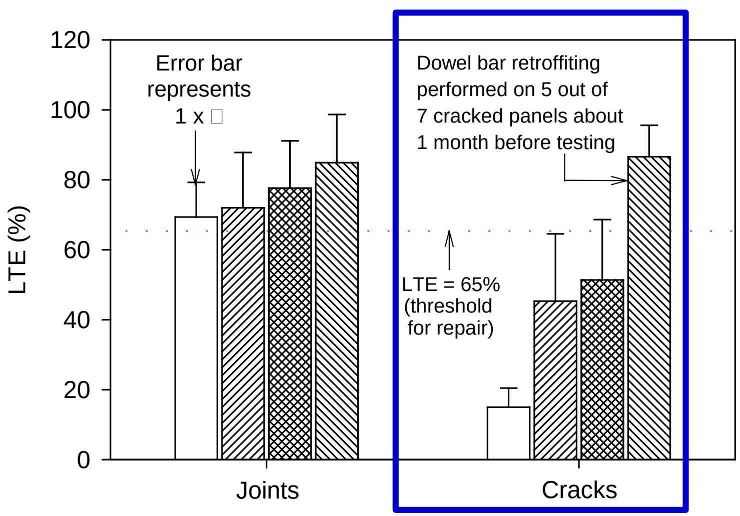
Lab Measurements

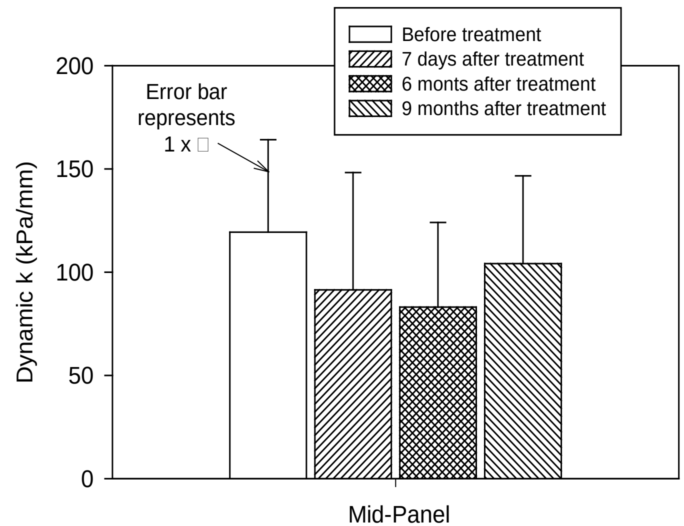
Material	Measurement	Average	Std. Dev.	COV (%)
OGS	E_{LWD-Z2}, MPa	106	21	**20**
	CBR_{OGS}, %	20	4	**20**
OGS + Foam	E_{LWD-Z2}, MPa	53	17	**32**
	CBR_{OGS}, %	**DCP refusal at surface (< 1mm/blow)**		

Field Measurements

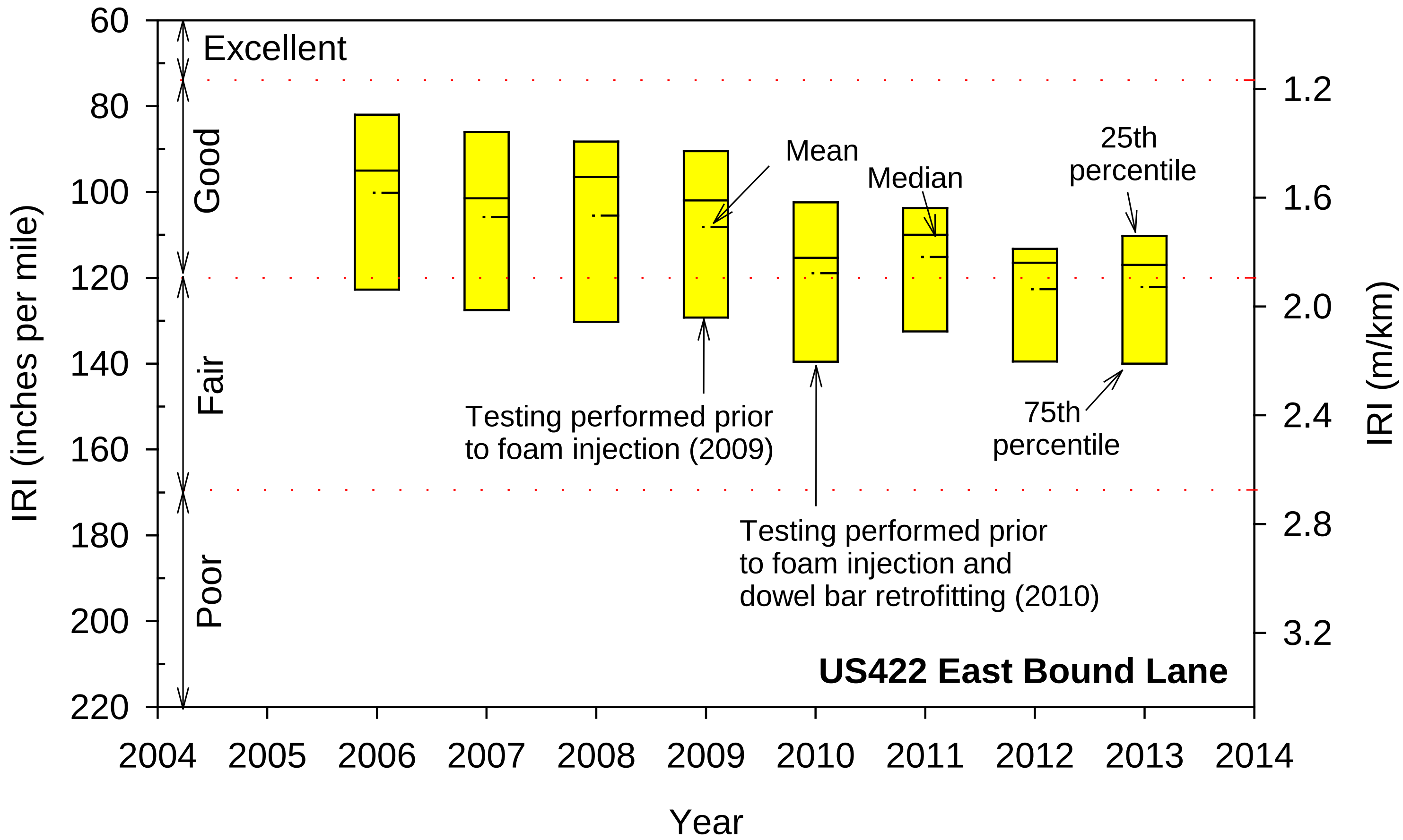
FWD testing after treatment showed statistically significant improvement near cracks, but not at joints or mid-panel



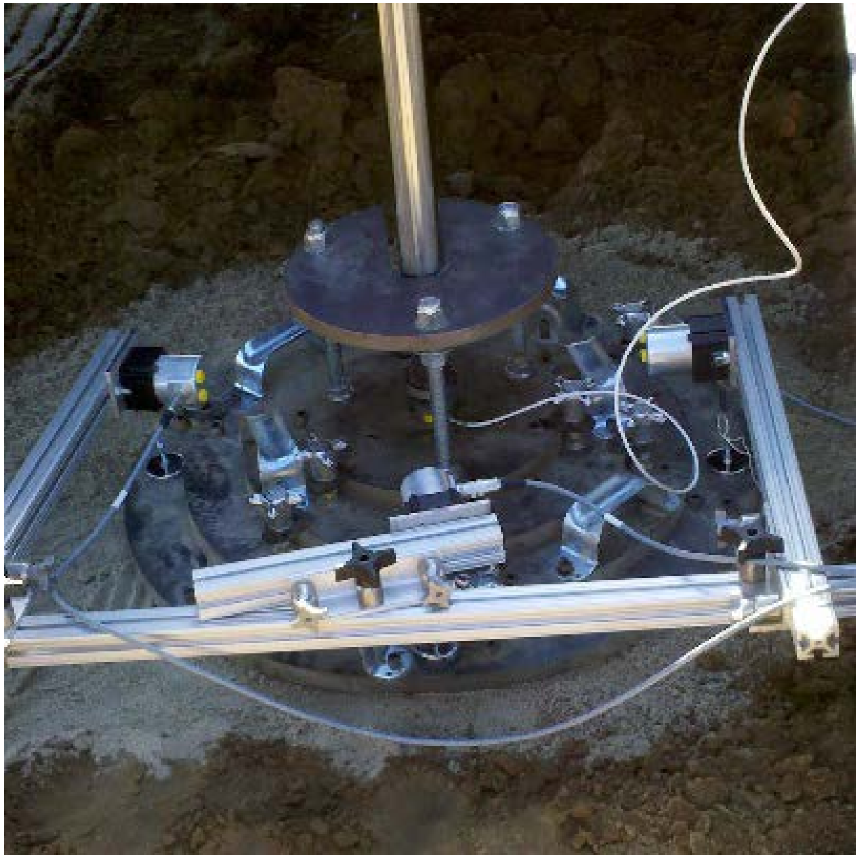




IRI testing indicated reduced ride quality after foam stabilization but maintained at the same level for 3 yrs

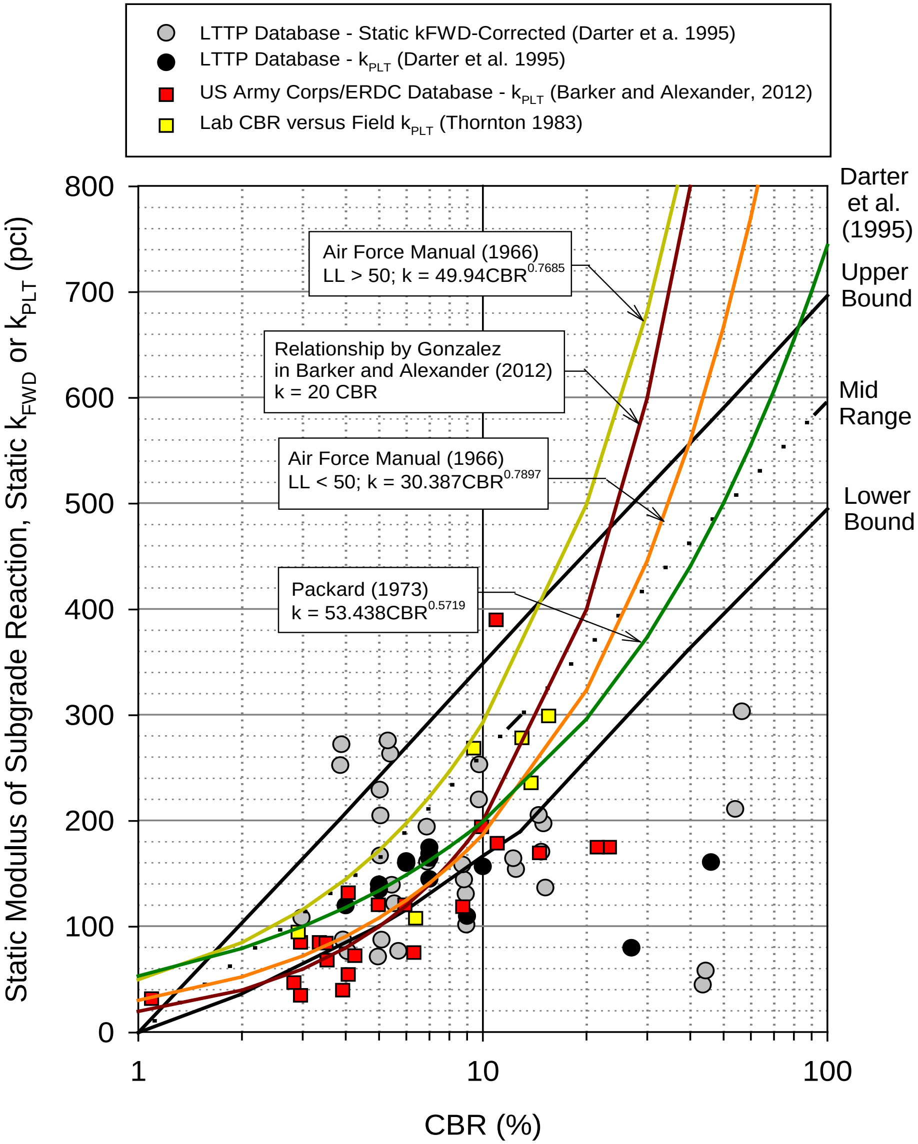


Stiffness or Modulus is a key design parameter in pavement design



Modulus of subgrade reaction ***k*-value** is determined from 30-in diameter plate load test

Empirical relationships published show significant variability in *k* estimated from FWD vs. PLT vs. CBR

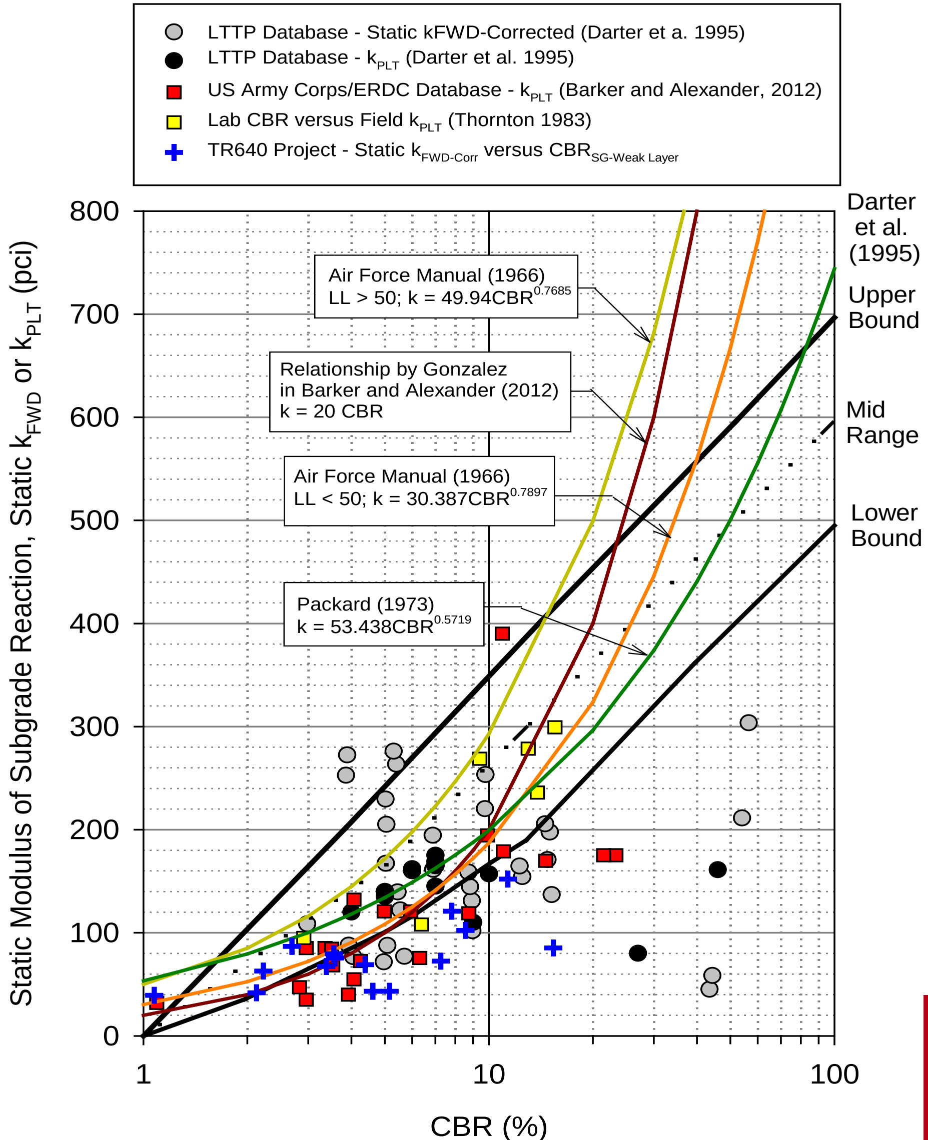


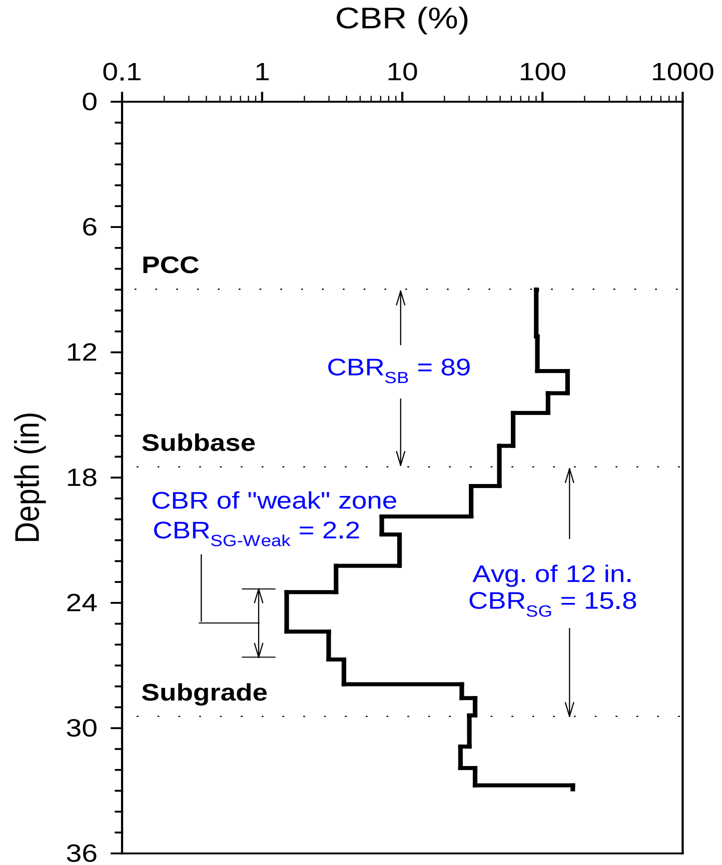
Results from

- LTPP Studies (Darter et al. 1995),
- Army Corps of Engineers (Barker and Alexander 2012),
- Thornton (1983)
- TR640 Study on Low Volume PCC Pavements (White and Vennapusa 2014)

Source: White and Vennapusa (2014)

CBR of a minimum 3 in. thick "weak" zone in top 18 in. subgrade relates strongly with *k* value from FWD

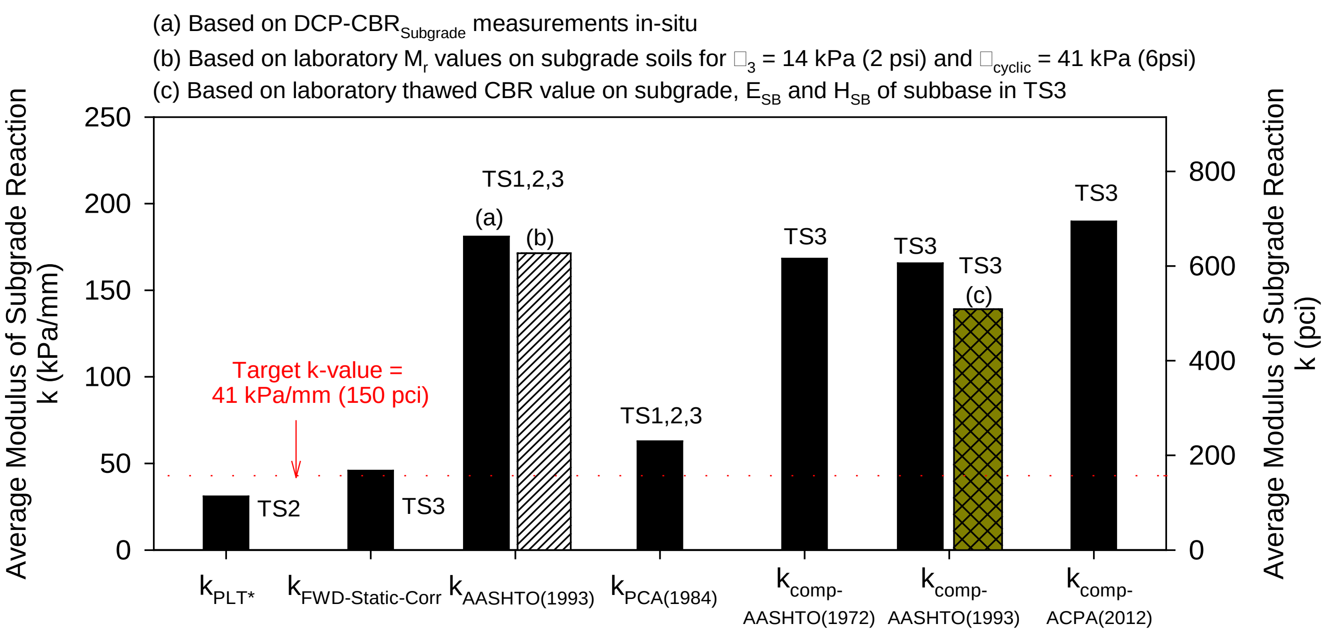




Source: White and Vennapusa (2014)

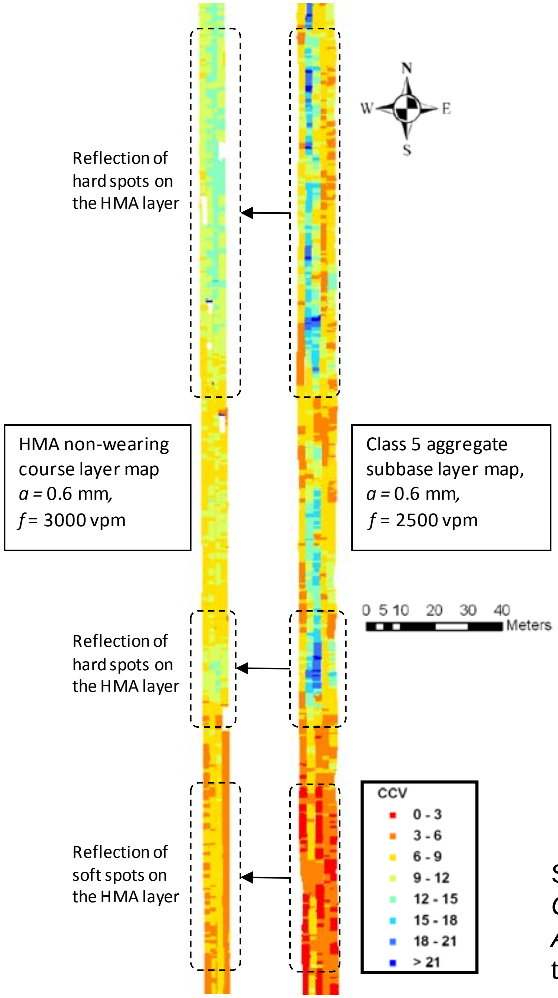
Center for Earthworks Engineering Research

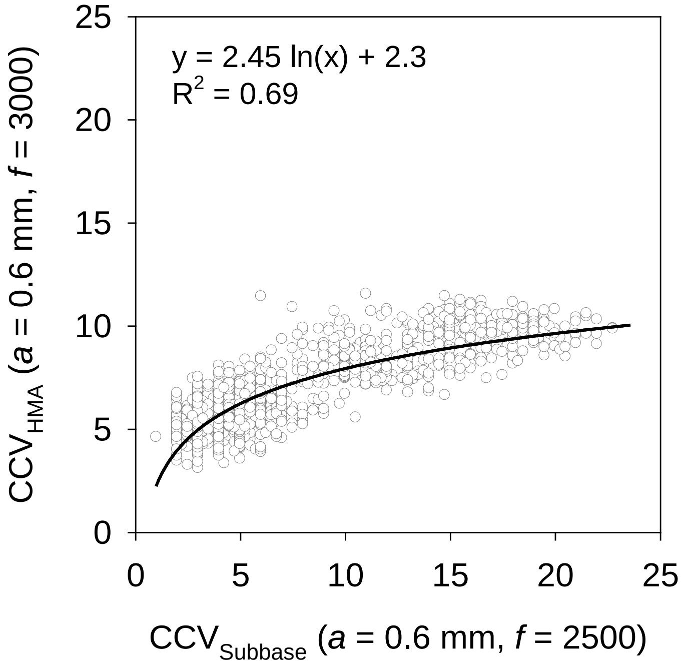
Comparison between *k* determined from PLT, FWD, DCP, and lab M_r testing revealed significant variability



NOTE: k_{comp} values are determined by accounting for subbase layer thickness and moduli values following ACPA and AASHTO design guide procedures

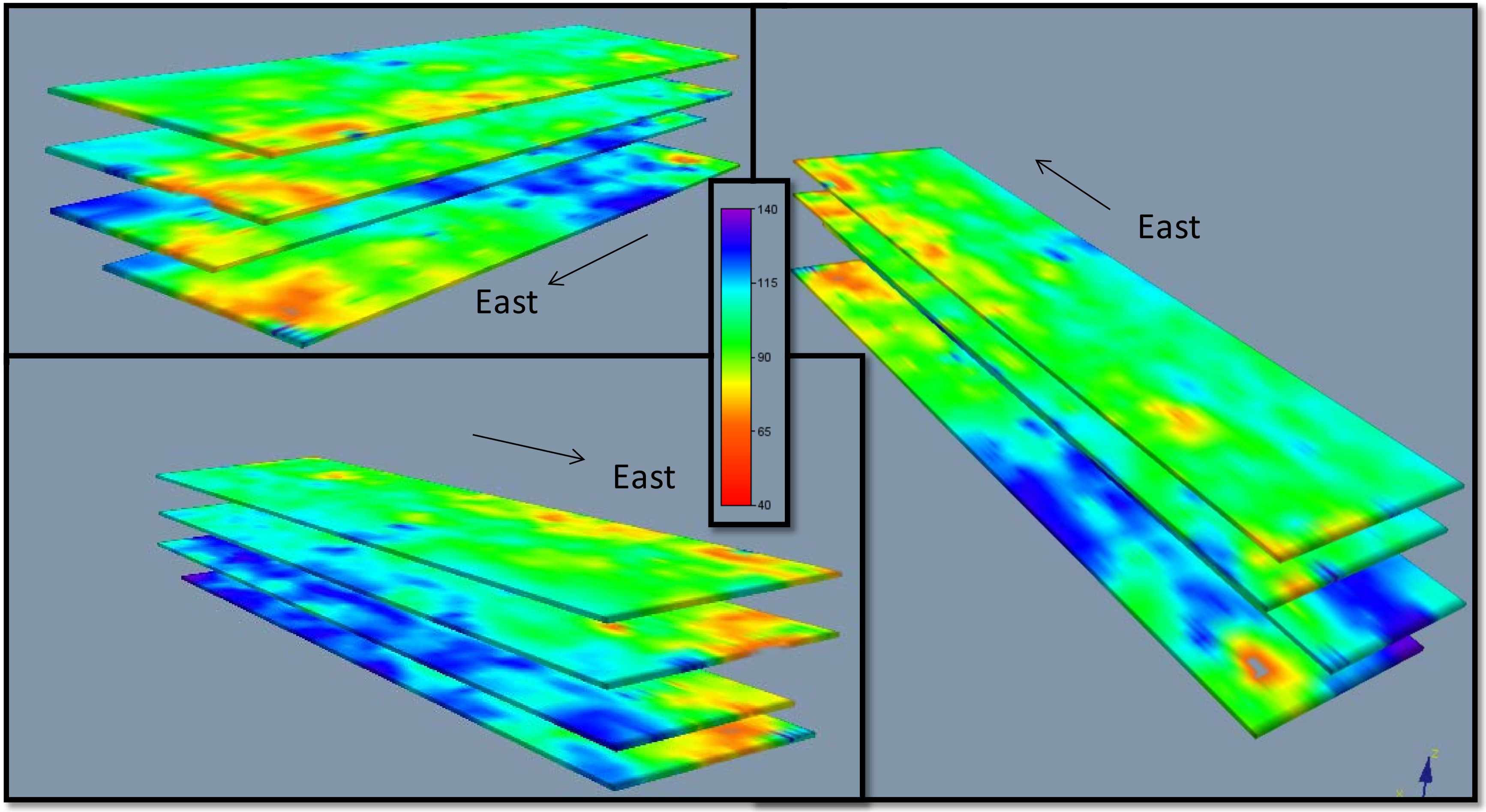
Foundation layer stiffness has a large influence on stiffness measurements over asphalt layer.





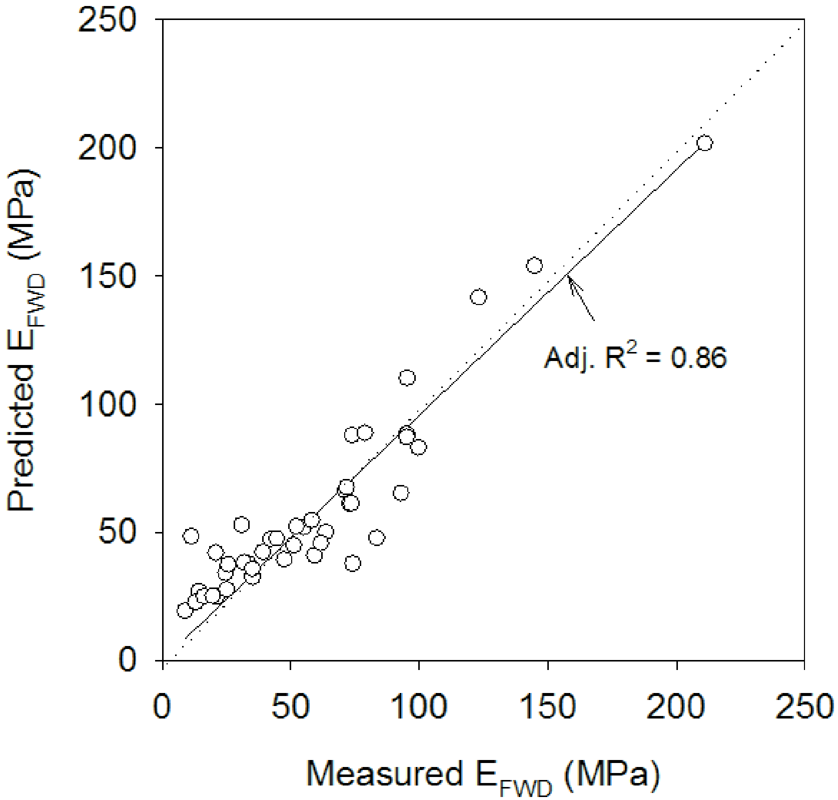
Source: White, D.J., Vennapusa, P. (2008). *Accelerated Implementation of Intelligent Compaction Monitoring Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials* TPF-5(128) – *Mn/DOT HMA IC Demonstration*, Report submitted to The Transtec Group, FHWA, June.

IC data from multiple embankment layers show that it takes multiple lifts to bridge "weak" subgrade layers



US30 Embankment Construction Project, Colo, Iowa - White et al. (2010)

“Weak” subgrade soils have a large influence on composite stiffness measurement on surface.



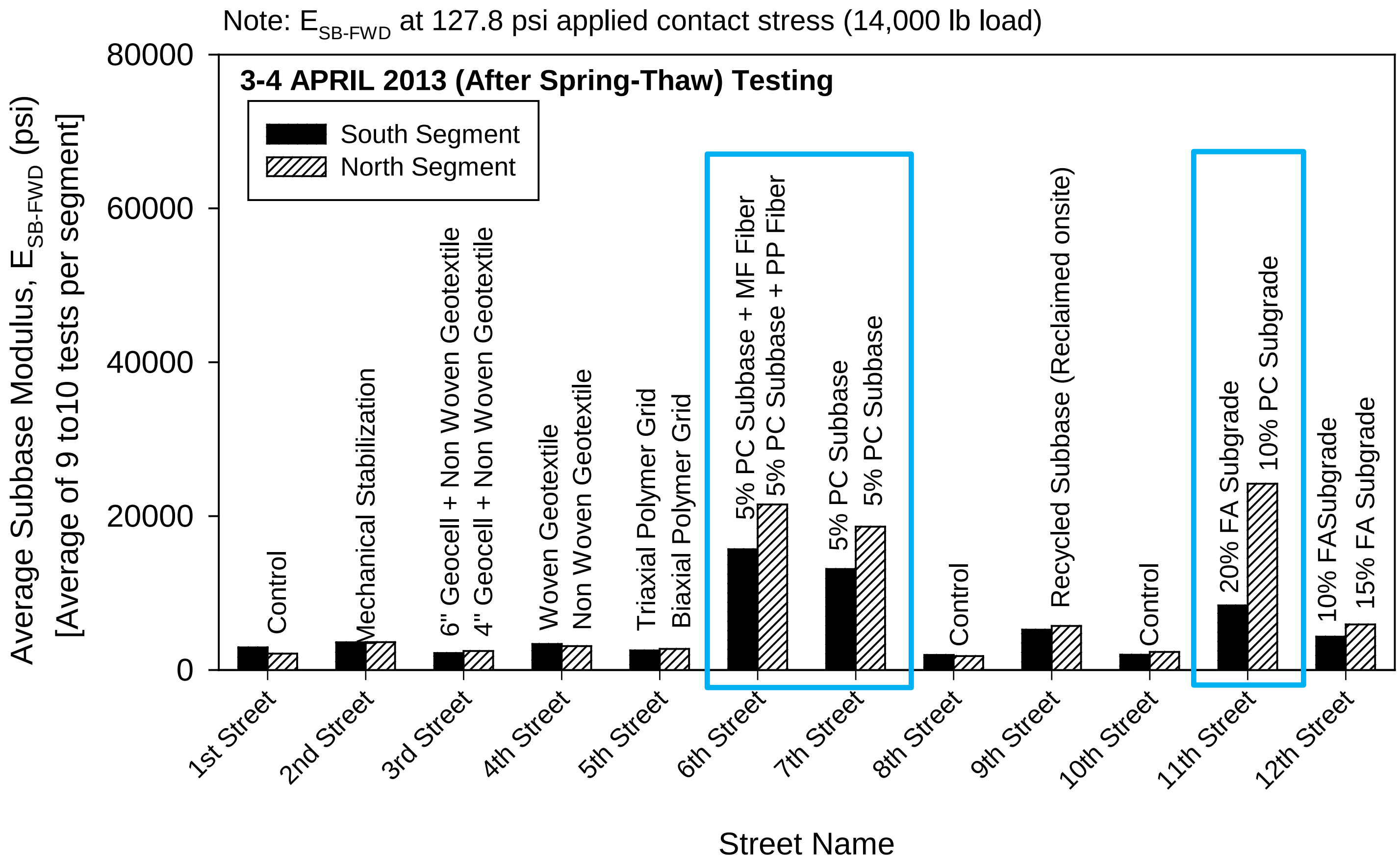
TERM	ESTIMATE	STD ERROR	t Ratio	Prob>|t|
Intercept	17.045	3.599	4.740	<0.0001
CBR_{Gravel}	0.229	0.035	6.510	<0.0001
$CBR_{Subgrade}$	1.395	0.129	10.84	<0.0001

Gravel layer – 14% influence
Subgrade layer – 86% influence

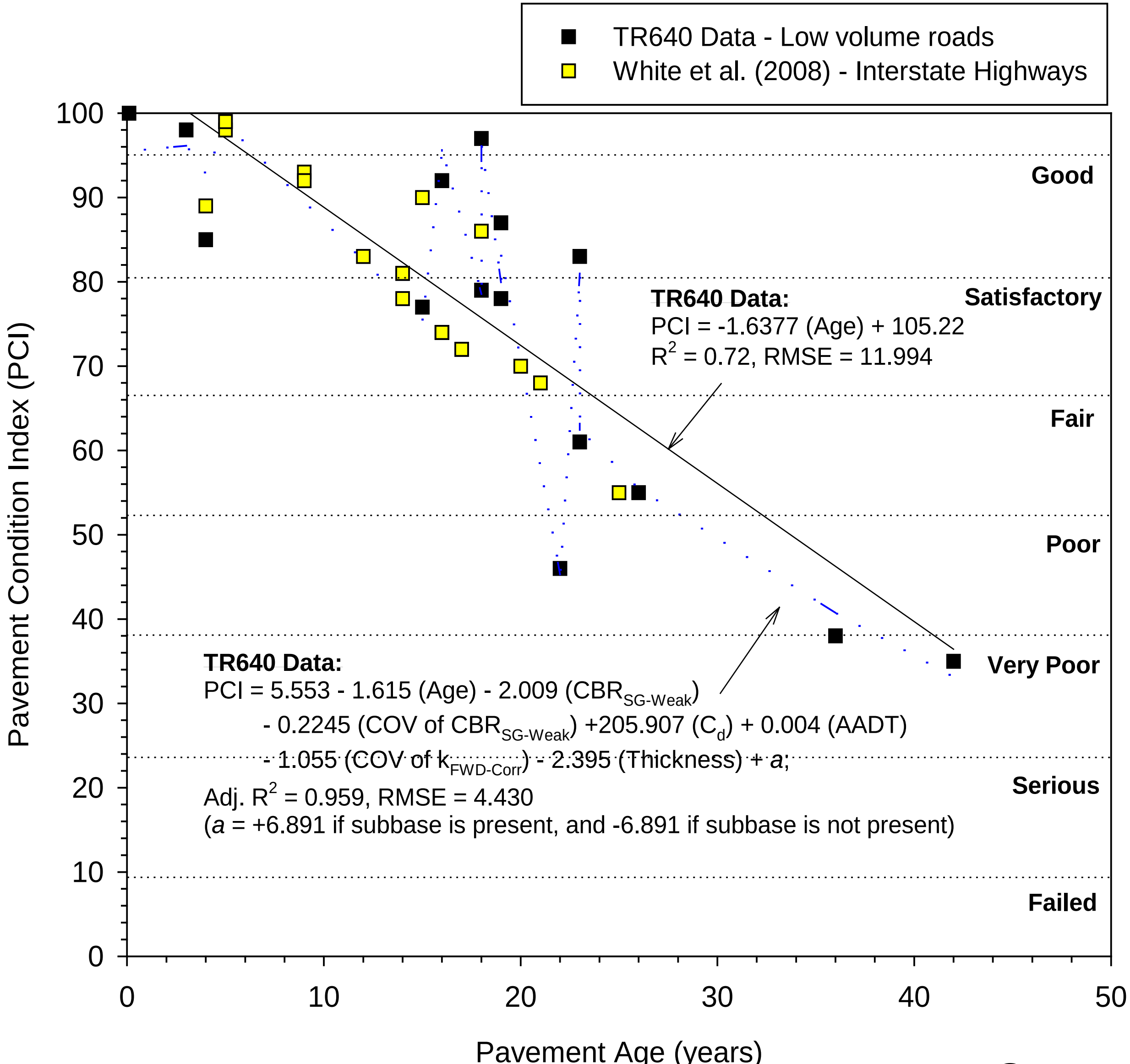
on FWD composite stiffness

Source: Vennapusa, P., White D.J., Miller, D.K. (2013). *Western Iowa Missouri River Flooding -- Geo-Infrastructure Damage Assessment, Repair and Mitigation Strategies*, TR-638 Final Report, Iowa Department of Transportation, Ames, Iowa.

FWD testing showed 5 to 20 times higher moduli on *cement stabilized sections* during spring-thaw



Source: White et al. (2014)

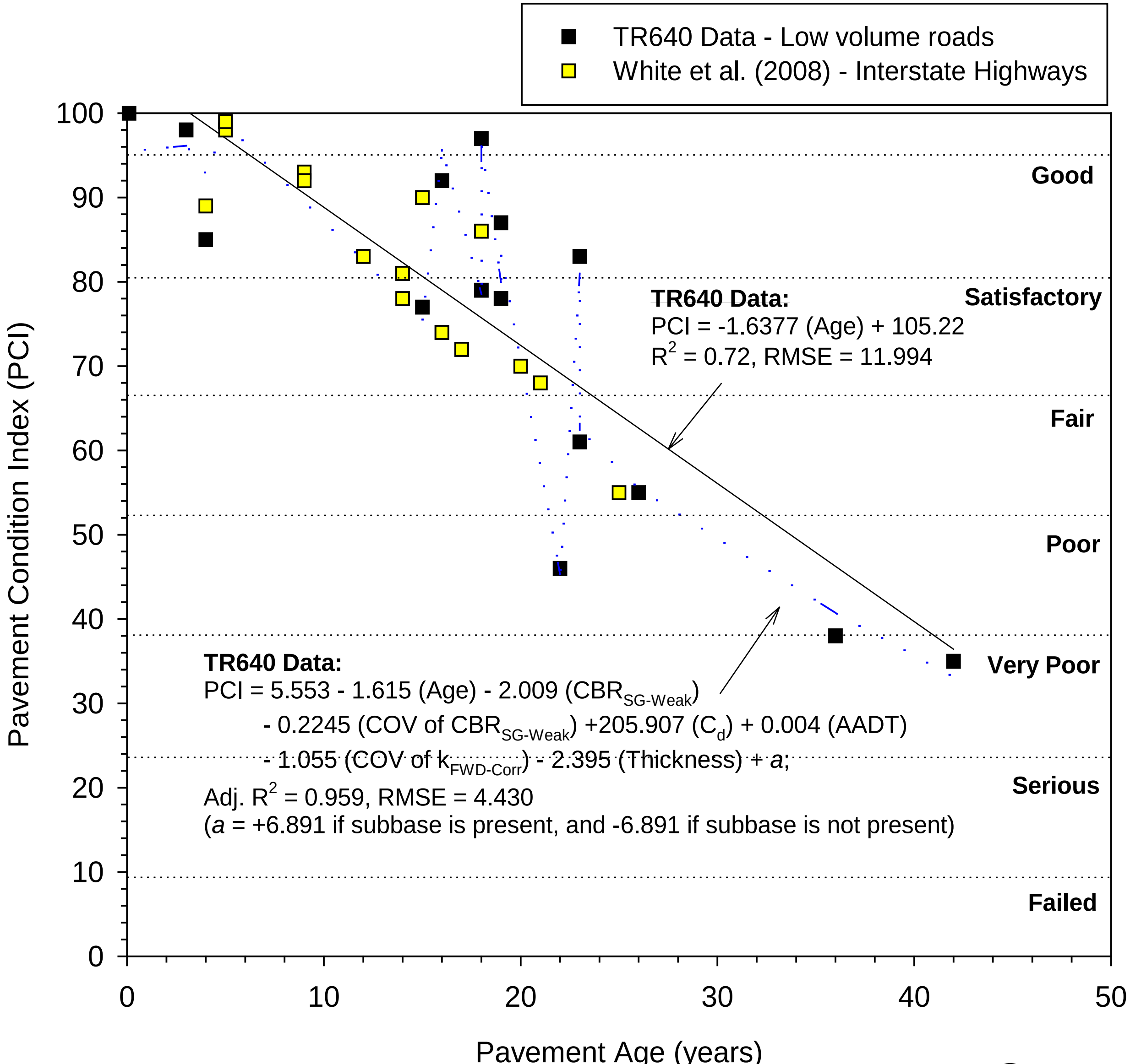


Age vs. PCI

RMSE = 5.1 for Interstates

RMSE = 12.0 for LVRs

Source: White and Vennapusa (2014)

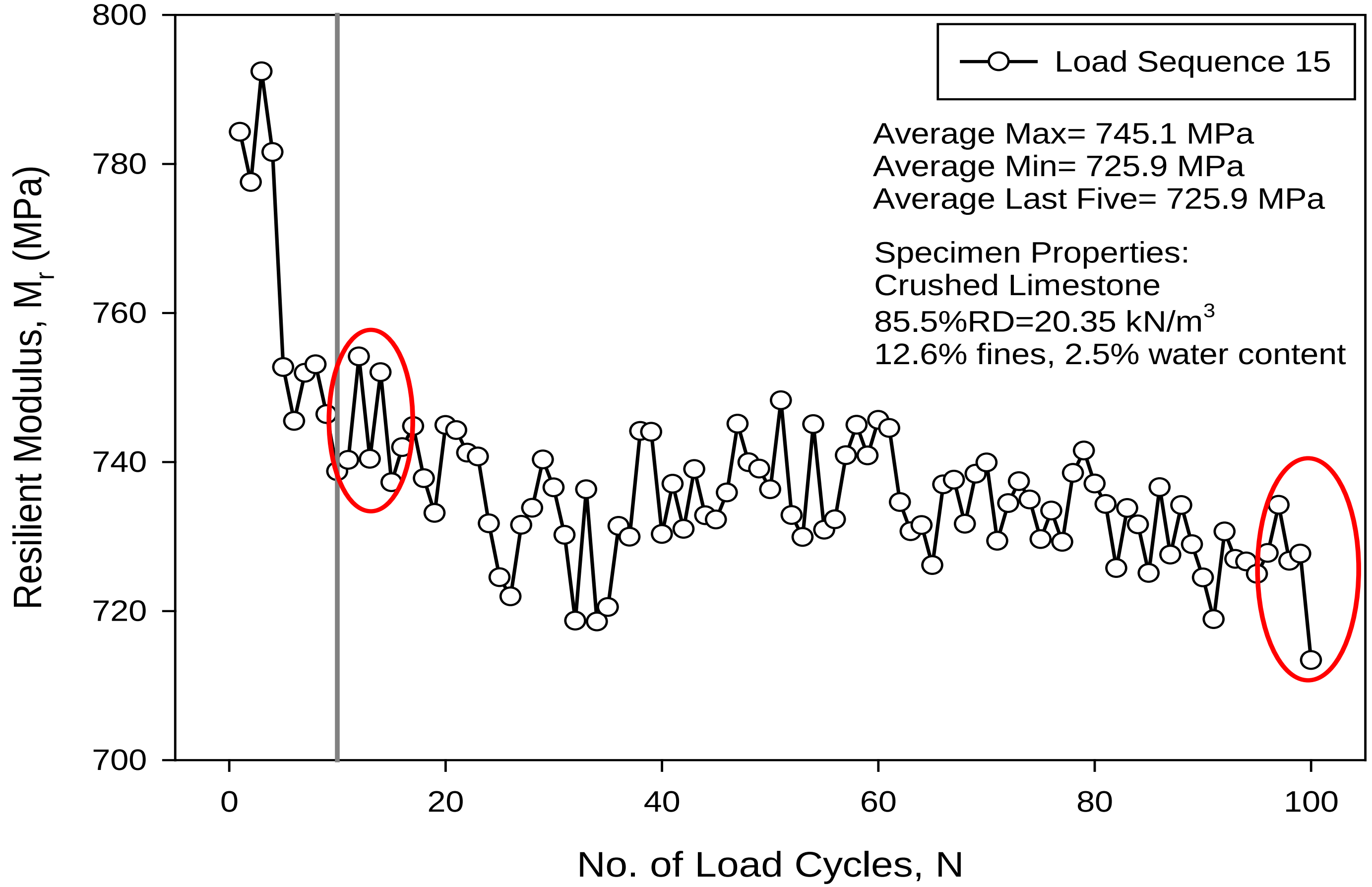


Statistical analysis revealed the following are key for improved PCI:

1. AGE
2. Drainage
3. Variability of stiffness
4. CBR of Subgrade
4. Traffic
5. Presence of Subbase
6. Pavement Thickness

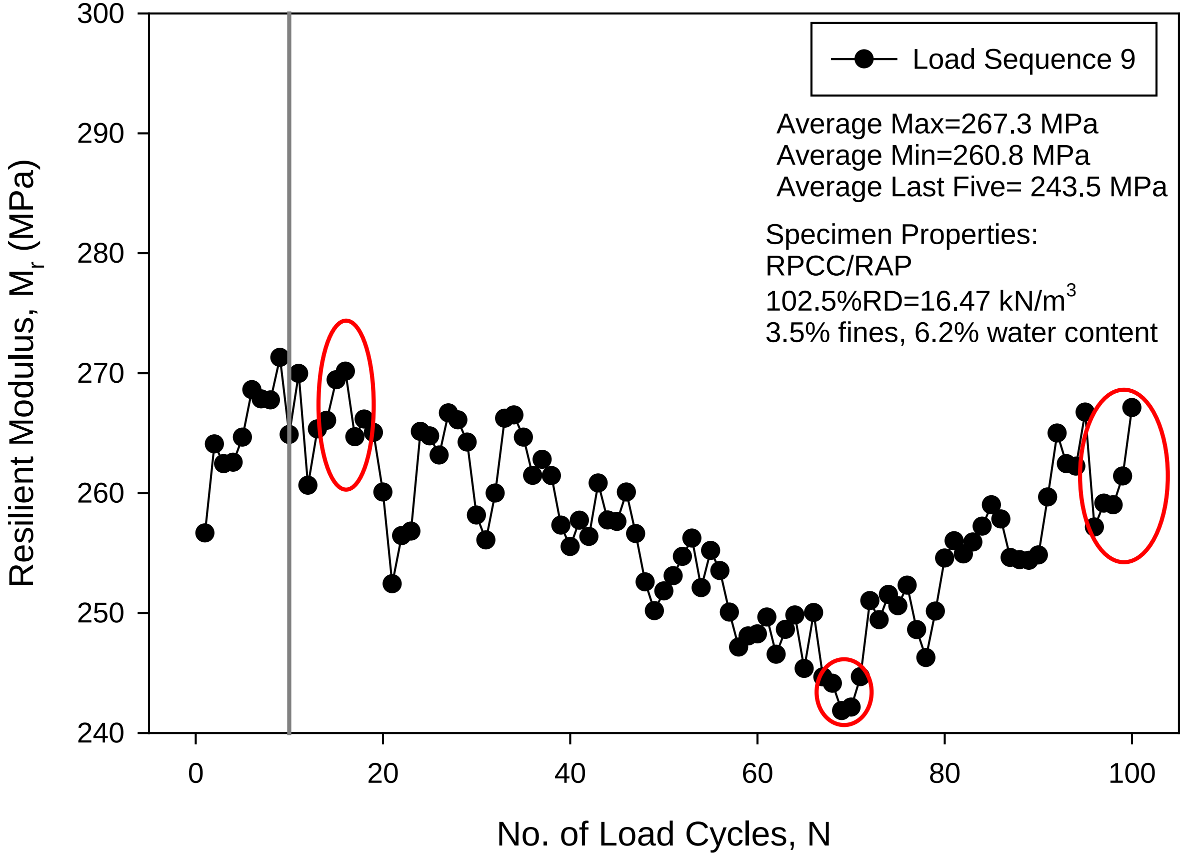
Source: White and Vennapusa (2014)

Lab M_r testing standards require averaging last five cycles which may not be always representative



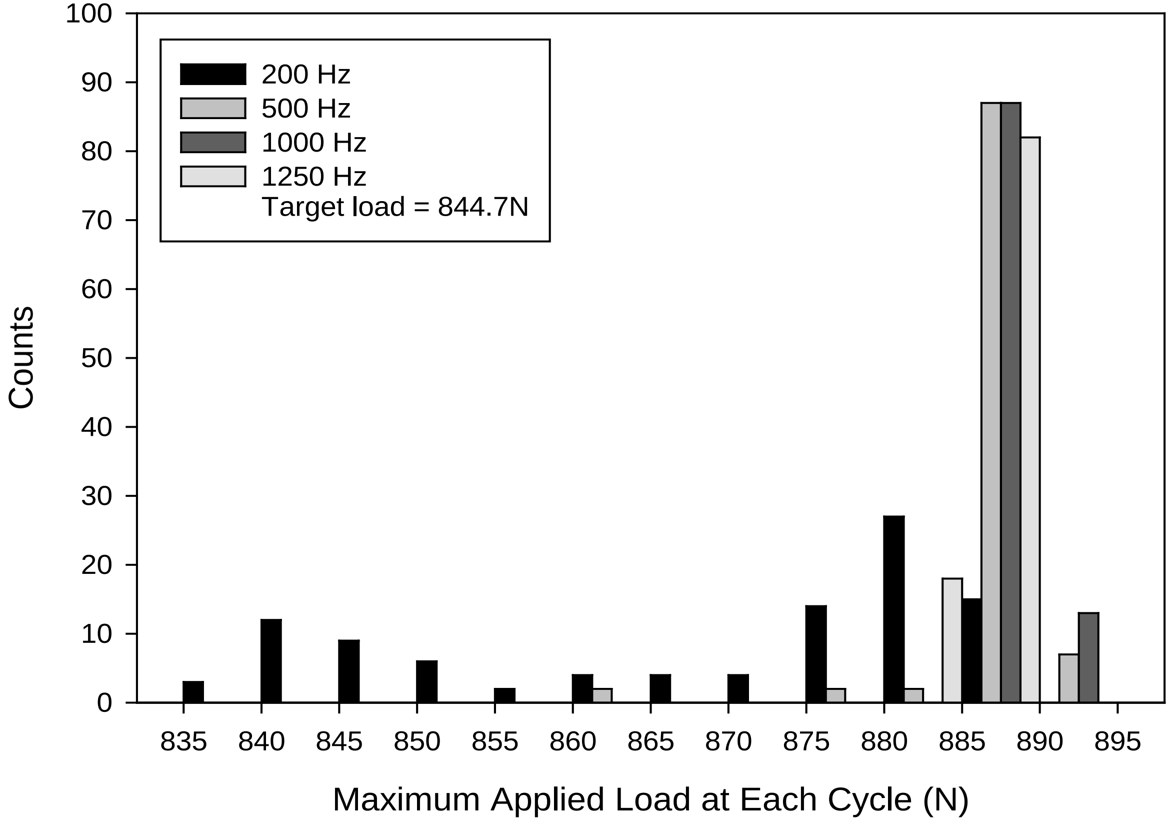
Source: Li, J., White, D.J., Stephenson, R.W. (2014). "Accuracy of resilient modulus test results and sources of error." *Geotechnical Testing Journal,* ASTM (in review)

Lab M_r testing standards require averaging last five cycles which may not be always representative



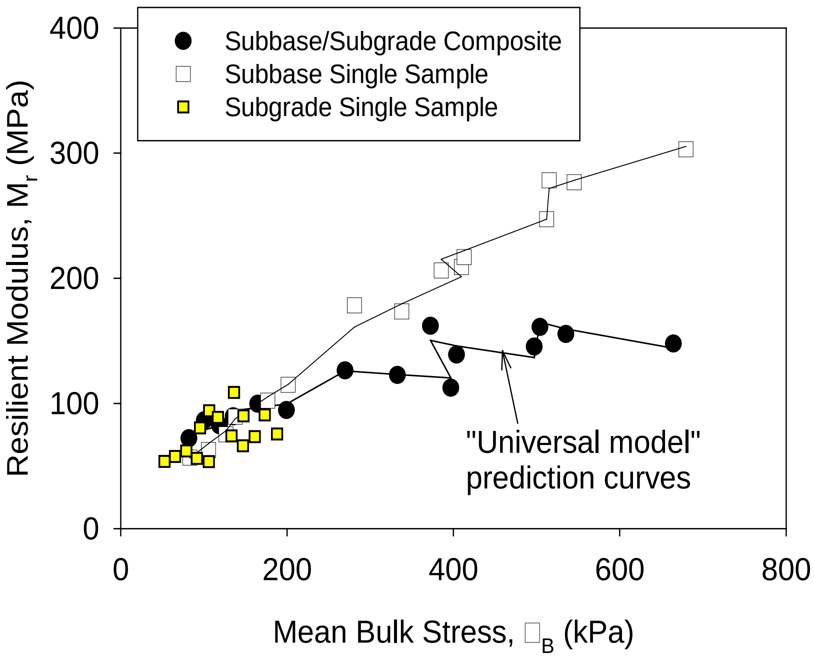
Source: Li, J., White, D.J., Stephenson, R.W. (2014). "Accuracy of resilient modulus test results and sources of error." *Geotechnical Testing Journal,* ASTM (in review)

AASHTO T307 protocol recommends sampling @ 200Hz which does not adequately capture the peak stresses – 500 Hz or greater is recommended.



Source: Li, J., White, D.J., Stephenson, R.W. (2014). "Accuracy of resilient modulus test results and sources of error." *Geotechnical Testing Journal,* ASTM (in review)

M_r testing on composite samples showed that the “weak” subgrade layer governs the composite sample modulus



Composite Sample:
17.04 kN/m^3 Subbase at 8.2% w
19.60 kN/m^3 Subgrade at 11.3%w
R^2 = 0.96

Subbase Single Sample:
17.15 kN/m^3 @ 11.6%w
R^2 = 0.99

Subgrade Single Sample:
19.36 kN/m^3 @ 14.1%w
R^2 = 0.75


Improving the Foundation Layers for Pavements

TECHNICAL REPORT:
Pavement Foundation Layer Construction Project – Wisconsin US-10 Field Study

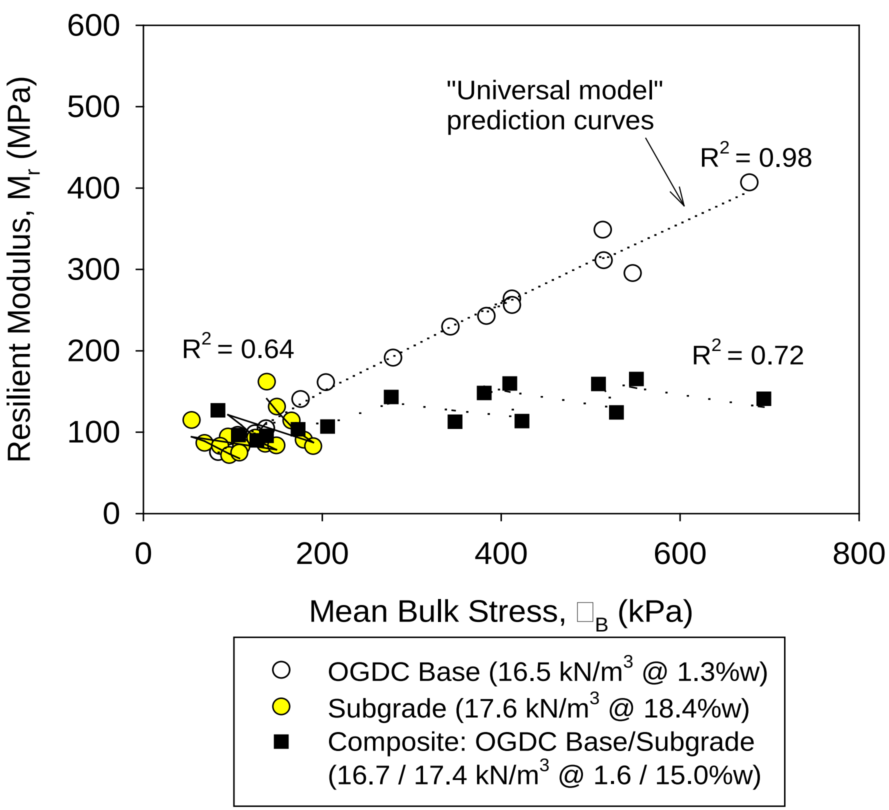
July 2012

Sponsored by

National Concrete Pavement Technology Center

CEER
Earthworks Engineering
Iowa State University

M_r testing on composite samples showed that the “weak” subgrade layer governs the composite sample modulus



Improving the Foundation Layers for Pavements

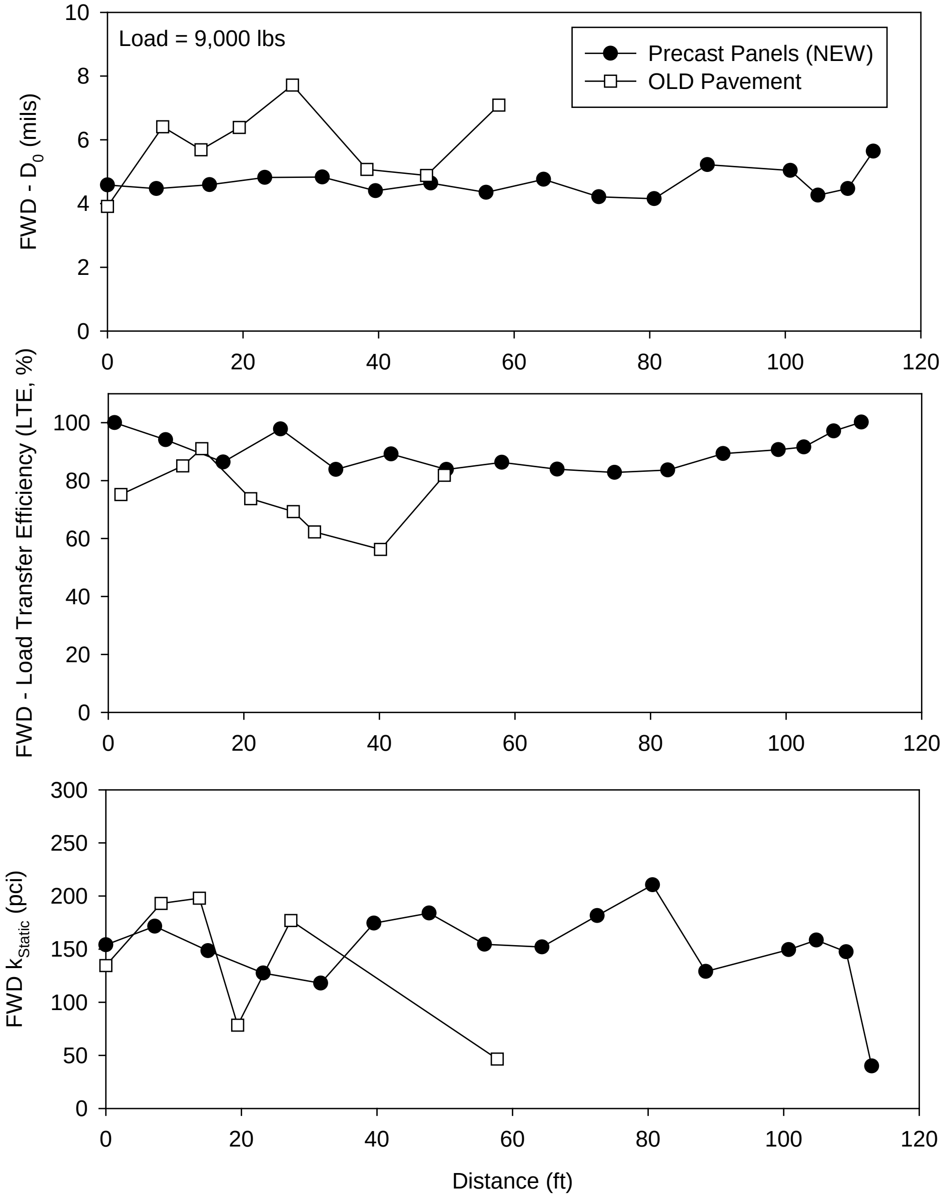
TECHNICAL REPORT:
Pavement Foundation Layer Reconstruction Project – Michigan I-94 Field Study

July 2012

Sponsored by
Federal Highway Administration (DTFH 61-06-H-00011 (Work Plan #18))
FHWA TPF-5(183): California, Iowa (lead state), Michigan, Pennsylvania, Wisconsin

National Concrete Pavement Technology Center

CENTER FOR CEER EARTHWORKS ENGINEERING
IOWA STATE UNIVERSITY



FWD testing on precast panels showed improvements in terms of FWD deflection and LTE


Improving the Foundation Layers for Pavements

TECHNICAL REPORT:
Pavement Rehabilitation Using Precast Prestressed Concrete Slabs – California I-15 Field Study

April 2013

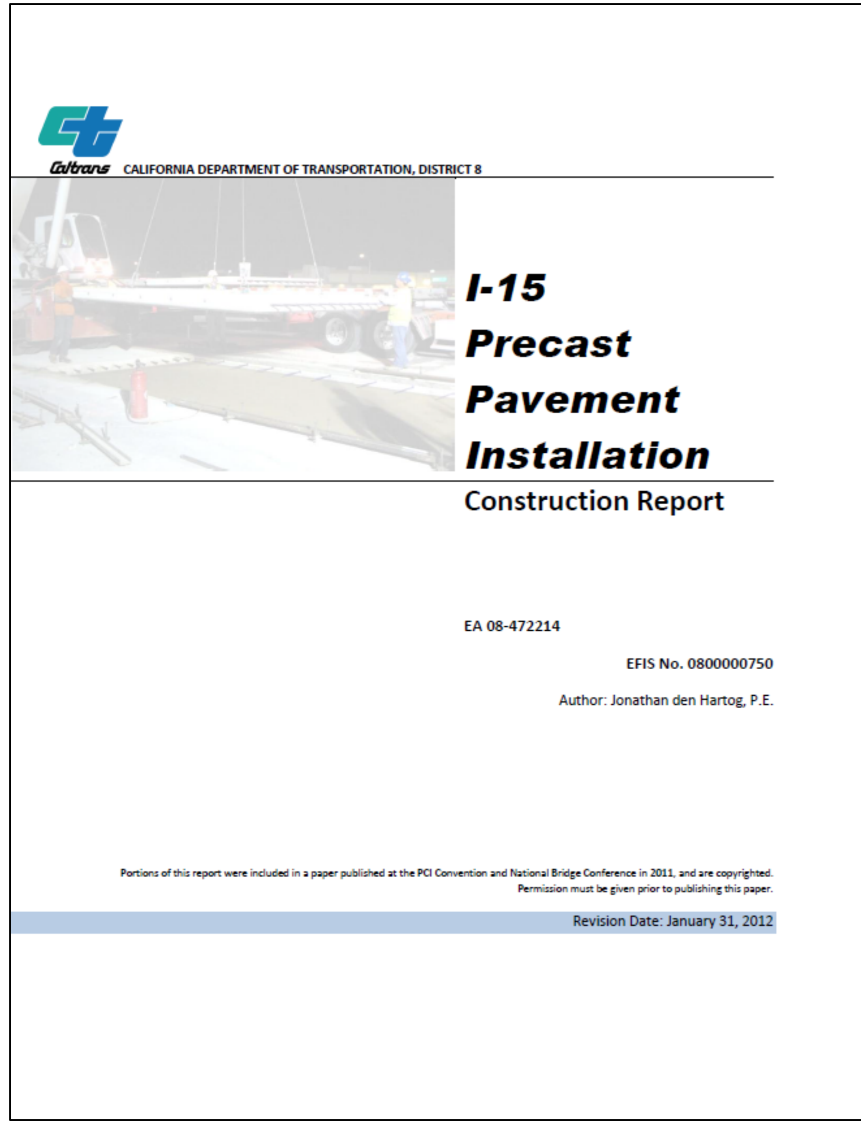
Sponsored by

National Concrete Pavement Technology Center

CEER

CalTrans Construction Observations Report indicated hairline cracks developed on precast panels several months after placement.

Report indicated strong correlation between contractor's grading practices (<u>stringline approach</u>) on the bedding layer and the incidence of cracking.



Caltrans CALIFORNIA DEPARTMENT OF TRANSPORTATION, DISTRICT 8

I-15 Precast Pavement Installation

Construction Report

EA 08-472214

EFIS No. 0800000750

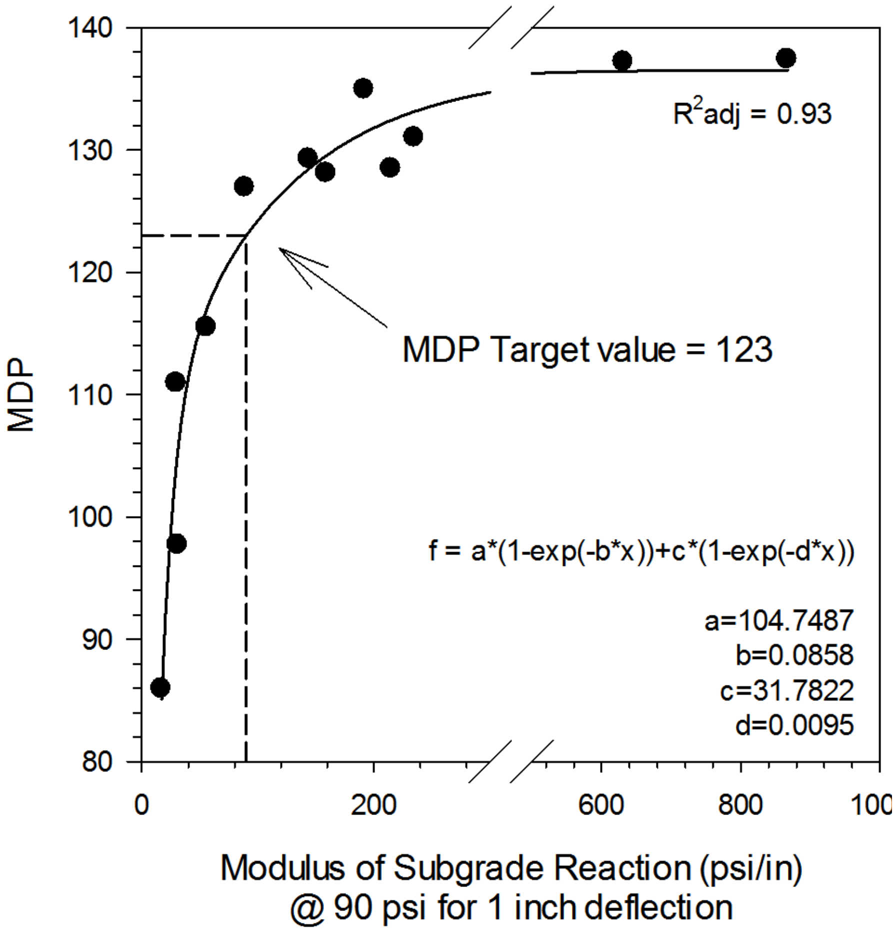
Author: Jonathan den Hartog, P.E.

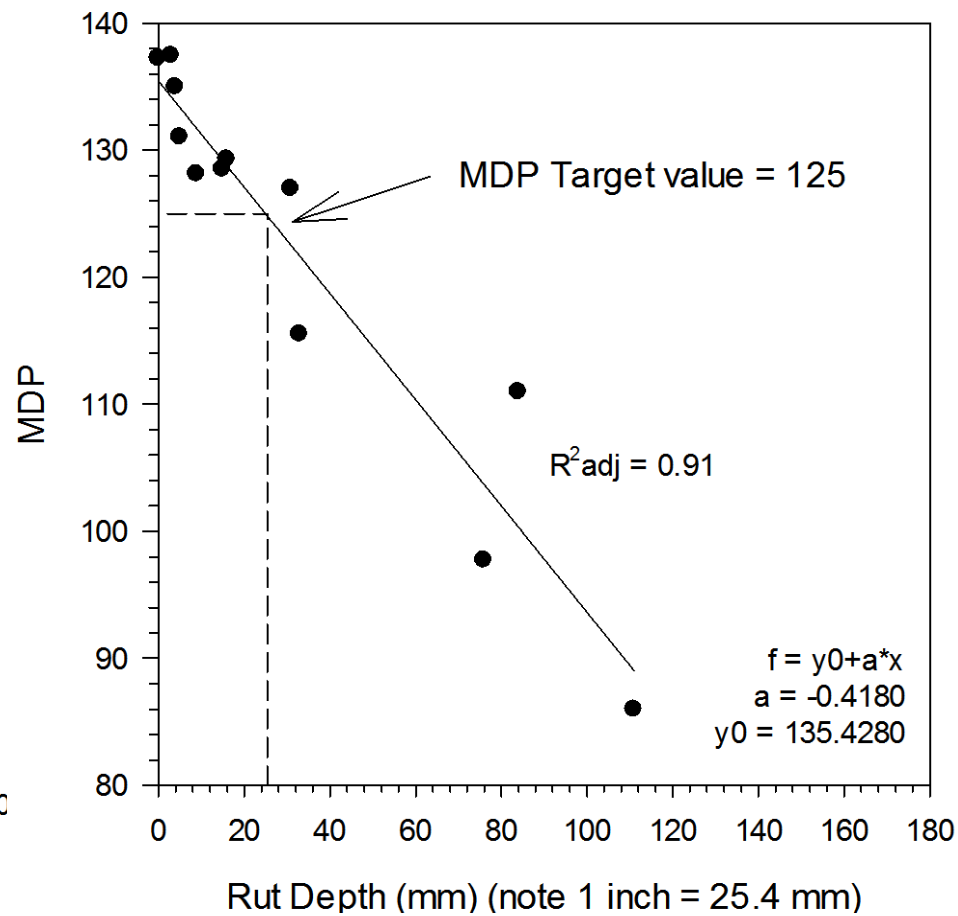
Portions of this report were included in a paper published at the PCI Convention and National Bridge Conference in 2011, and are copyrighted. Permission must be given prior to publishing this paper.

Revision Date: January 31, 2012

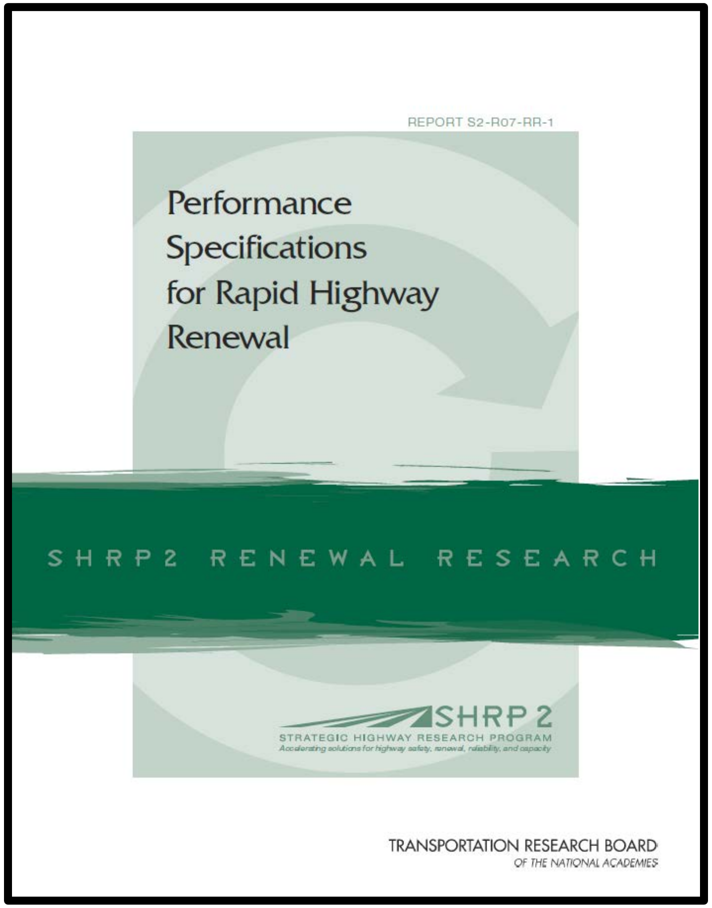
Proof rolling can be substituted with stiffness-based assessment.

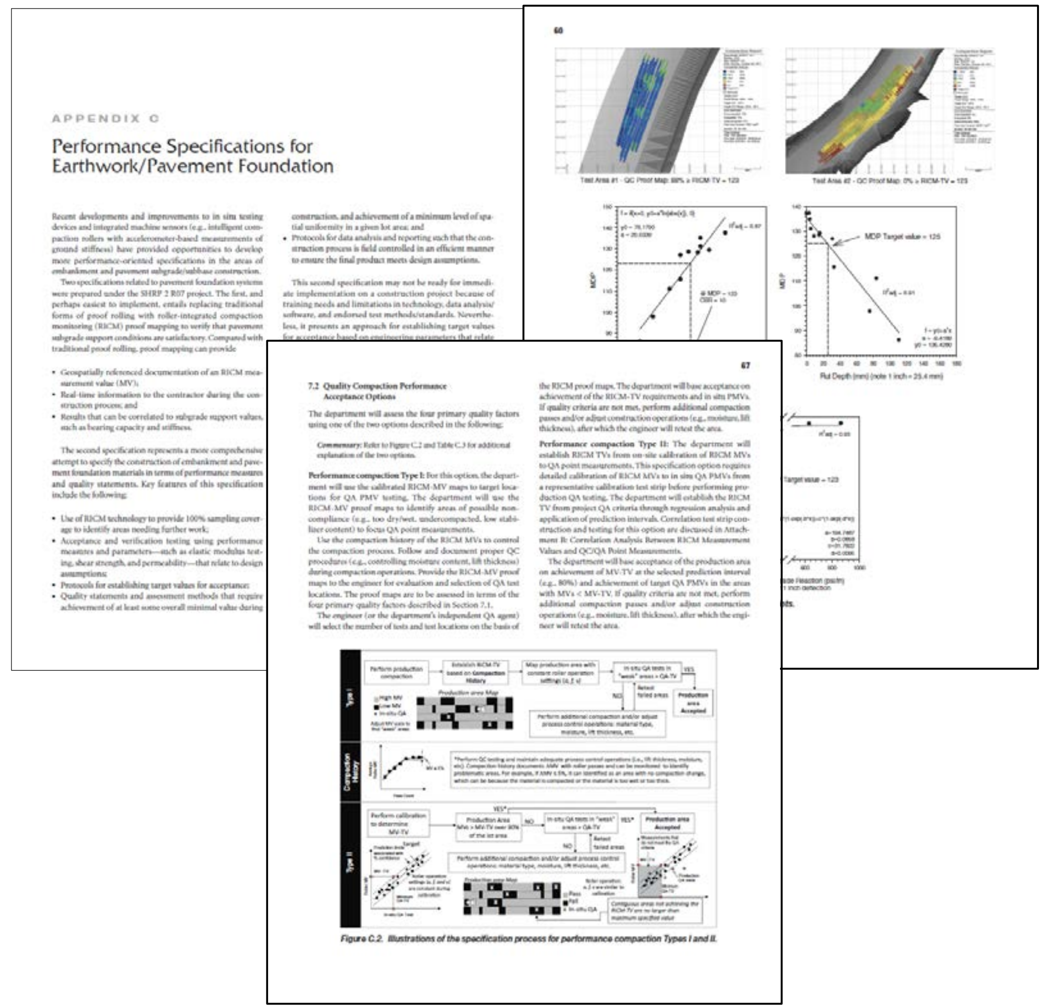
Proof rolling can be substituted with stiffness-based assessment.





SHRP2R07 published options to implement *performance-based* specifications for pavement foundations



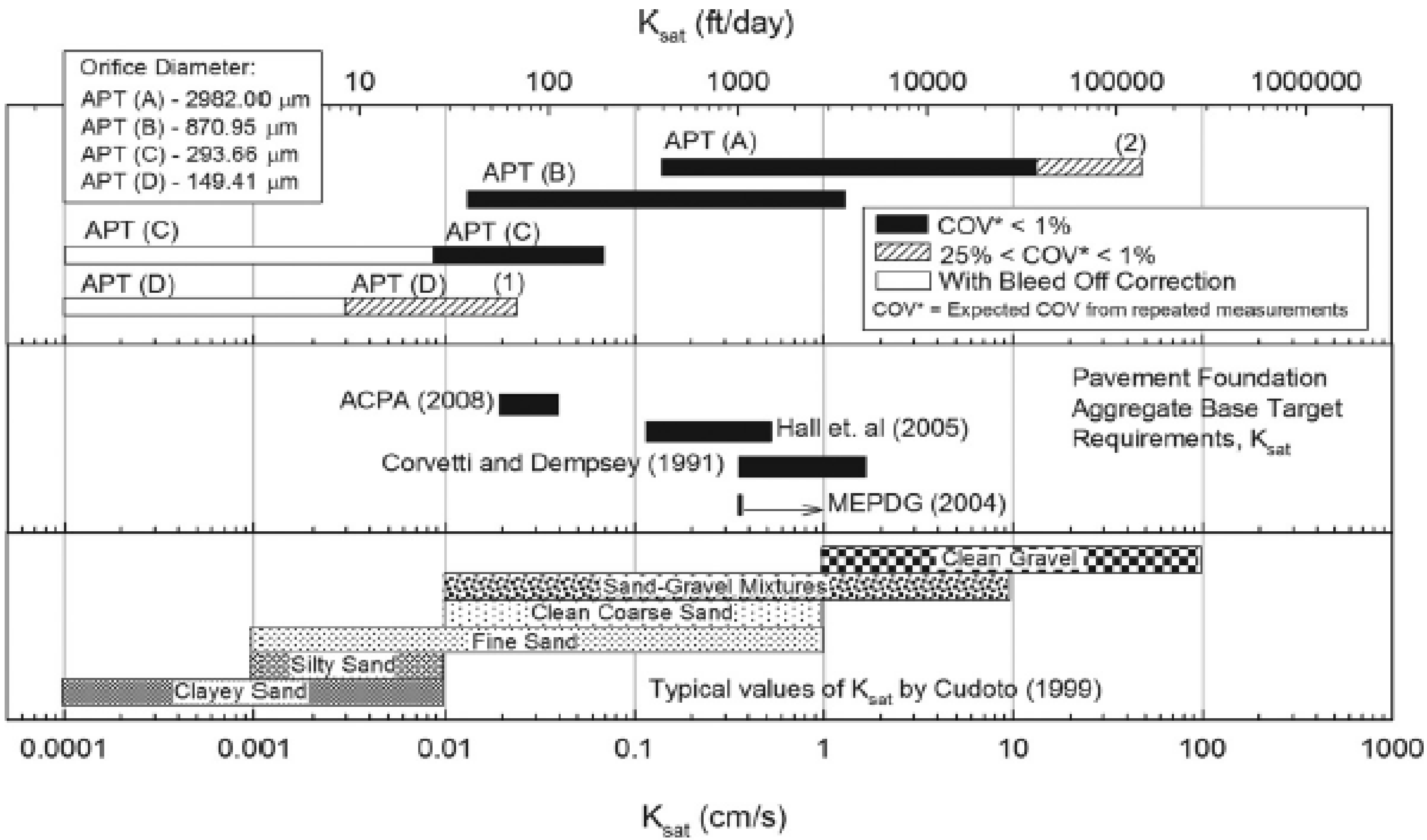


Drainage is an important component of pavement design and is critical in achieving good pavement performance.

A New In-Situ Testing Device (APT) was developed to overcome problems with rapid field testing

$$K_{\text{sat}} = \left[\frac{2u_{\text{gas}}QP_1}{rG_o(P_1^2 - P_2^2)}\right] \cdot \frac{\rho g}{\mu_{\text{water}}(1 - S_e)^2\left(1 - S_e^{(2+\lambda)/\lambda}\right)}$$

APT has a wide measurement range



Notes:

APT testing was performed in dense-grid pattern to identify segregated areas

Spatial variability in fines content showed a strong correlation with field permeability

Avg. K = 13,900 ft/day
COV = 119%
Recycled Steel Slag

Improving the Foundation Layers for Pavements

TECHNICAL REPORT:
Pavement Foundation Layer Reconstruction Project – Michigan I-94 Field Study

July 2012

Sponsored by
Federal Highway Administration (DTFH 61-06-H-00011 (Work Plan #18))
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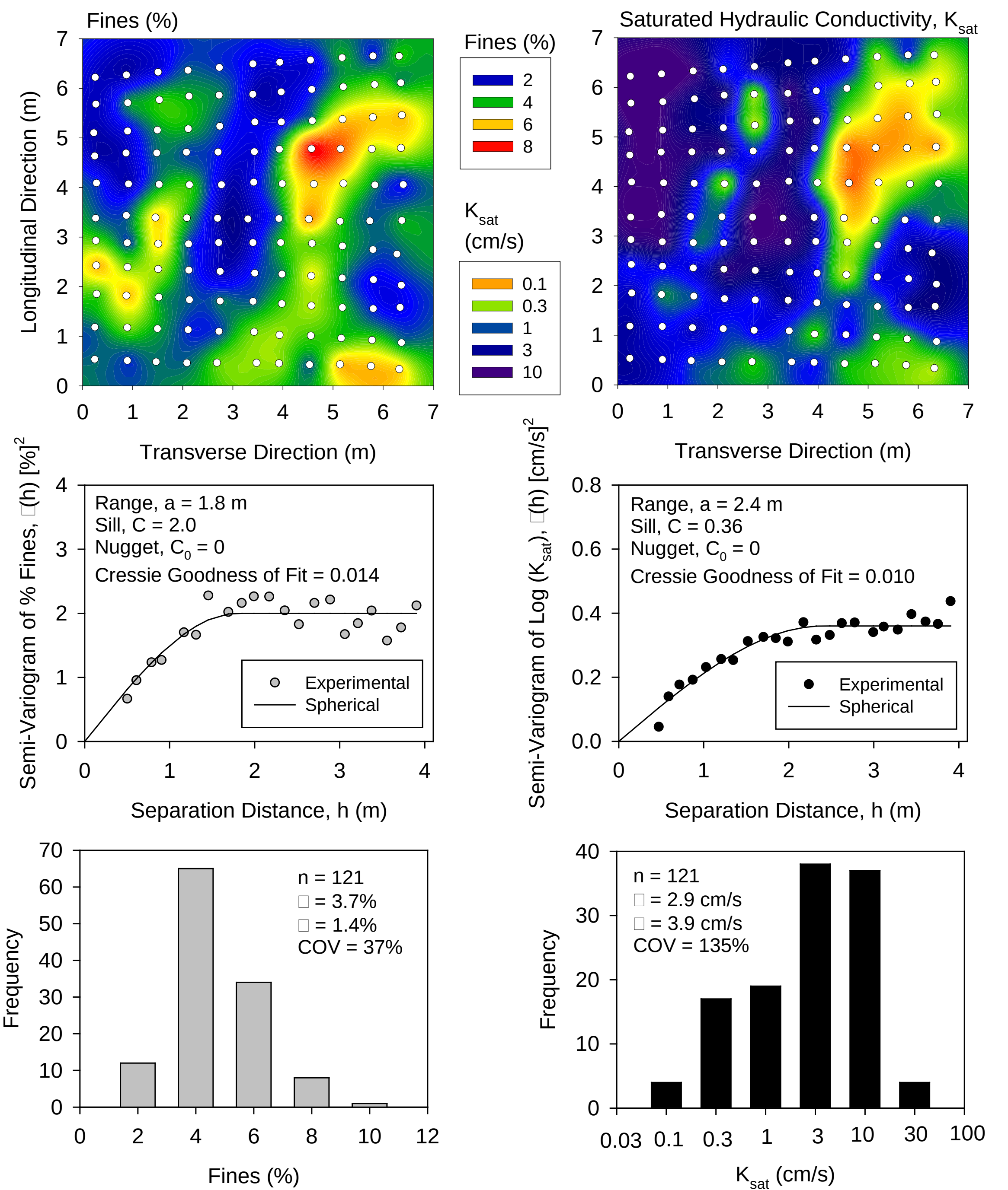
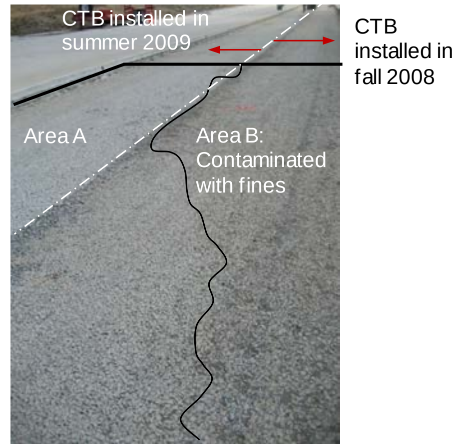
National Concrete Pavement Technology Center

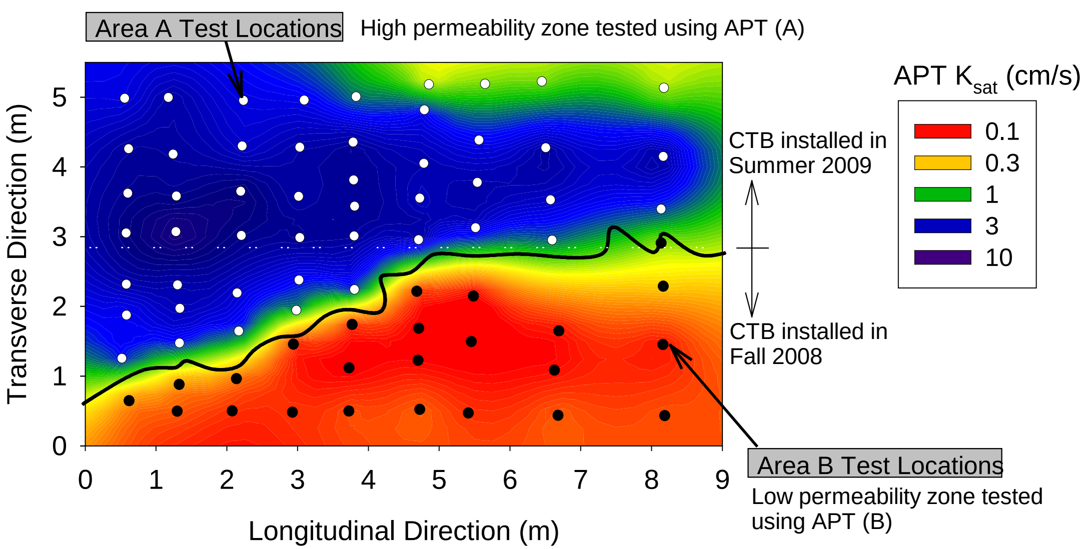
CENTER FOR CEER EARTHWORKS ENGINEERING
IOWA STATE UNIVERSITY



Cement-treated bases can be contaminated with fines due to construction activities

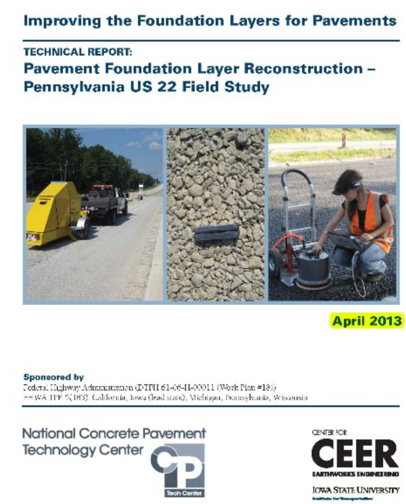
Cement Treated Base
SR22, Blairsville, PA





Area A:
Avg. K = 19,800 ft/day
COV = 45%

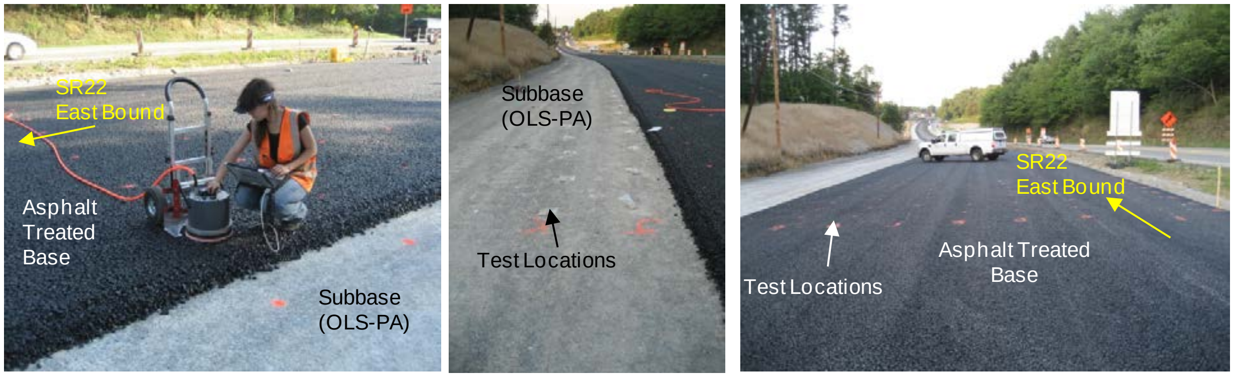
Area B:
Avg. K = 566 ft/day
COV = 101%



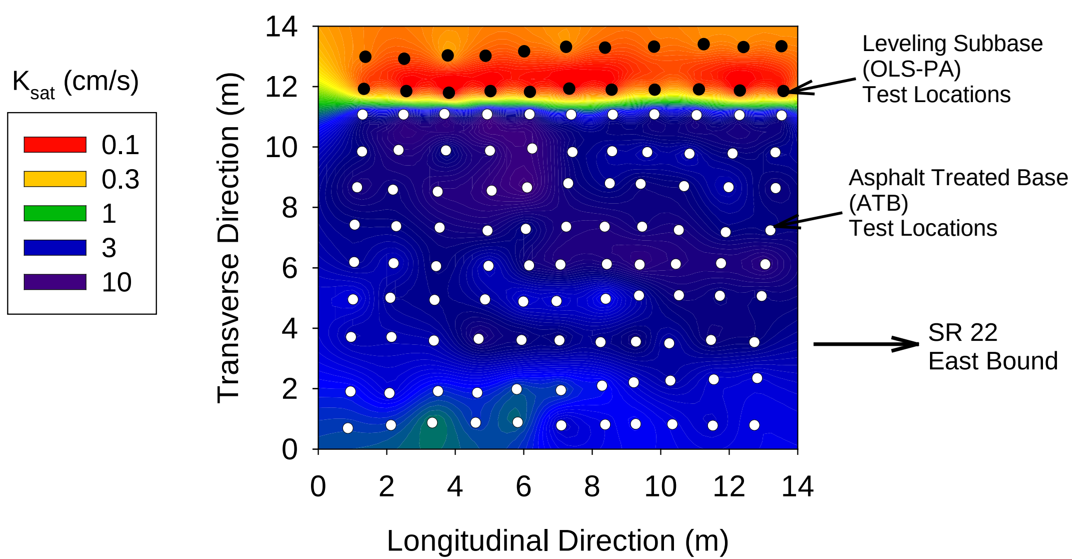
Center for Earthworks Engineering Research

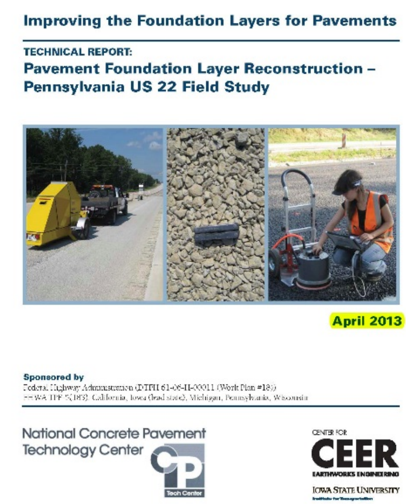
APT measurements on asphalt-treated base

Asphalt Treated Base
SR22, Blairsville, PA



Avg. K = 13,040 ft/day
COV = 42%





White et al. (2010)

COV of permeability is higher for virgin and recycled aggregate materials than treated aggregate materials

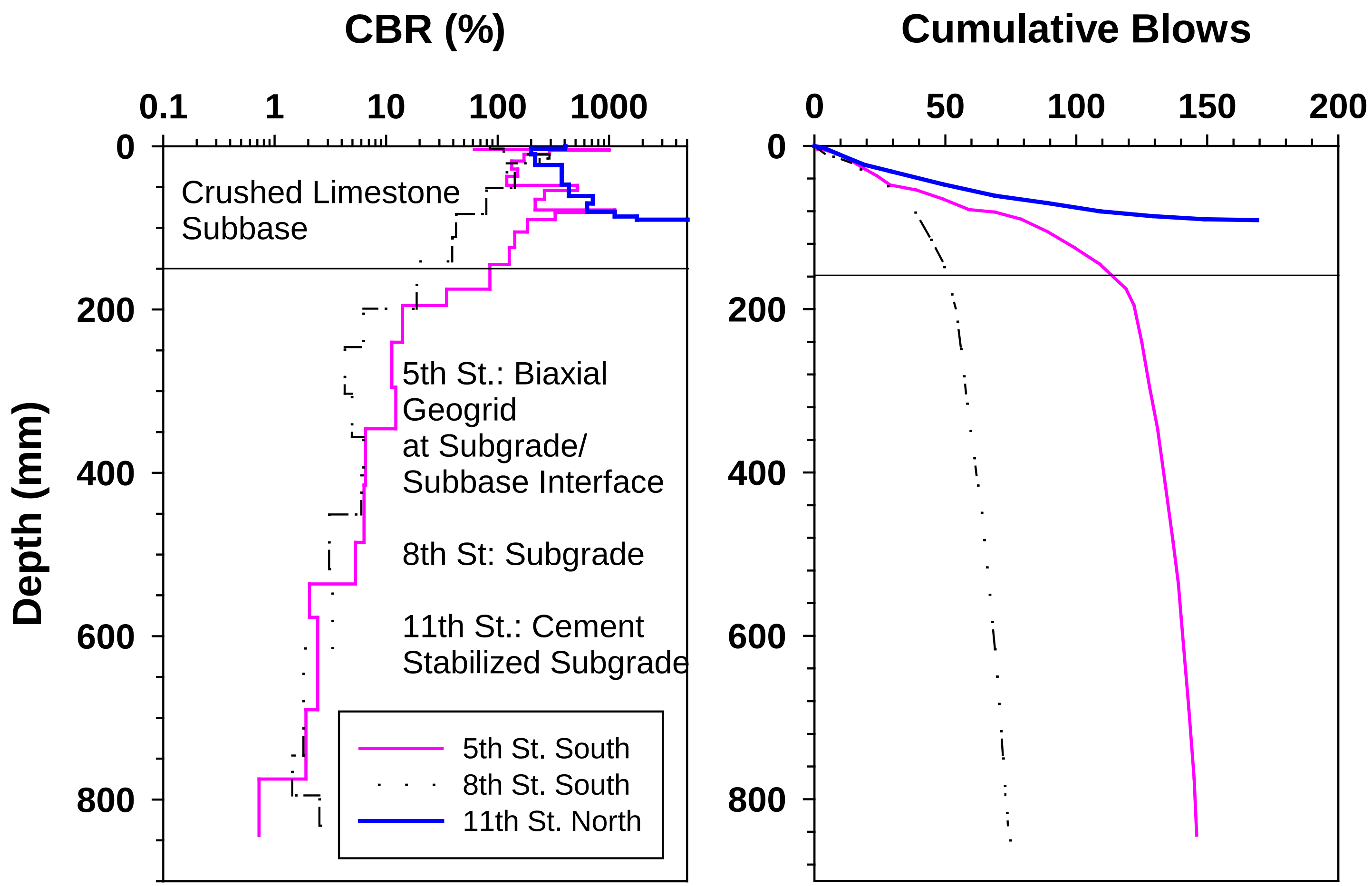
Material	Crushed Limestone (OLS-63)	Steel slag (OS-MI)	Cement treated AASHTO # 57 base (CTB)		Asphalt treated AASHTO#57 base (ATB)
			Area A	Area B	
Saturated Hydraulic Conductivity, K_{sat} Statistics					
Number of measurements, N	89	120	49	23	99
Mean, μ (ft/day)	5,380	13,890	19,840	560	13,040
Standard Deviation, σ (ft/day)	4,800	16,720	8,780	560	5,380
Coefficient of Variation, COV (%)	**91**	**119**	**45**	**101**	**42**

White et al. (2010)

Subgrade support conditions and trafficking affect particle breakdown

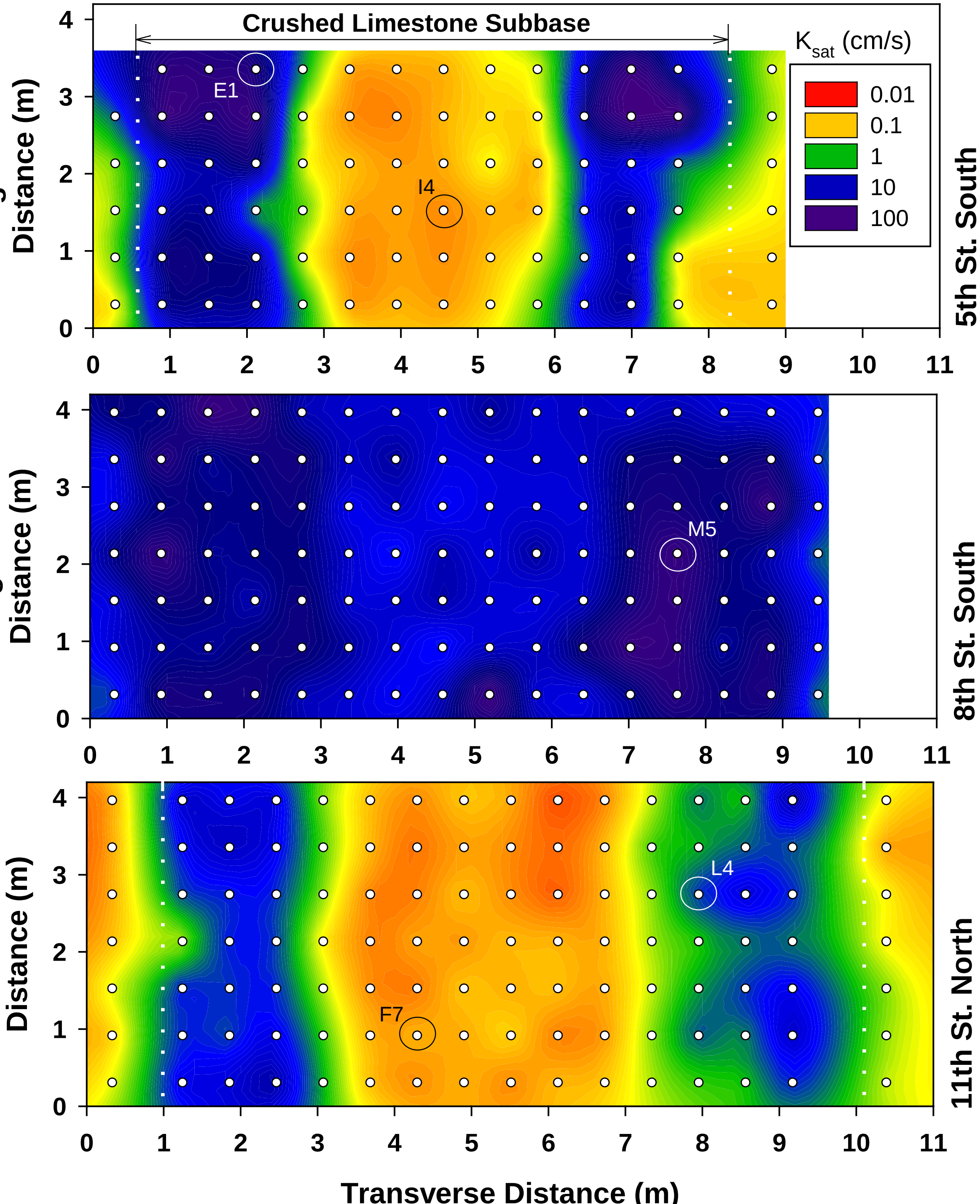
White and Vennapusa (2014)

Representative CBR profiles from the three test sections



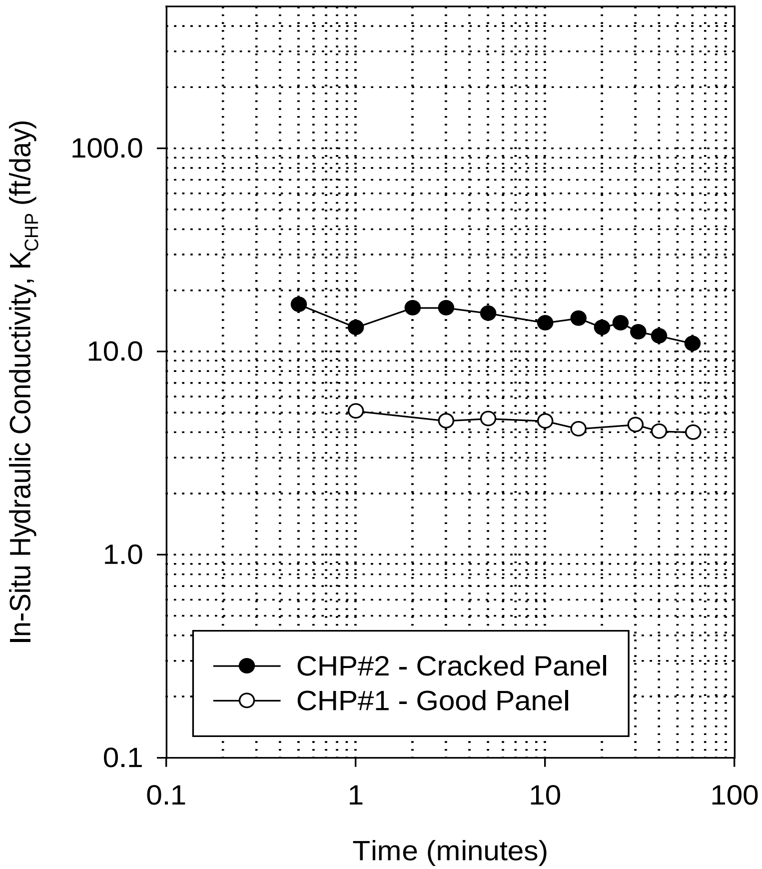
White and Vennapusa (2014)

Subgrade support conditions and trafficking affect particle breakdown



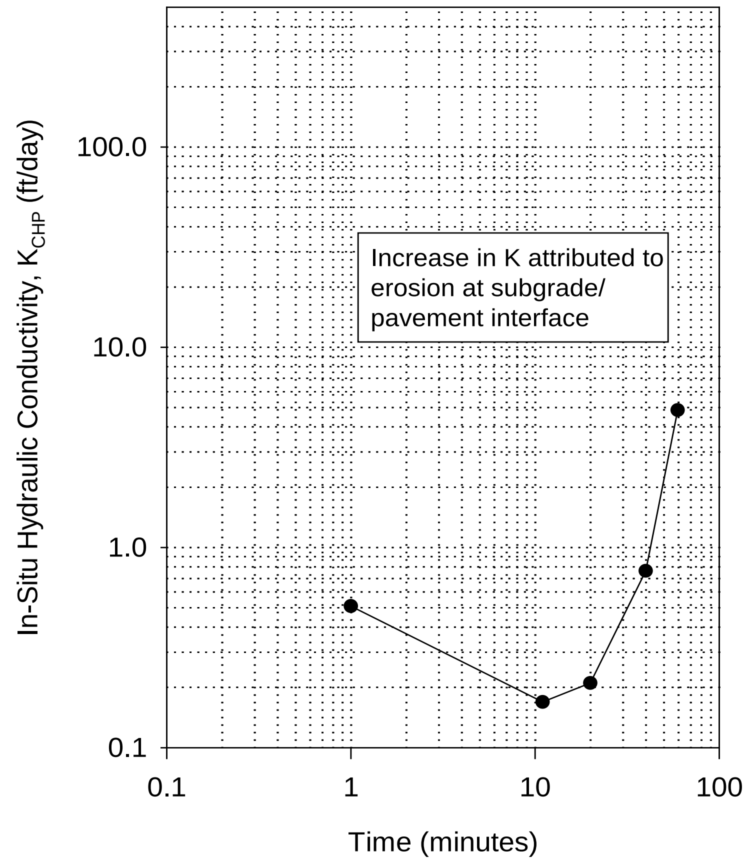
White and Vennapusa (2014)

CHP Tests can be used to measure permeability of materials under pavements



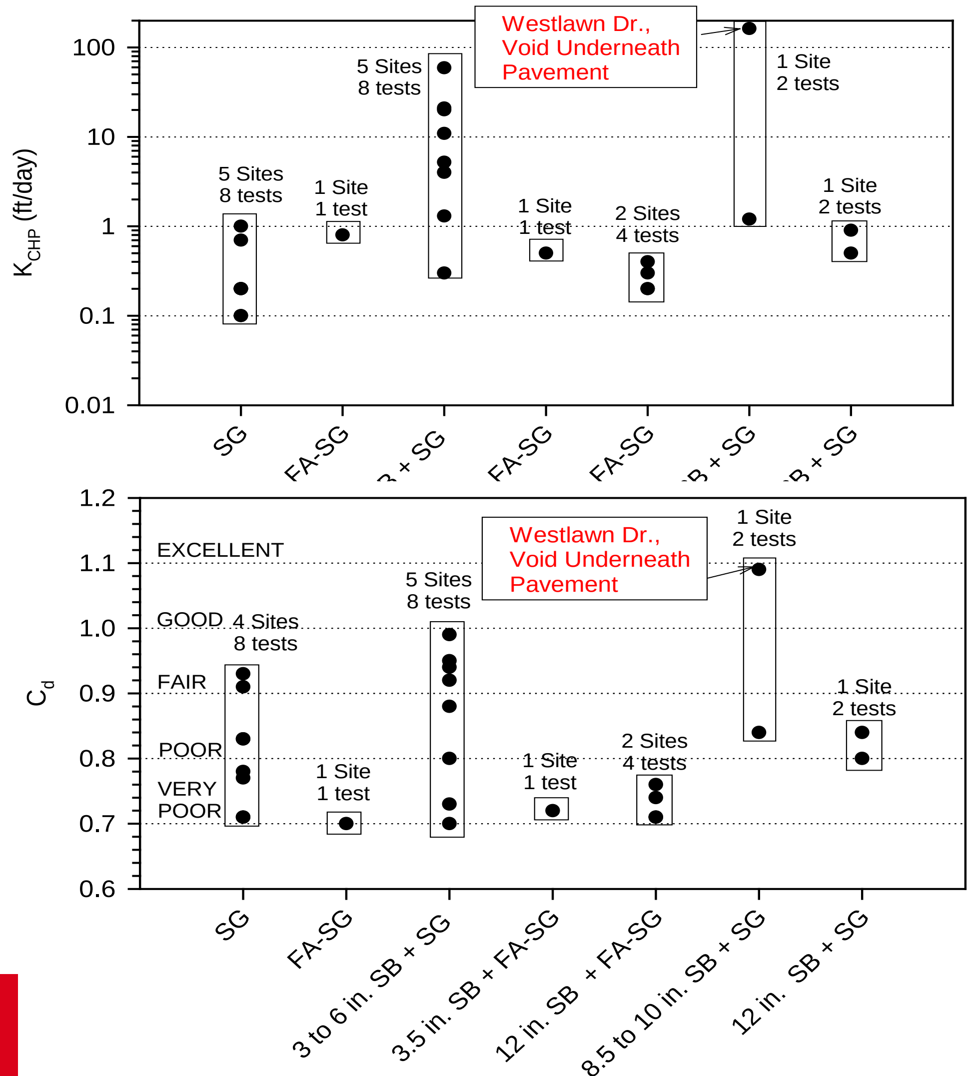
White and Vennapusa (2014)

CHP Tests under existing pavements showed evidence of erosion at the interface



White and Vennapusa (2014)

CHP tests results on a wide range of support conditions (Low Volume Pavements)



Tests conducted at 16 Sites (28 tests)

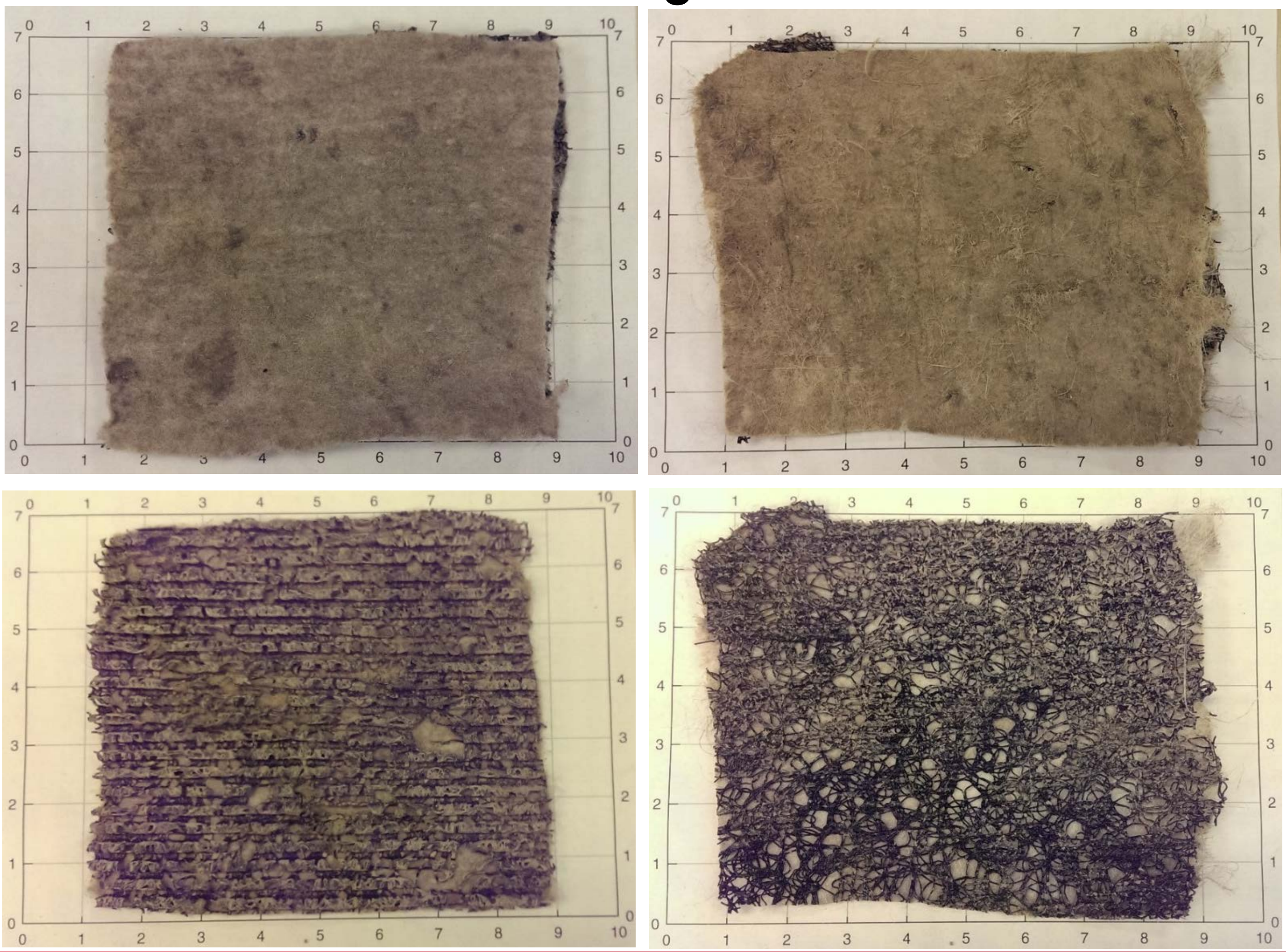
Increasing subbase layer thickness did not necessarily improve C_d or K value

Notes:
SG – subgrade
FA – fly ash
SB – subbase

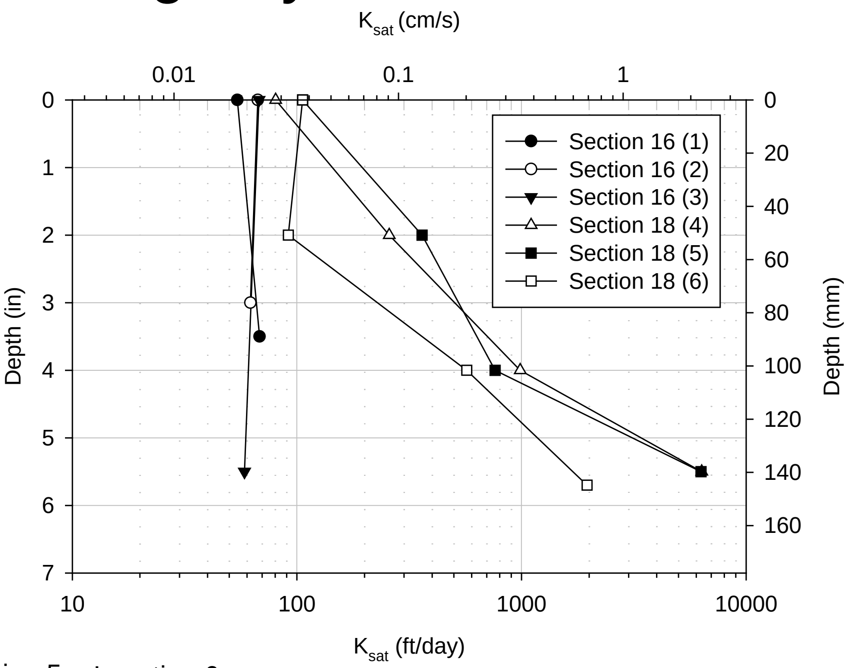
White and Vennapusa (2014)

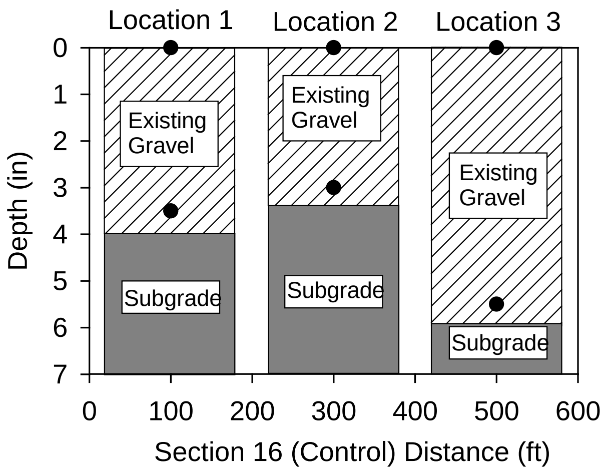
Use of geocomposite active drainage systems can improve subsurface drainage

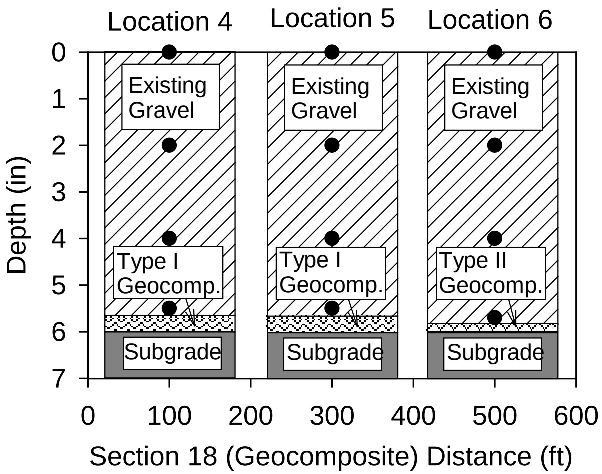
Use of geocomposite active drainage systems can improve subsurface drainage



Use of geocomposite active drainage systems can improve subsurface drainage

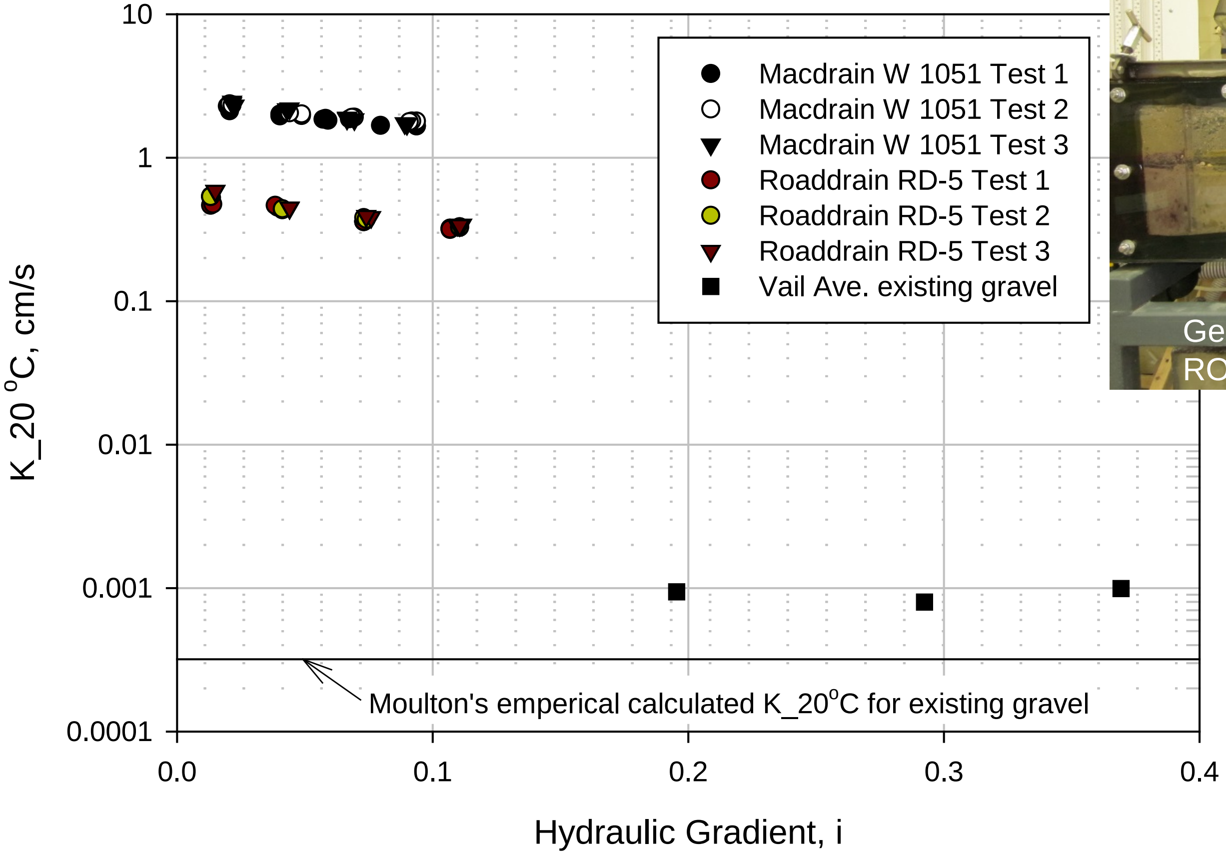


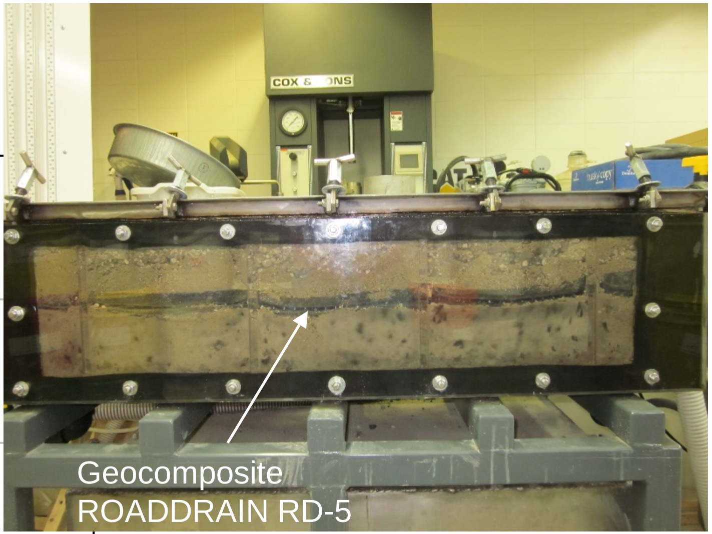




Laboratory horizontal permeability test device was fabricated at ISU to simulate field drainage conditions

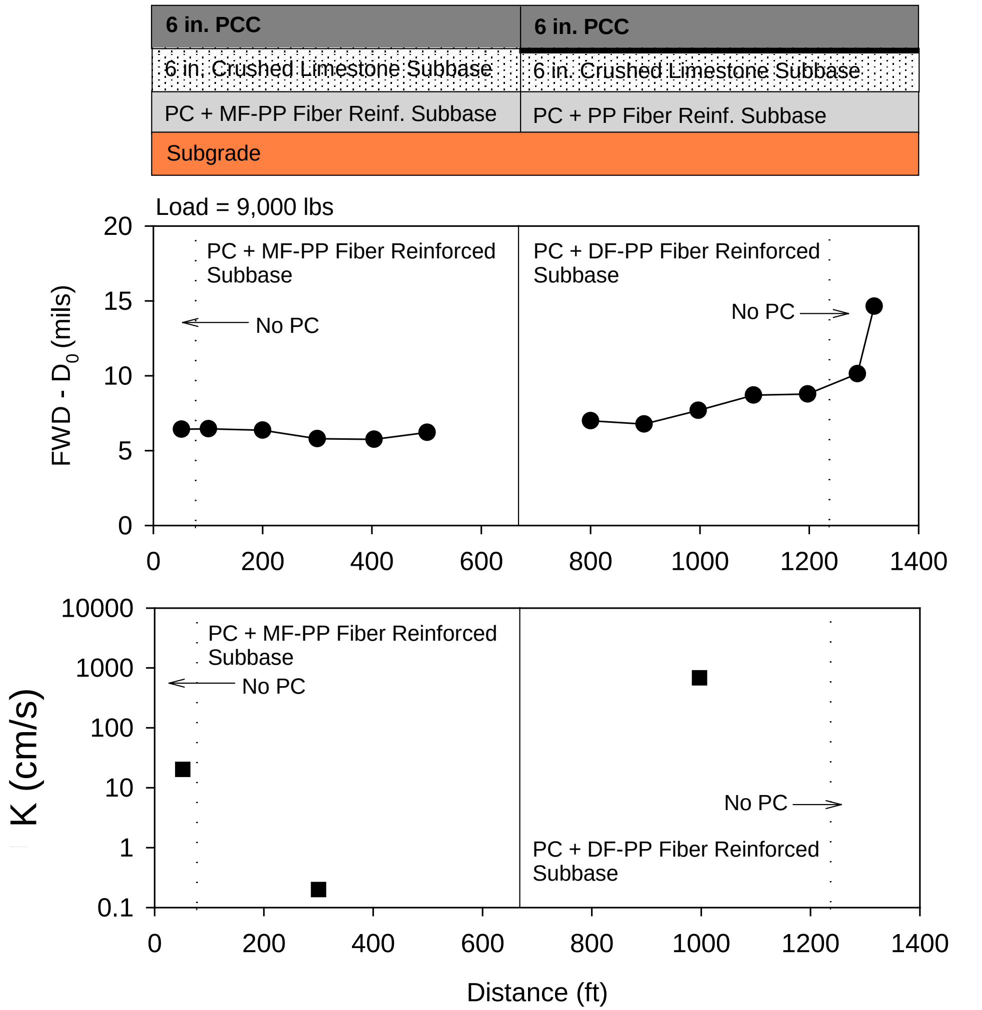
Lab HPT tests confirm field results of improved drainage with geocomposite drainage layers





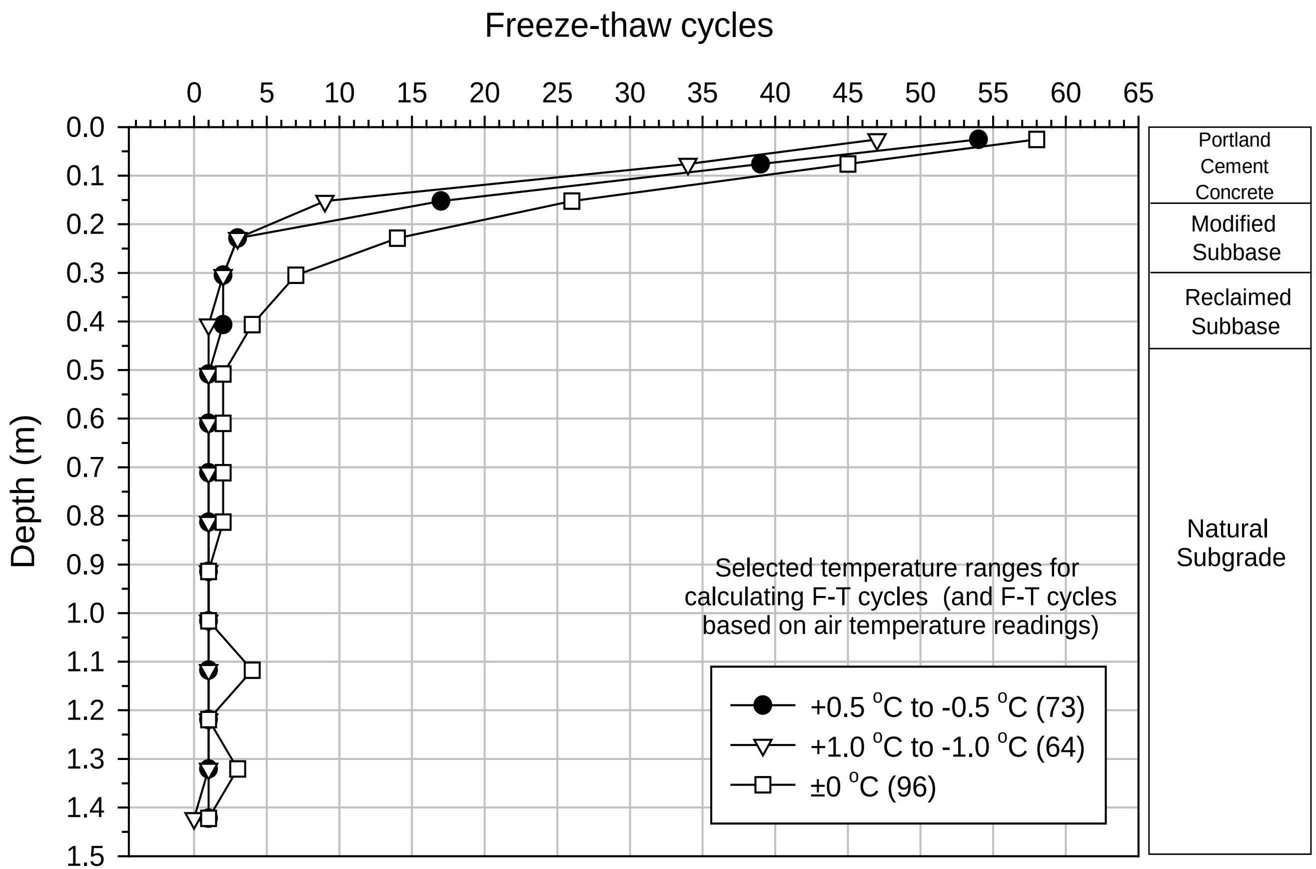
Placing geocomposite drainage layer at PCC/Subbase layer interface for improved drainage

2 to 4 orders of magnitude higher K_{sat} can be achieved with geocomposite without reducing stiffness



Frost-heave and thaw-weakening susceptibility is important to assess seasonal variations in support conditions

Pavement and foundation layers are subjected to significant number of freeze-thaw cycles



Source: Zhang, Y., Johnson, A., White, D.J. (2014). "Laboratory freeze-thaw assessment of stabilized pavement foundation materials," *Geotechnical Testing Journal,* ASTM (in review)

Poor drainage beneath pavement causes joint deterioration due to trapped water

K_{SAT} < 1 ft/day

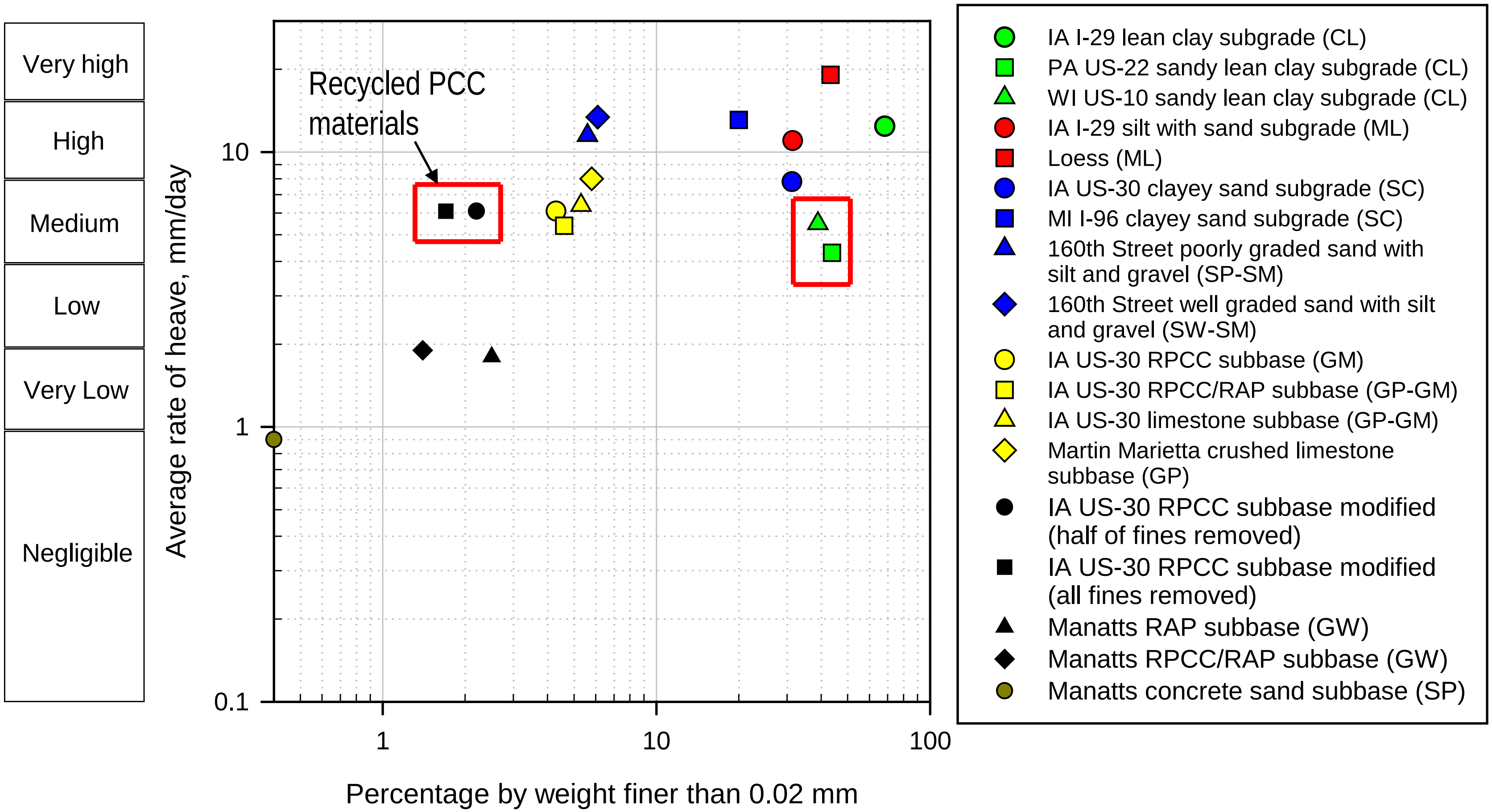
Source:

Urbandale, IA Project Report – PF2

Frost susceptibility ratings vary for similar materials

Material	USCS Classification	2nd Frost-Heave Susceptibility (mm/day)		Thaw-Weakening Susceptibility (% CBR)	
IA I-29 lean clay subgrade	CL	**High**	12.4	**Very High**	0.7
PA US-22 sandy lean clay subgrade	CL	**Medium**	4.3	**High**	3.0
WI US-10 sandy lean clay subgrade	CL	**Medium**	5.5	**Medium**	7.2
IA I-29 silt with sand subgrade	ML	**High**	11.0	**Very High**	1.4
Loess	ML	**Very High**	19.1	**Very High**	0.5
IA US-30 clayey sand subgrade	SC	**Medium**	7.8	**High**	2.7
MI I-96 clayey sand subgrade	SC	**High**	13.1	**Medium**	5.8
160th Street poorly graded sand with silt and gravel	SP-SM	**High**	11.5	**Negligible**	28.9
160th Street well graded sand with silt and gravel	SW-SM	**High**	13.4	**Very Low**	15.0
Manatts concrete sand subbase	SP	**Negligible**	0.9	**Medium**	8.1
IA US-30 RPCC subbase	GM	**Medium**	6.1	**Negligible**	33.3
IA US-30 RPCC/RAP subbase	GP-GM	**Medium**	5.4	**Negligible**	37.6
IA US-30 limestone subbase	GP-GM	**Medium**	6.4	**Negligible**	33.2
Martin Marietta crushed limestone subbase	GP-GM	**Medium**	8.0	**Negligible**	47.5
Manatts RAP subbase	GW	**Very Low**	1.8	**Medium**	8.7
Manatts RPCC/RAP subbase	GW	**Very Low**	1.9	**Negligible**	33.2

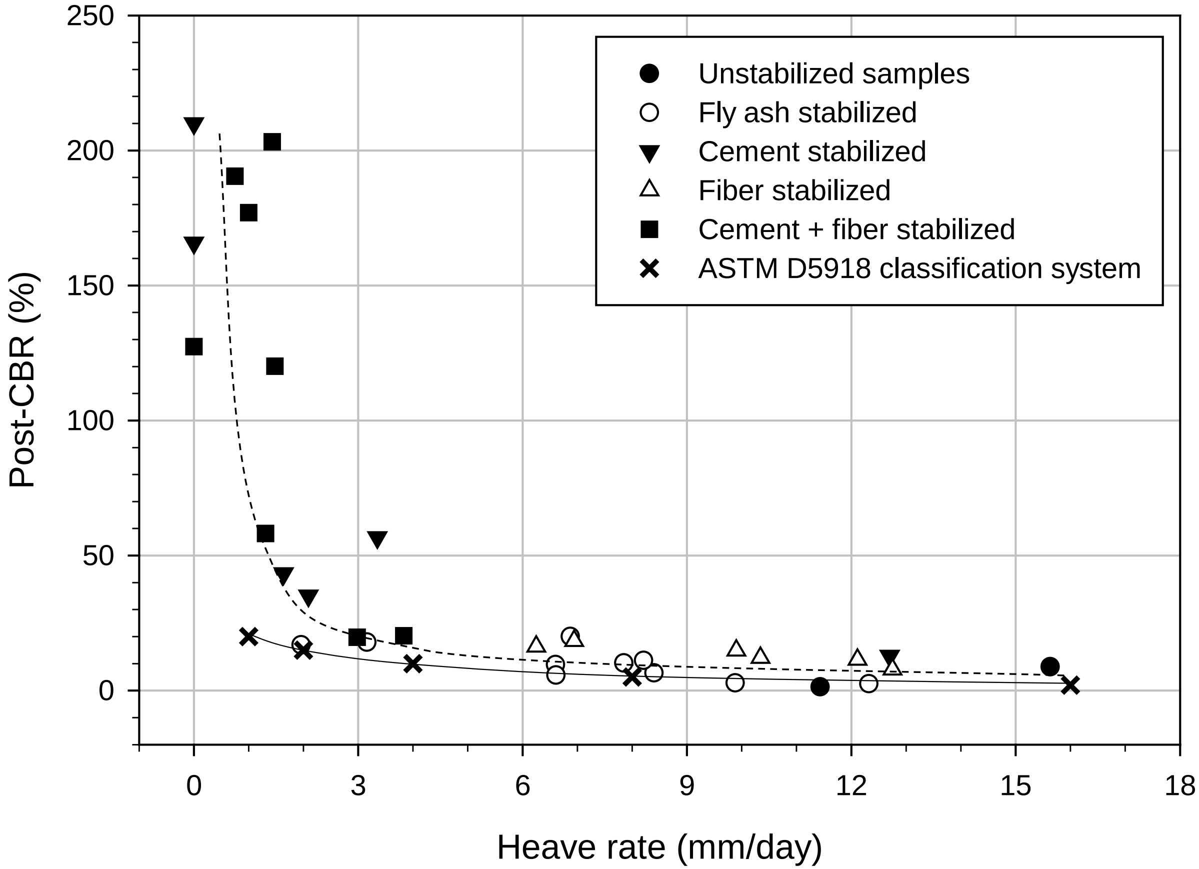
The frost-heave rate of recycled PCC granular material showed as much heave rate as cohesive materials.



Stabilized loess showed expected and unexpected frost-heave and thaw-weakening results.

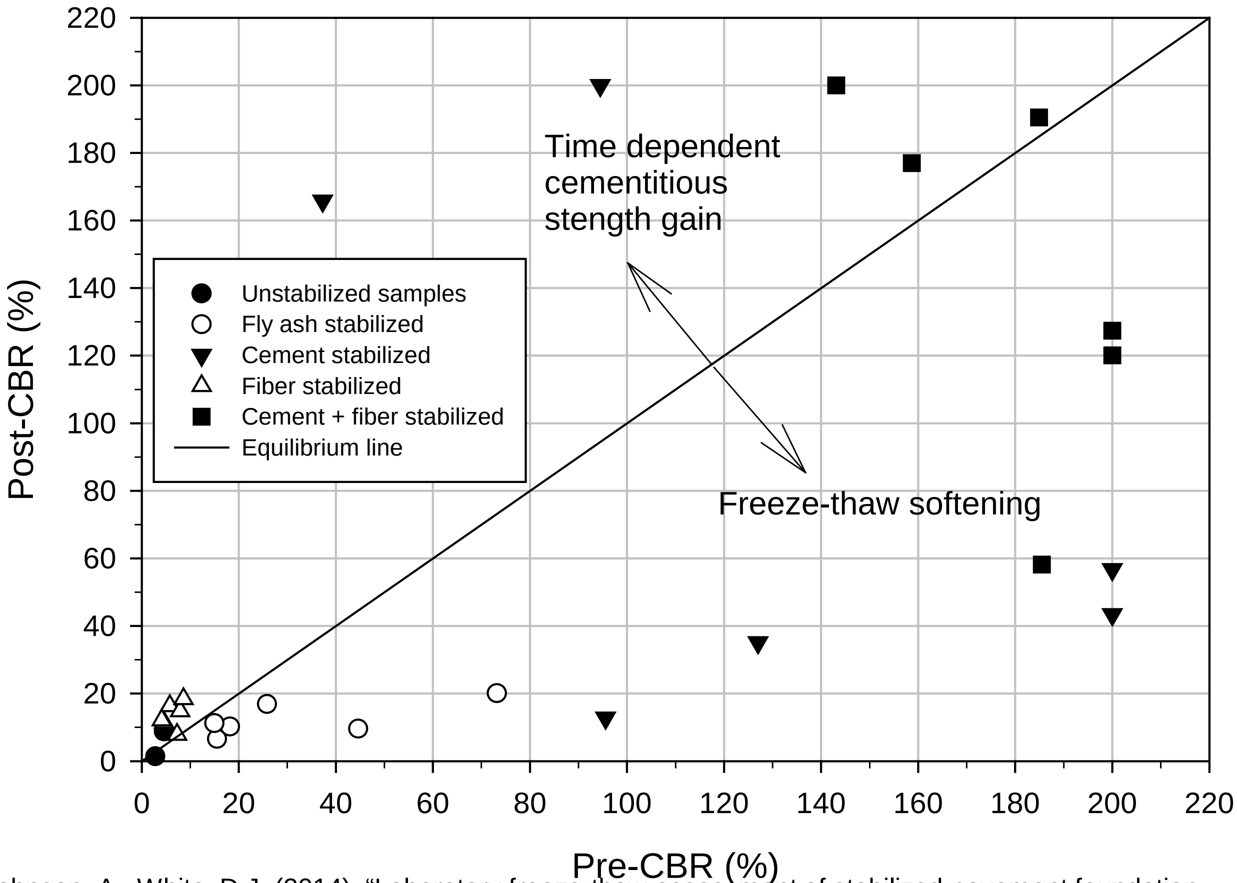
Stabilizer Type	Stabilizer Content (%)	Water Content (%)	2nd Frost-Heave Susceptibility (mm/day)		Thaw-Weakening Susceptibility (% CBR)	
Cement	9	13	**Negligible**	0	**Negligible**	>100
Cement	9	20	**Negligible**	0	**Negligible**	>100
Cement	11	20	**Negligible**	0	**Negligible**	>100
Cement	13	22	**Negligible**	0	**Negligible**	>100
Fly Ash	10	10	**High**	15.8	**High**	3.0
Fly Ash	10	19	**Very High**	22.2	**Medium**	5.0
Fly Ash	15	19	**High**	14.1	**Medium**	7.1
Fly Ash	20	22	**High**	11.0	**Negligible**	25.5
Untreated	—	17.5	**Very High**	19.1	**Very High**	0.5

After thaw CBR decreases as heave rate increases



Source: Zhang, Y., Johnson, A., White, D.J. (2014). "Laboratory freeze-thaw assessment of stabilized pavement foundation materials," *Geotechnical Testing Journal,* ASTM (in review)

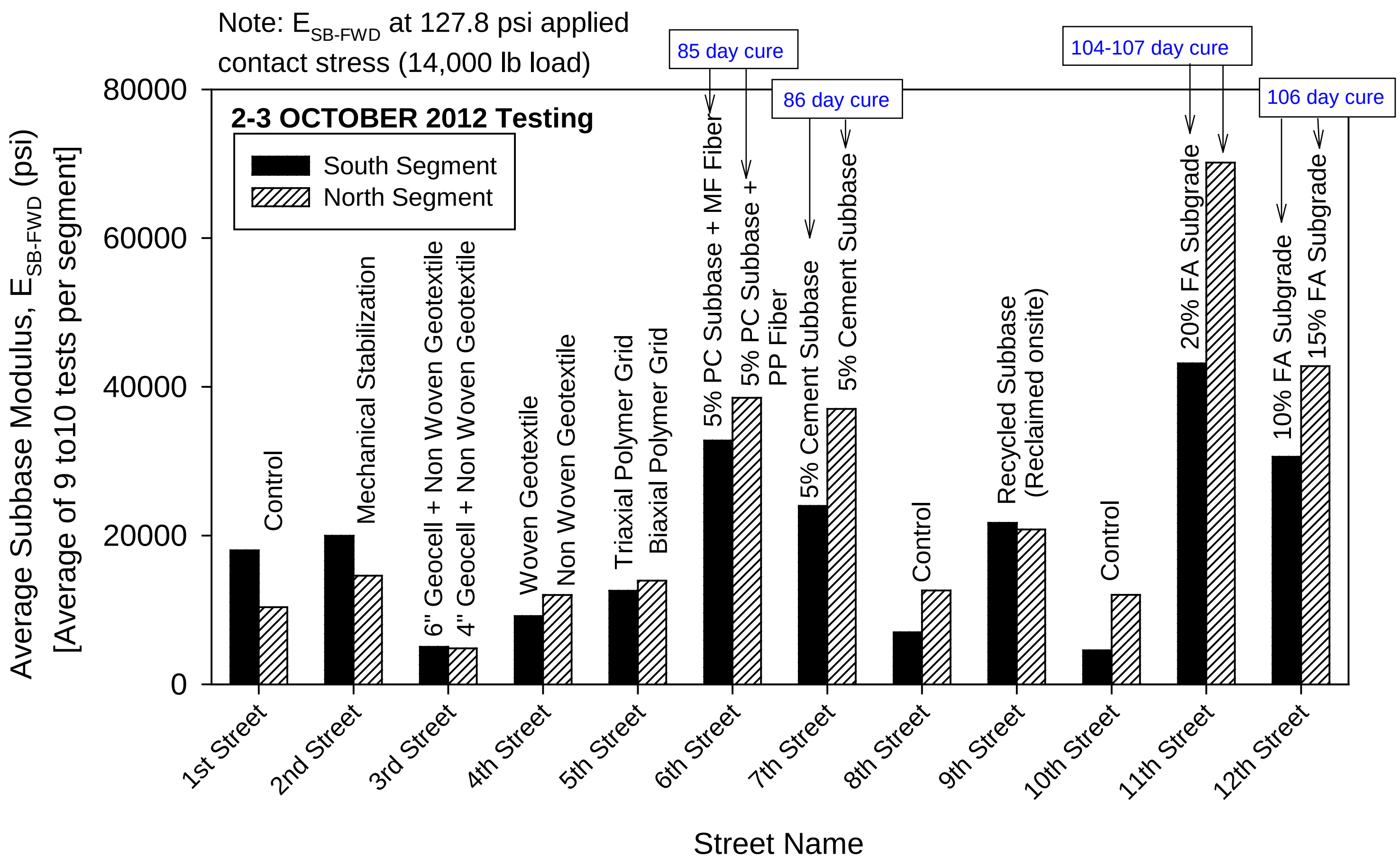
CBR values comparison before and after thawing



Source: Zhang, Y., Johnson, A., White, D.J. (2014). “Laboratory freeze-thaw assessment of stabilized pavement foundation materials,” *Geotechnical Testing Journal,* ASTM (in review)

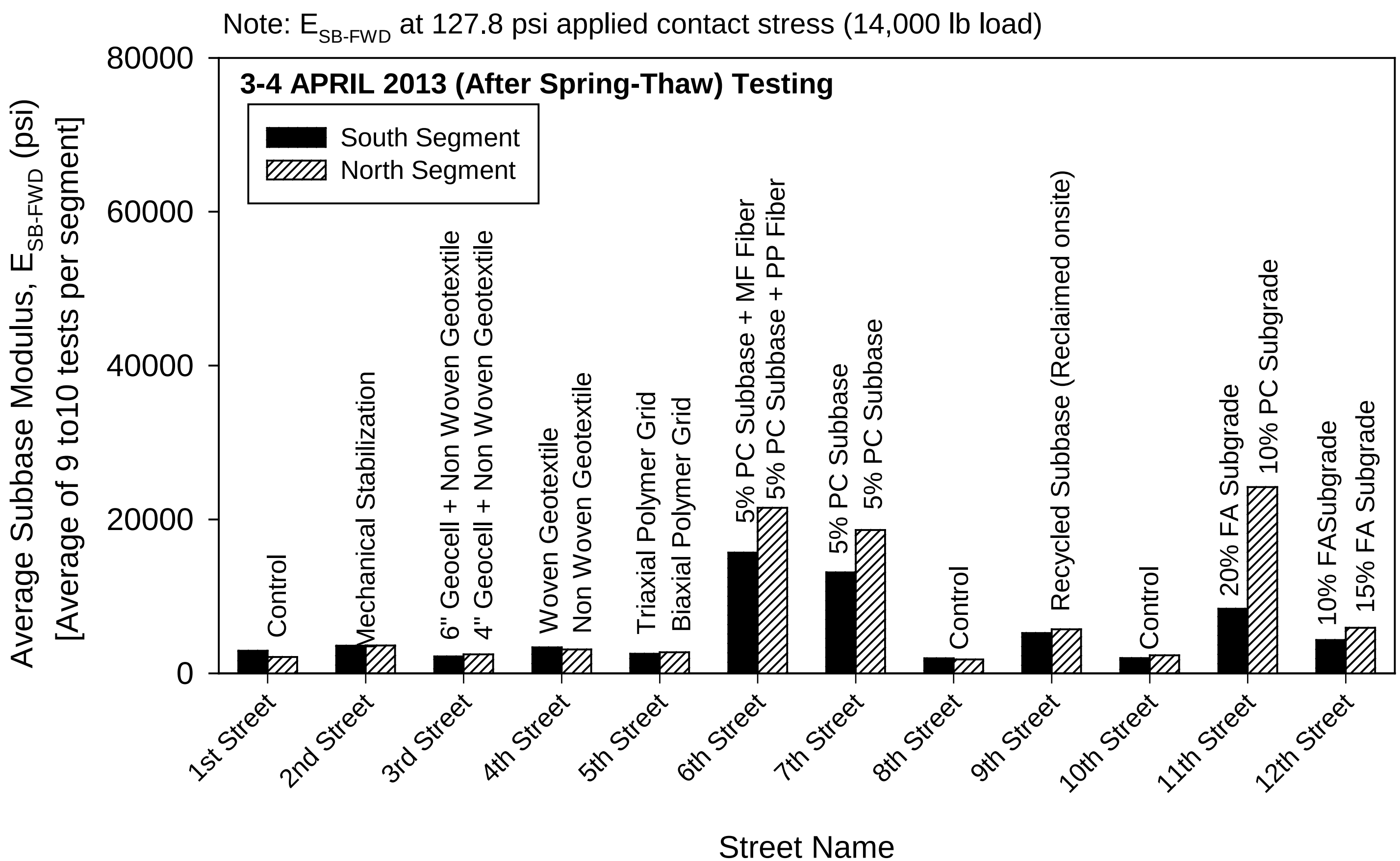
FWD testing show significant thaw-weakening in all sections except cement treated sections

OCTOBER 2012

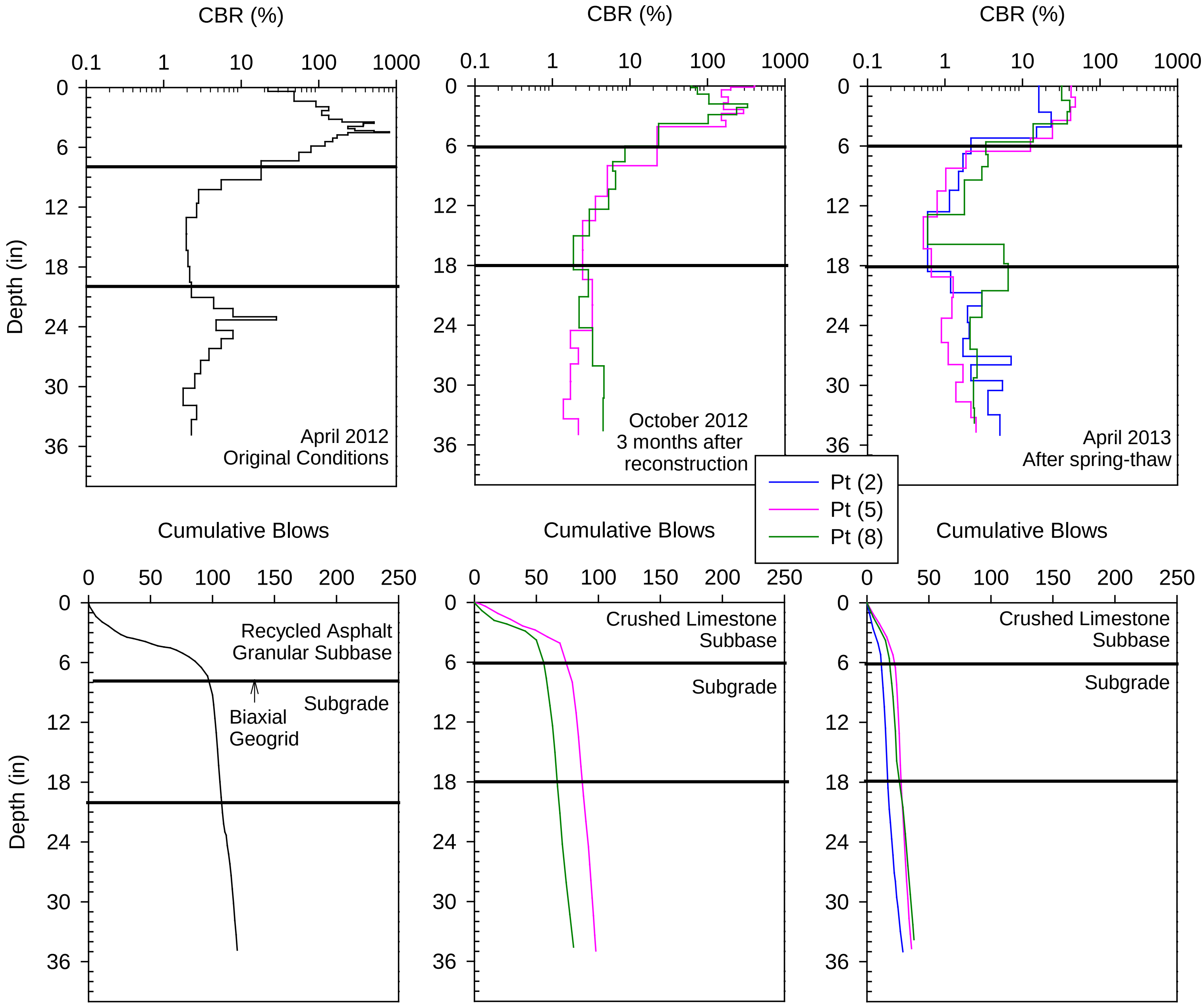


FWD testing show significant thaw-weakening in all sections except cement treated sections

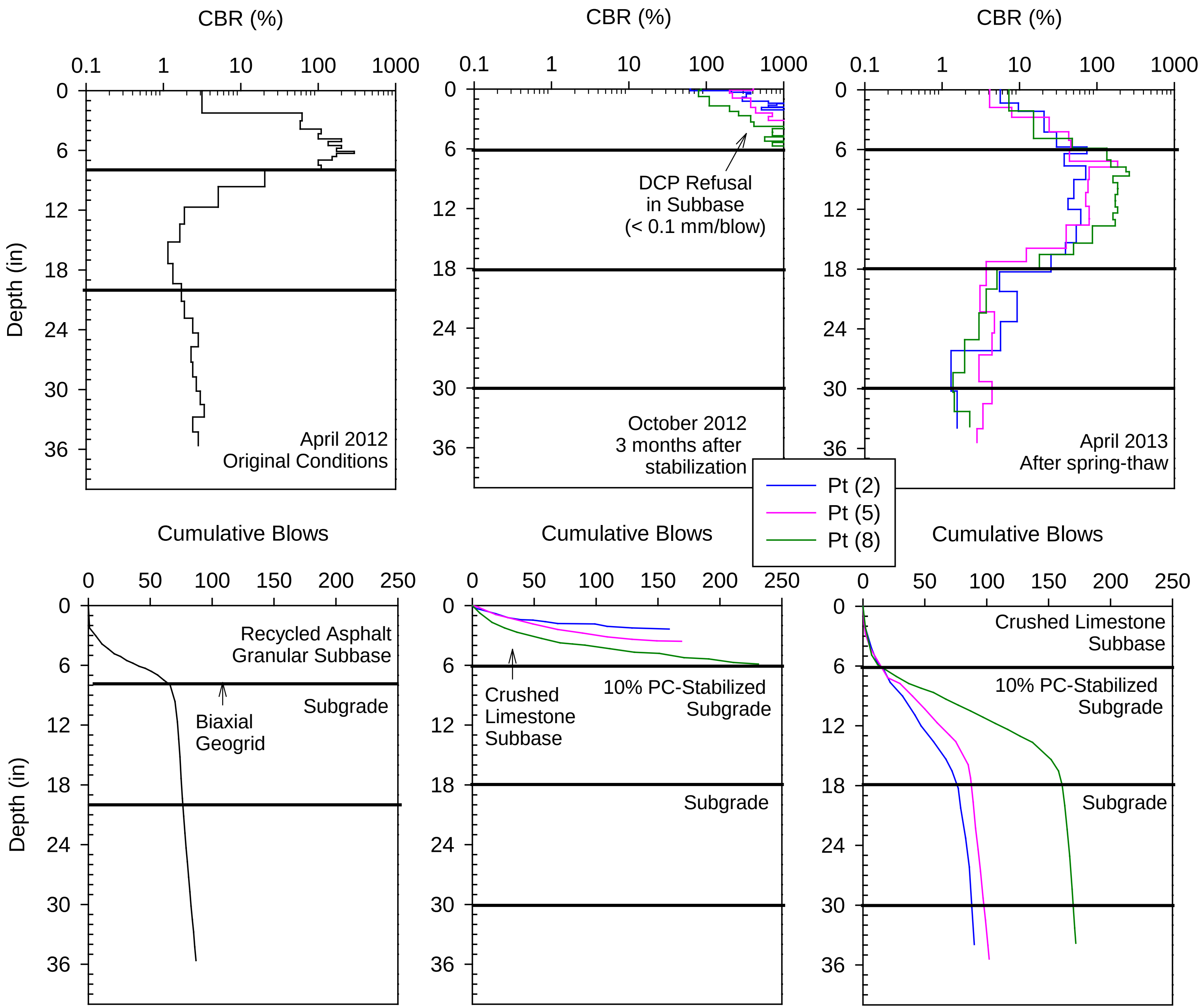
APRIL 2013



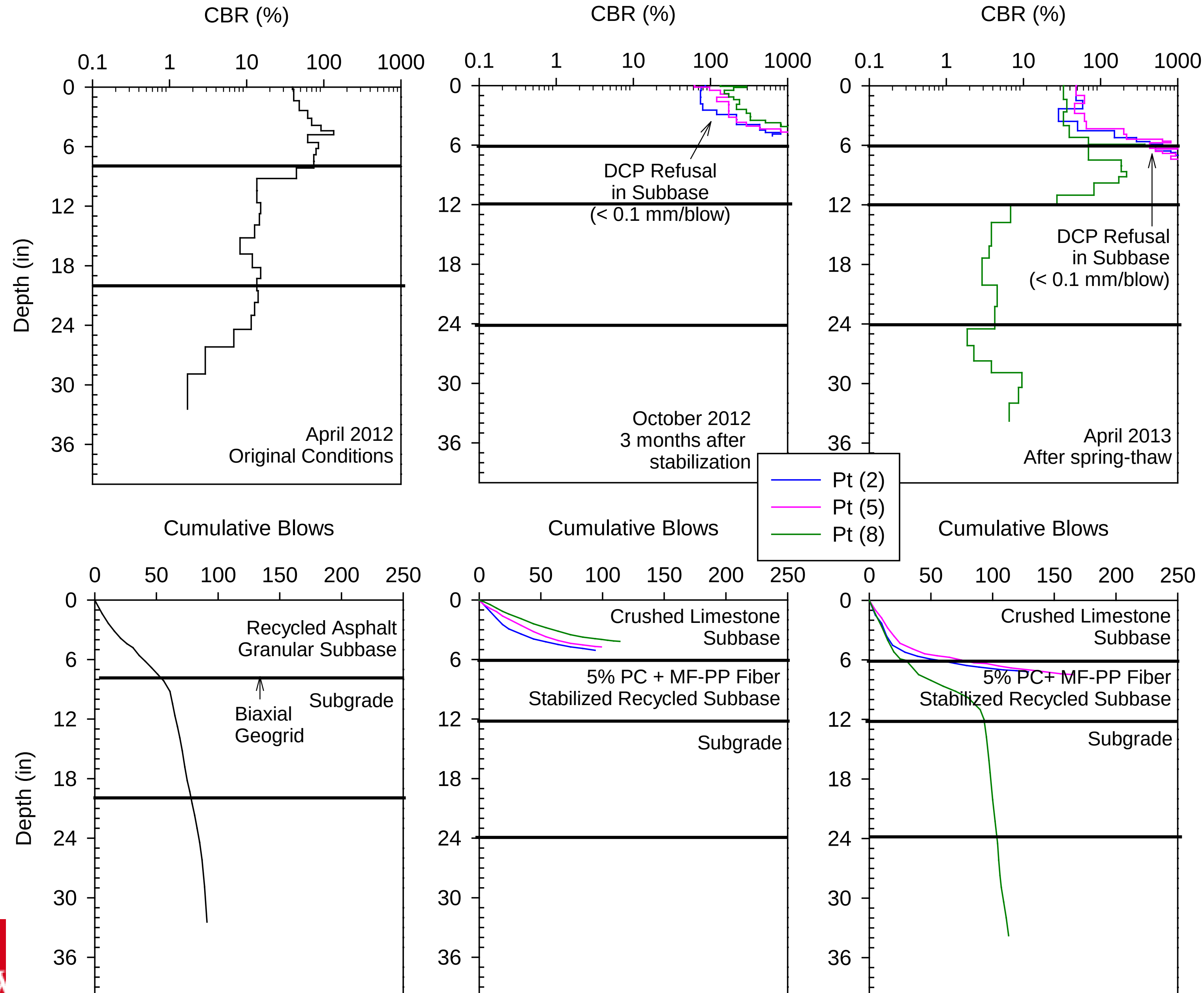
10th St. North Control



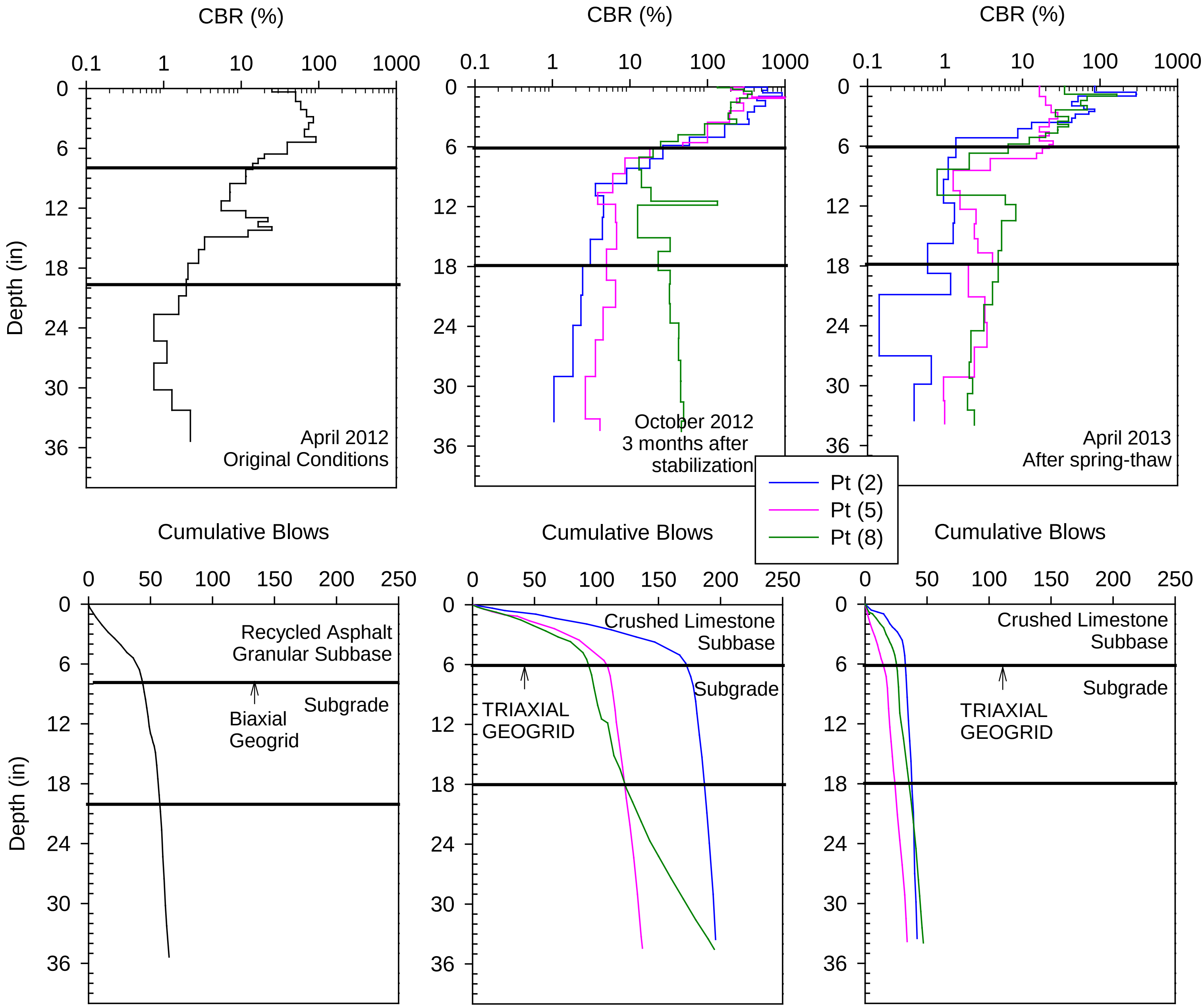
11th St. North 10% PC Stabilized Subgrade



6th St. South 5% PC+MF-PP Stabilized Recycled



5th St. North Triaxial Geogrid



Thank you!

- Please check out our pavement foundation manual coming in 2015.

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