UNDERSTANDING THE EFFECTS OF SUBGRADES & SUBBASES ON PAVEMENT SERVICE LIFE

David J. White, Ph.D., P.E.
Jerod P. Gross, P.E., LEED AP

Tech Center

Optimizing Pavement Base, Subbase, and Subgrade Layers for Cost and Performance of Local Roads – TR640

David J. White, Ph.D., P.E.
Associate Professor
Director, CEER
Pavana KR. Vennapusa, Ph.D.
Research Assistant Professor
Asst. Director, CEER

CENTER FOR CEER EARTHWORKS ENGINEERING RESEARCH

IOWA STATE UNIVERSITY

Acknowledgements

- Iowa Highway Research Board (TR-640)
- Snyder and Associates
- City of Ankeny
- City of Ames
- City of Knoxville
- City of Council Bluffs
- City of Burlington
- Story County
- Winneshiek County
- CPTech Center, Iowa State University
- CEER, Iowa State University

Summary of Pavements Tested

- Test sites located in
  - Central Iowa
  - South East Iowa
  - Western Iowa, and
  - North East Iowa
- Pavement Age: 30 days to 42 years
- Surface Distress Conditions: Poor to Excellent (PCI – 35 to 100)
- Support Conditions:
  - Natural Subgrade
  - Fly Ash Stabilized Subgrade
  - 6 in. to 12 in. Granular Subbase
- Pavement Thickness: 6 to 11 in.
- Traffic (AADT): 110 to 8900

Tech Center

Design Input Parameters

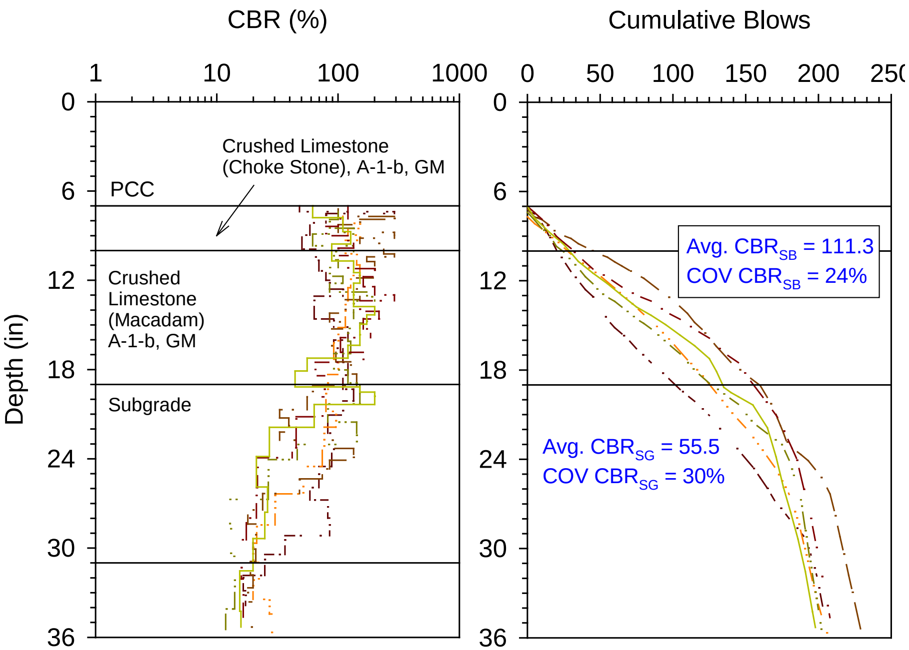
- Modulus of Subgrade Reaction (*k*)
- Composite Modulus of Subgrade Reaction (k_c)
- Loss of Support (LS)
- Coefficient of Drainage (C_d)

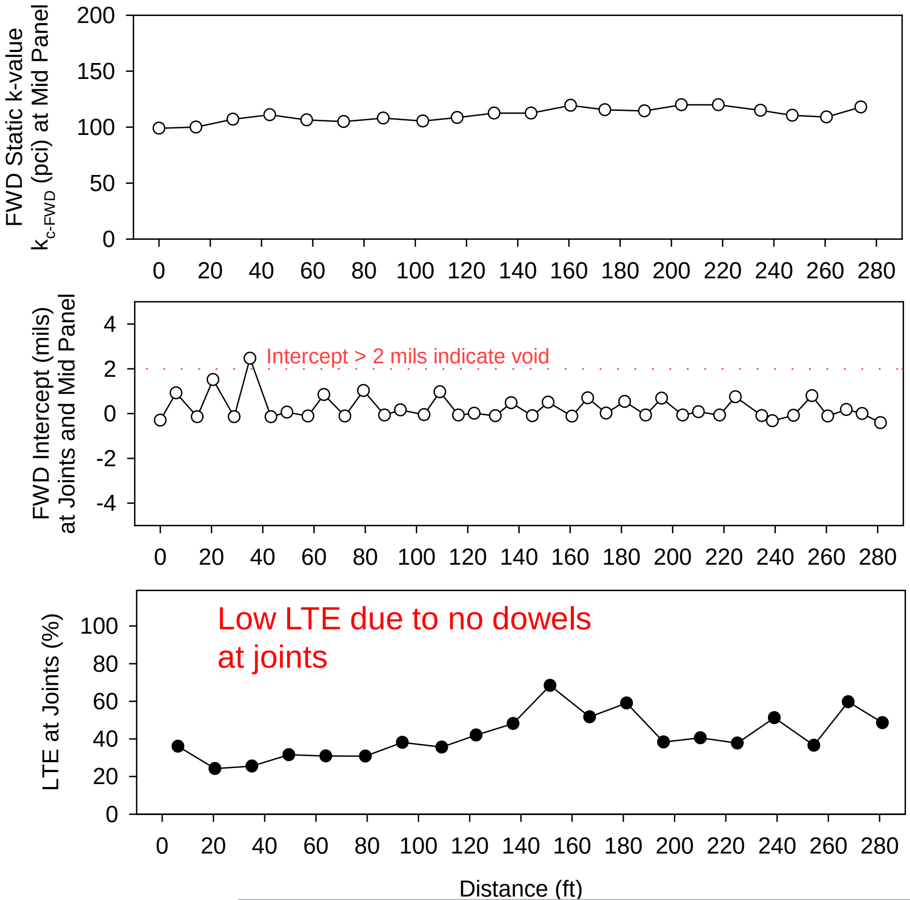
FWD, DCP

CHP

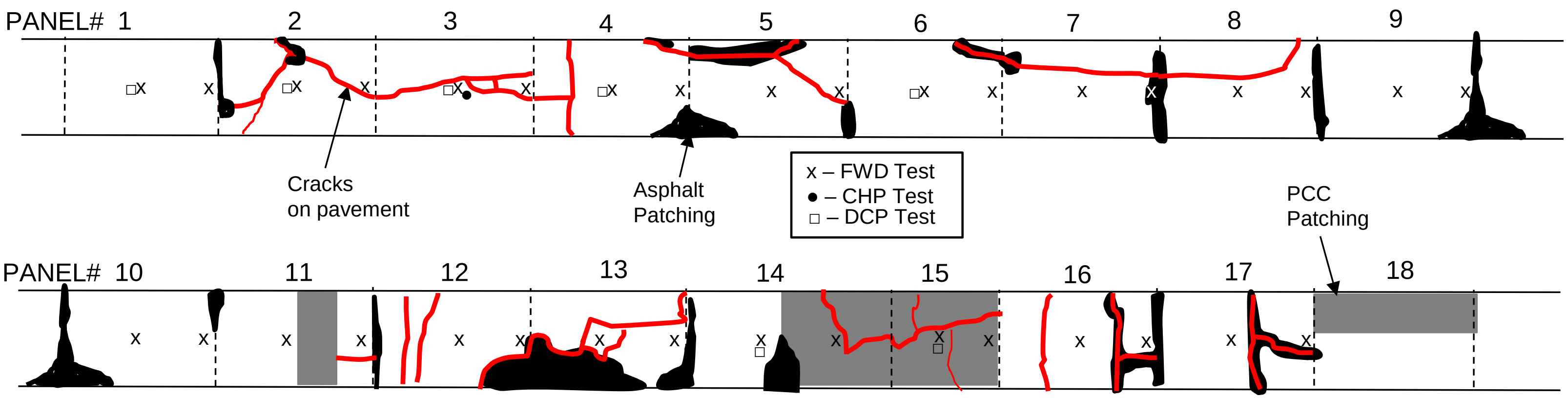
Section with highest k-values was with 12 in. granular base (9 in. macadam) over subgrade

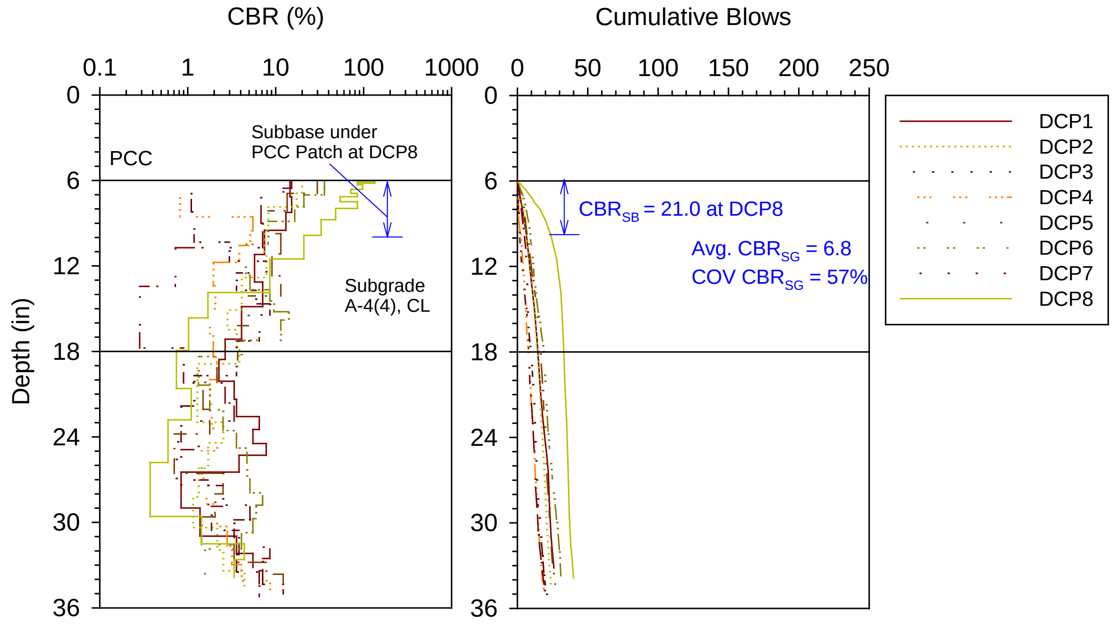
PCC: 7 to 7.5 in.
Age: 16 years
PCI: 92
AADT: 660 with 6% trucks





Section with lowest k-values was with PCC directly over subgrade





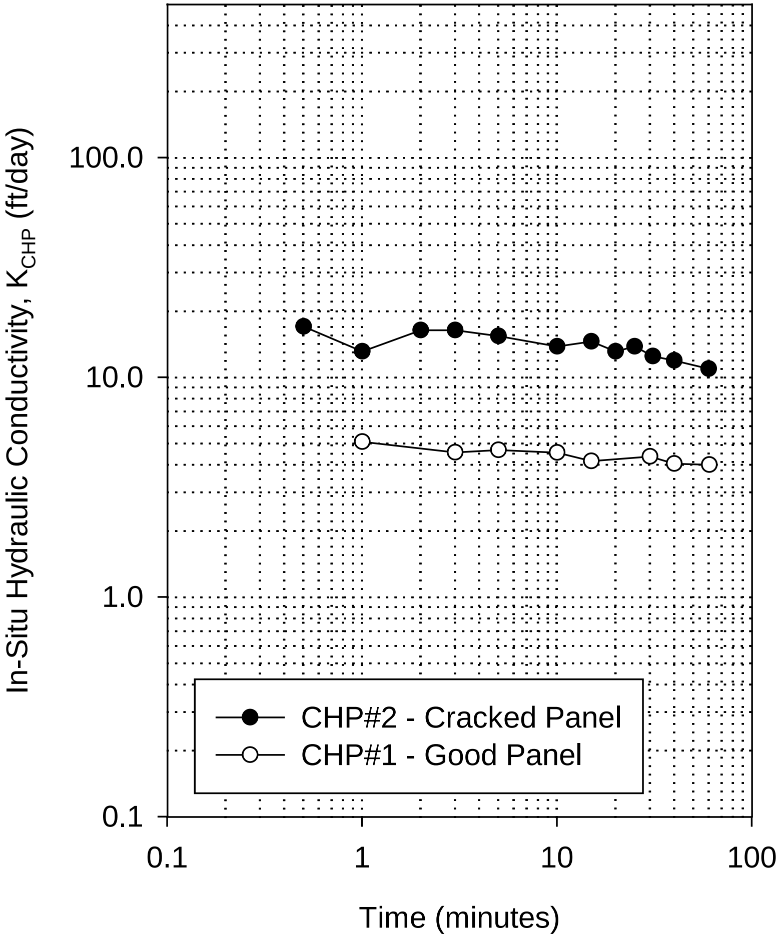
PCC: 6 in., Age: 42 years

PCI: 35, AADT: 560 with 3% trucks

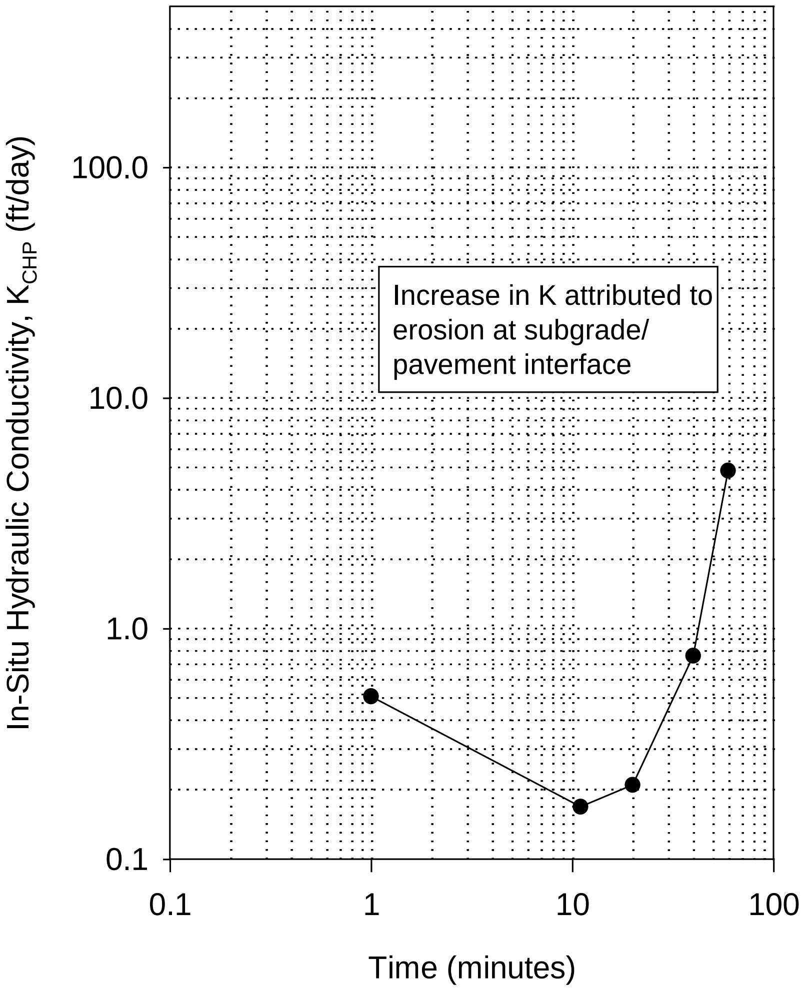
CHP Tests to measure permeability of materials under pavements

CHP#1

CHP#2



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



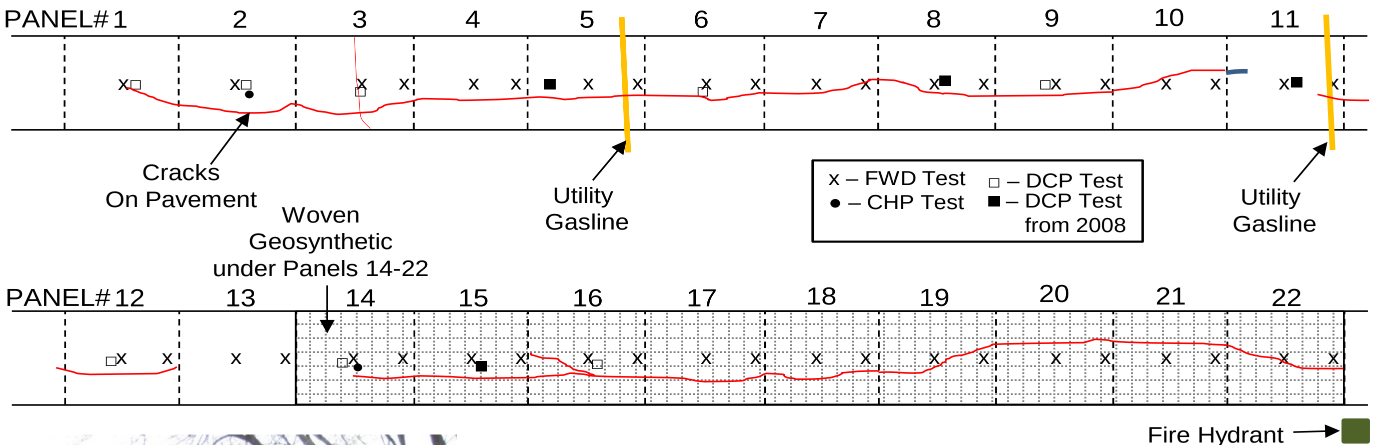
White and Vennapusa (2013)

Section with poor utility backfill compaction showed evidence of loss of support and non-uniformity

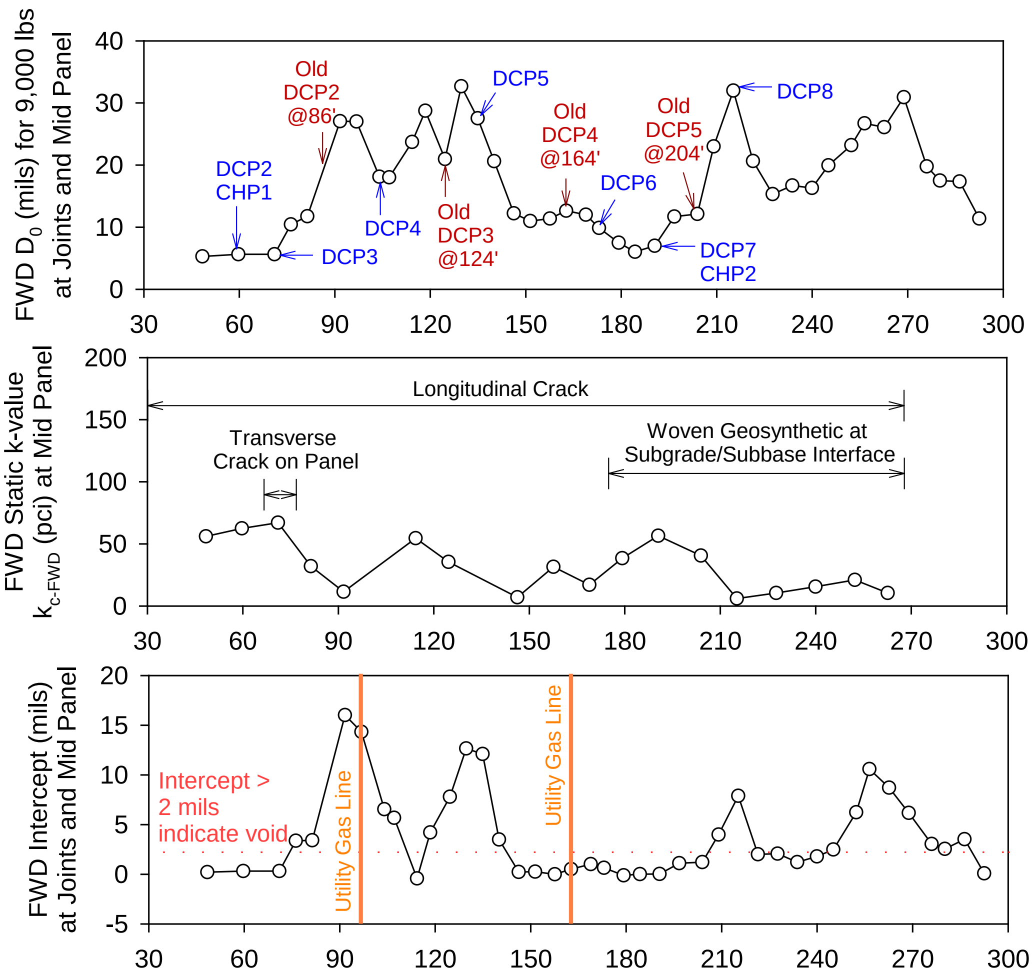
PCC: 9 in., Age: 4 years

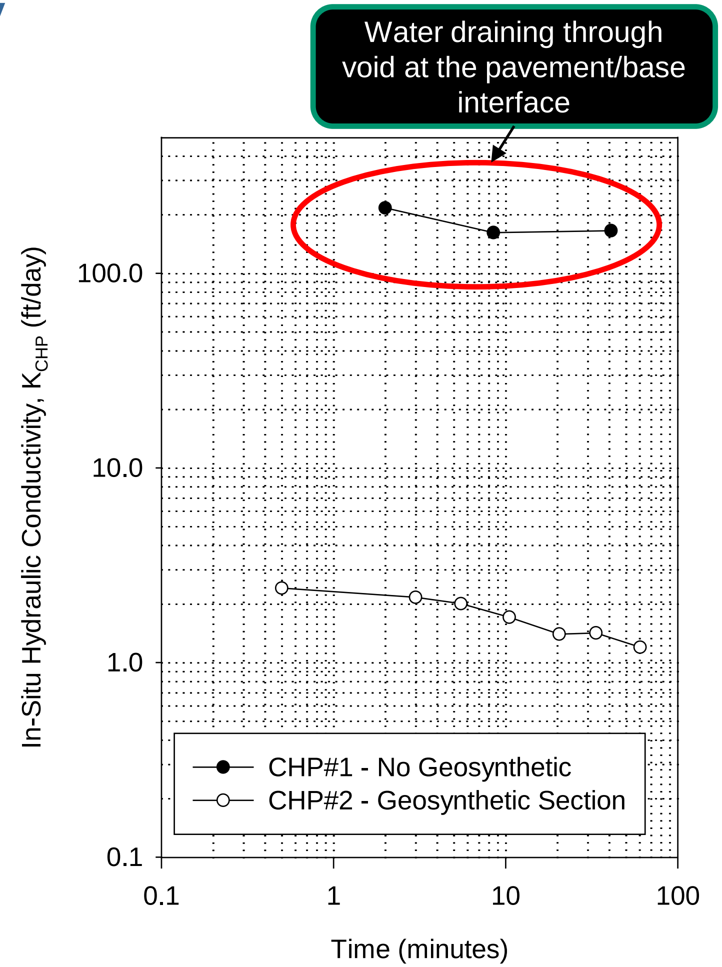
PCI: 85, AADT: 1000, 1% trucks

In Situ Test Locations and Crack Map
22 Panels tested on SW Westlawn Drive
Just South of SW 4th St., Ankeny



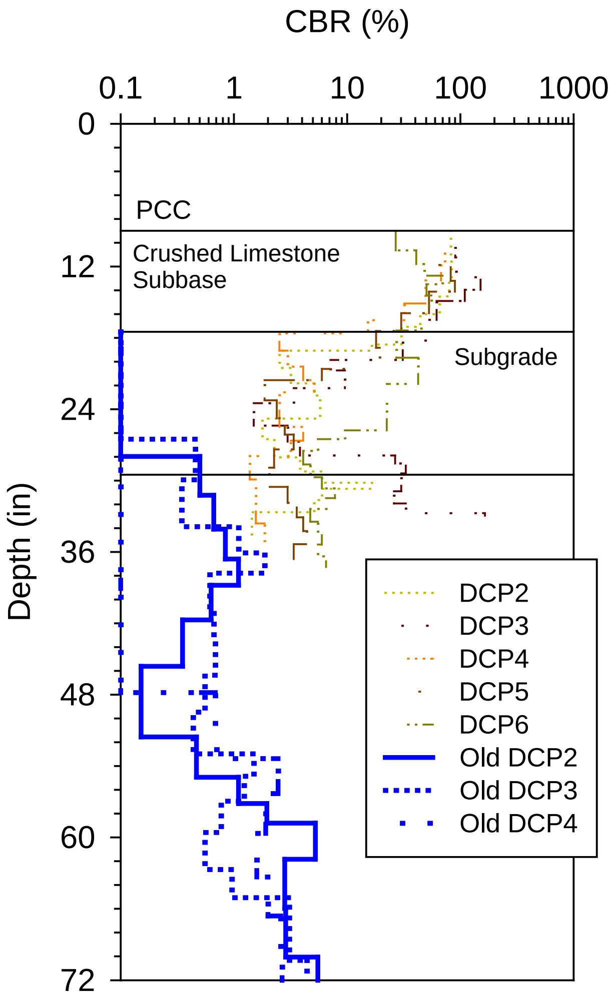
Section with poor utility backfill compaction showed evidence of loss of support and non-uniformity

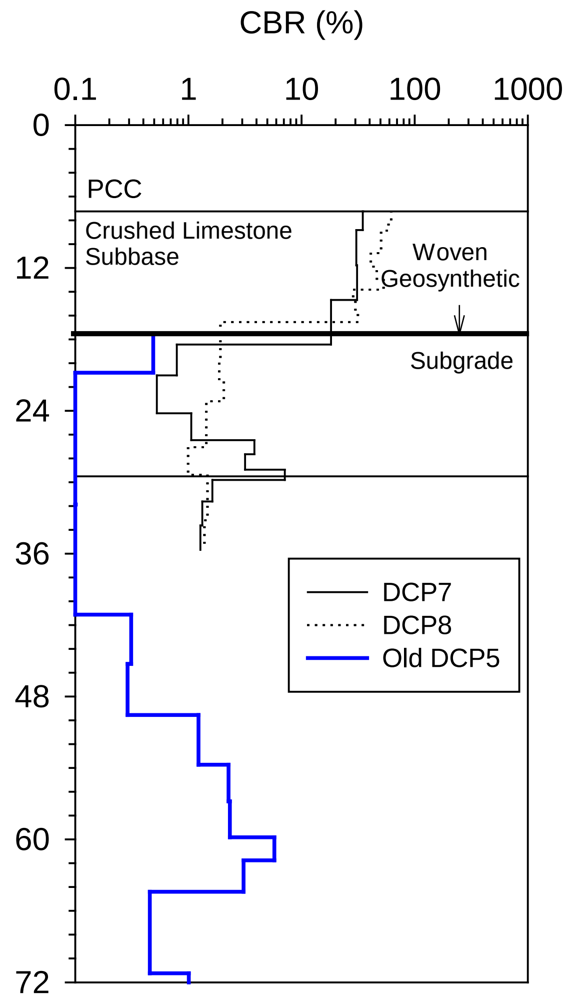




Comparison of DCP profiles during and 4 years after construction

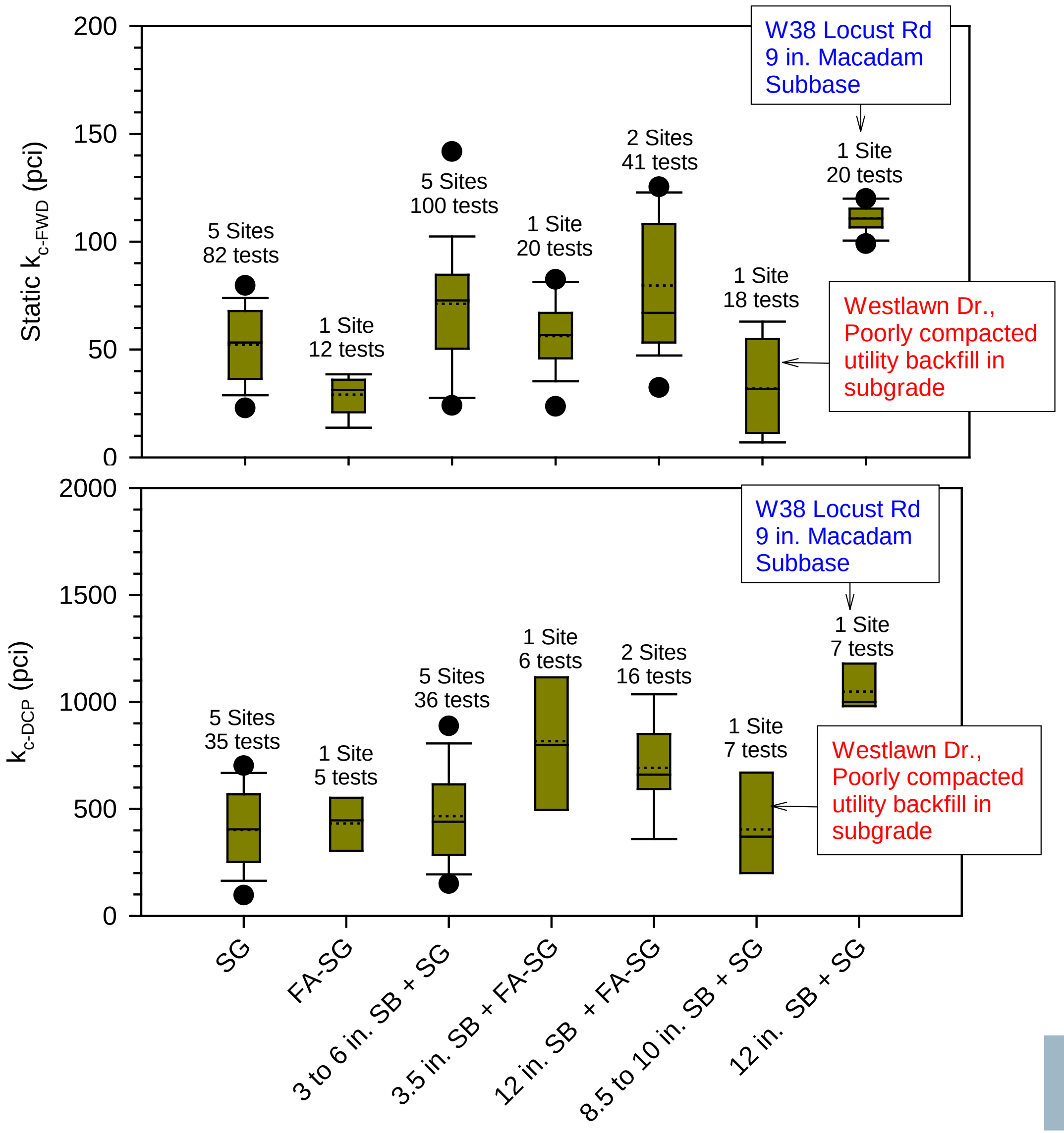
Indicate increase in CBR due to potential post-construction settlement and moisture content variations



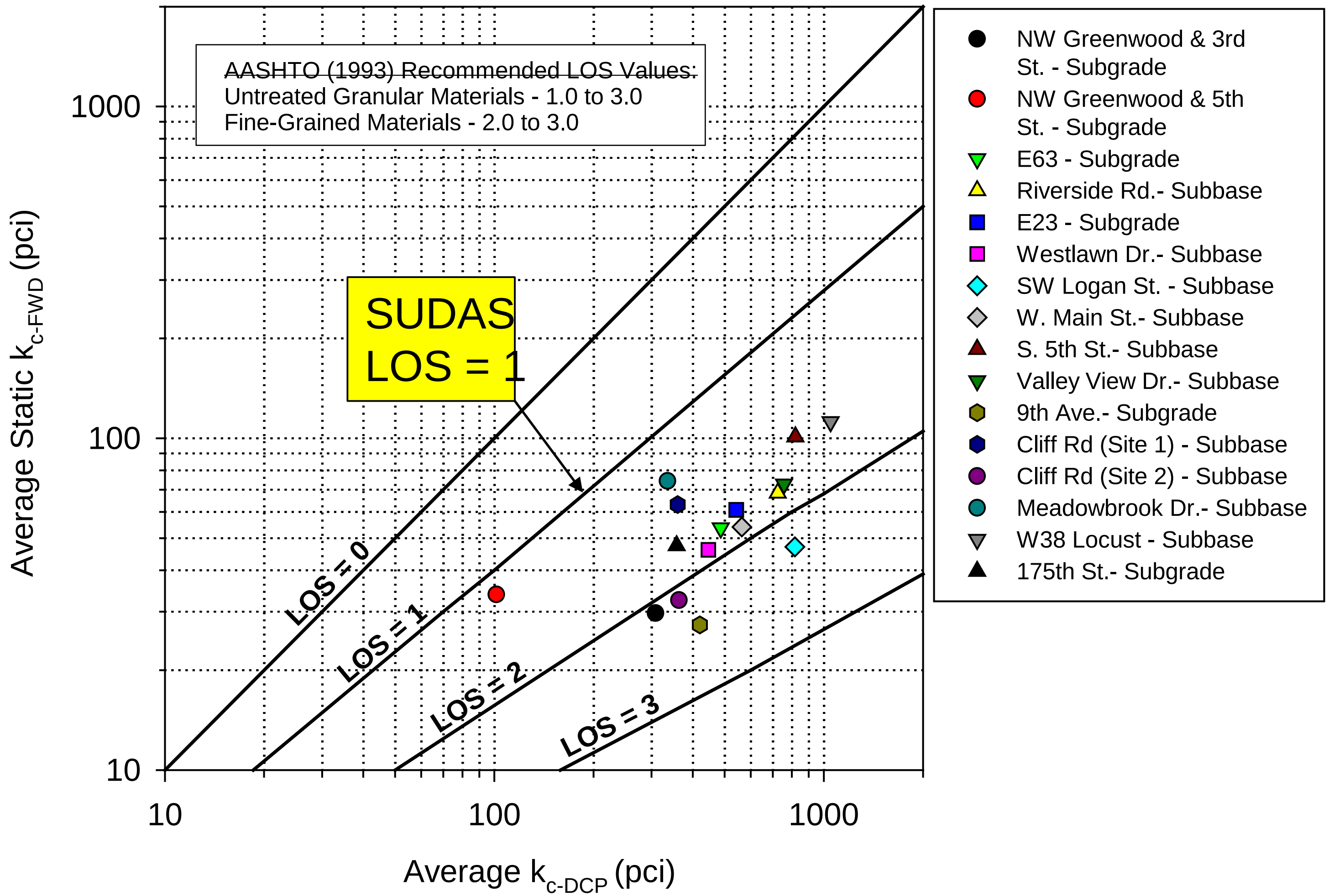


Tech Center

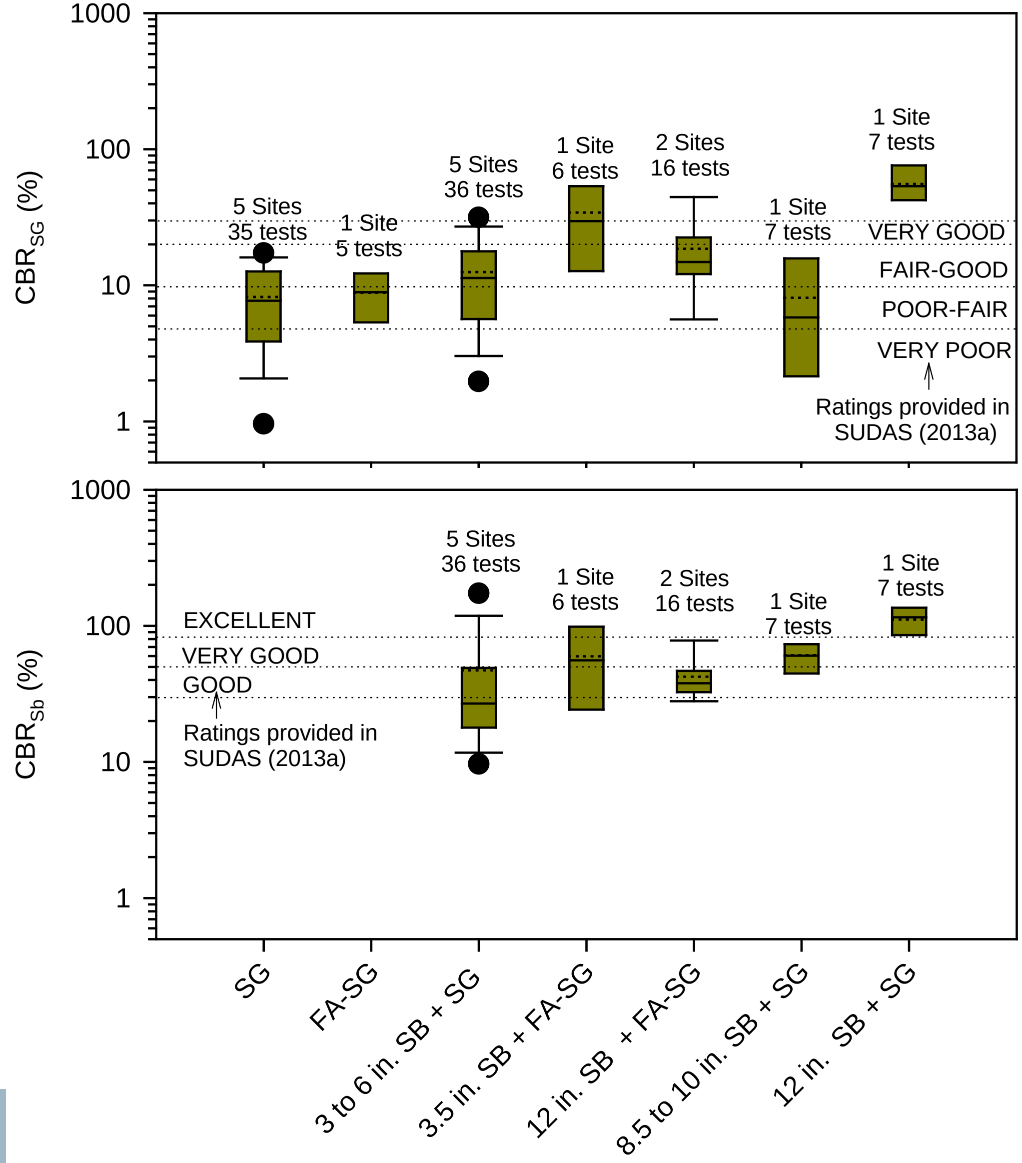
k-values from FWD and DCP



Comparing k-values from FWD and DCP provides an indication of LOS

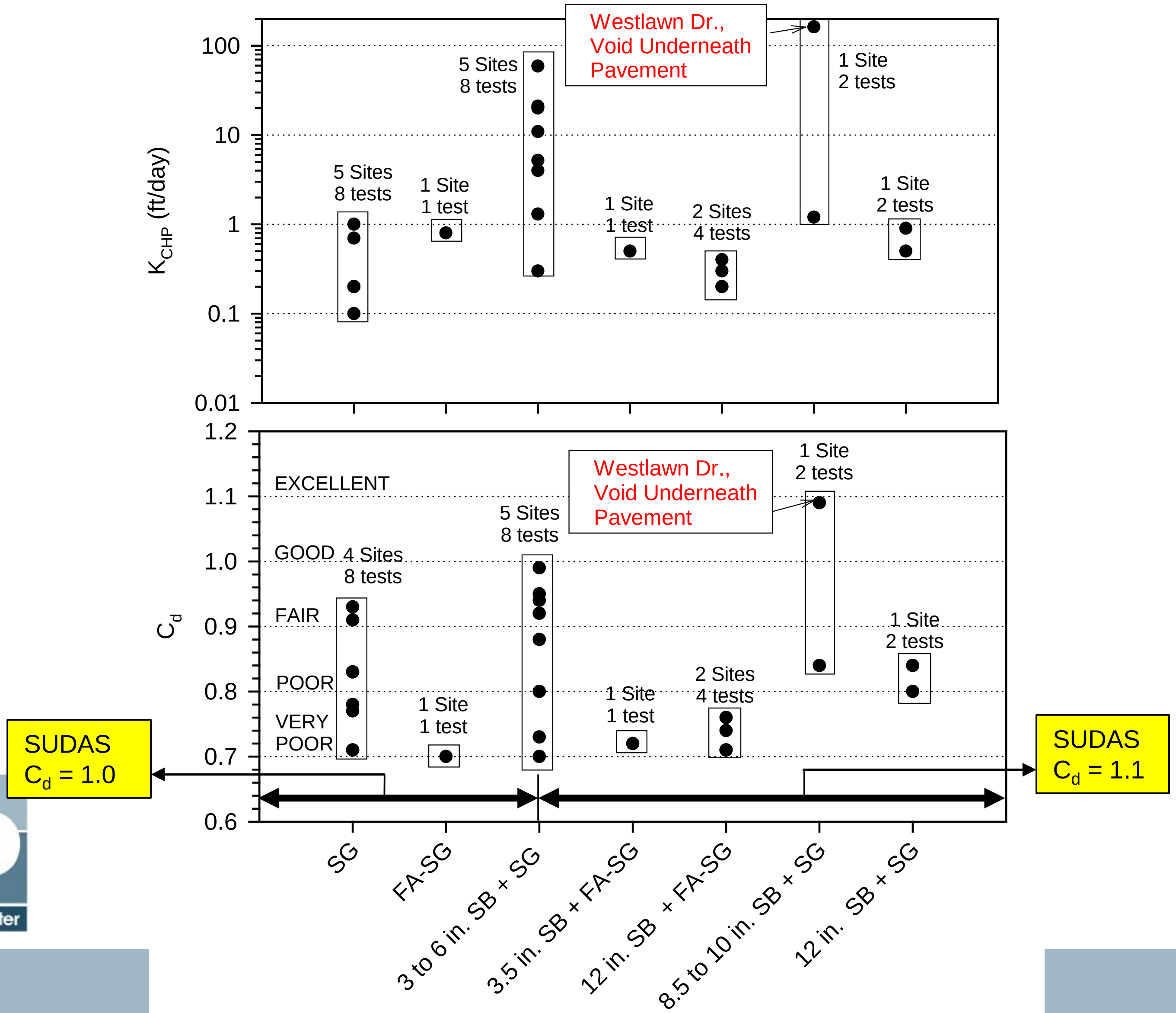


CBR values of subgrade and base layers



Tech Center

In Situ Permeability and C_d values



Field results indicate that the following are key factors affecting performance

- Poor support (due to low stiffness or CBR)
- Poor drainage
- Seasonal variations (freeze-thaw and frost-heave)
- Shrink-swell due to moisture variations
- Loss of support (due to erosion, non-uniform settlement, curling/warping)
- Poorly compacted utility trench backfill
- Differential settlement of foundation layers
- Overall non-uniformity

CP Tech Center

Recommendations for typical foundation treatment options to improve performance

Foundation treatment	Issues that can be mitigated
Engineered Subgrade and Backfill Compaction with Moisture, Density, and Lift Thickness Control	• Poorly compacted utility trench backfill • Differential settlement of foundation layers • Loss of support (due to non-uniform settlement) • Shrink-swell potential due to moisture variations (if high plasticity clays are excavated and replaced with engineered fill)
Portland Cement Stabilization of Subgrade	• Frost-heave and thaw-softening • Shrink-swell potential (applicable for high plasticity clays) • Wet/soft subgrade conditions during construction (to serve as construction platform) • Non-uniformity of stiffness[1]
Fly Ash Stabilization of Subgrade (Self-Cementing)	• Wet/soft subgrade conditions during construction (to serve as construction platform) • Shrink-swell potential (applicable for high plasticity clays) • Non-uniformity of stiffness[1]
Lime Stabilization of Subgrade	• Shrink-swell potential (applicable for high plasticity clays) • Non-uniformity of stiffness[1]
Granular Subbase (Untreated)	• Poor drainage[2] • Frost-heave[3] and thaw-softening • Poor support (low stiffness)[4]
Cement or Asphalt Stabilization of Subbase	• Poor drainage[5] • Poor support (low stiffness) • Frost-heave and thaw-softening
Cement + Fiber Stabilization of Subbase	• Poor drainage[5] • Poor support (low stiffness) • Frost-heave and thaw-softening
Geotextile Separation Layer at Subbase/Subgrade Interface	• Poor drainage[6] • Poor support (low CBR)
Geogrid Reinforcement at Subbase/Subgrade Interface	• Poor support (low CBR)
Geocomposite Drainage System at Subbase/Subgrade Interface	• Poor drainage
Granular Macadam Subbase with Choke Stone Cover	• Poor drainage[7] • Poor Support (low stiffness and CBR)[8] • Frost-heave and thaw-softening
Emulsified Asphalt Stabilized Granular Macadam Subbase	• Poor drainage[9] • Poor Support (low stiffness and CBR)[9] • Frost-heave and thaw-softening

Additional information: http://www.ceer.iastate.edu

David J. White, Ph.D., P.E.
Associate Professor and holder of Richard L. Handy Professorship
Director, Center for Earthworks Engineering Research (CEER)
Department of Civil, Construction and Environmental Engineering
Iowa State University
Phone: 515.294.1463
Email: djwhite@iastate.edu


DRAFT

Optimizing Pavement Base, Subbase and Subgrade Layers for Cost and Performance on Local Roads

JULY 2013

Final Report

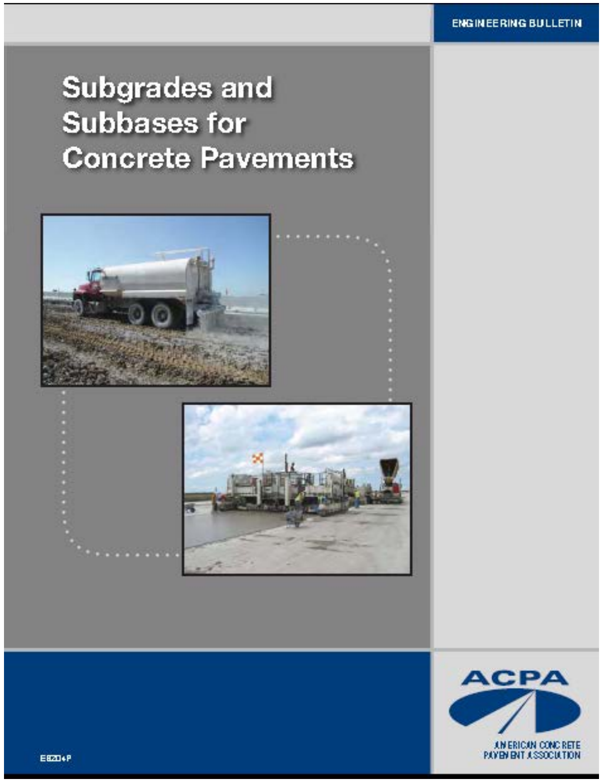
CENTER FOR CEER EARTHWORKS ENGINEERING RESEARCH

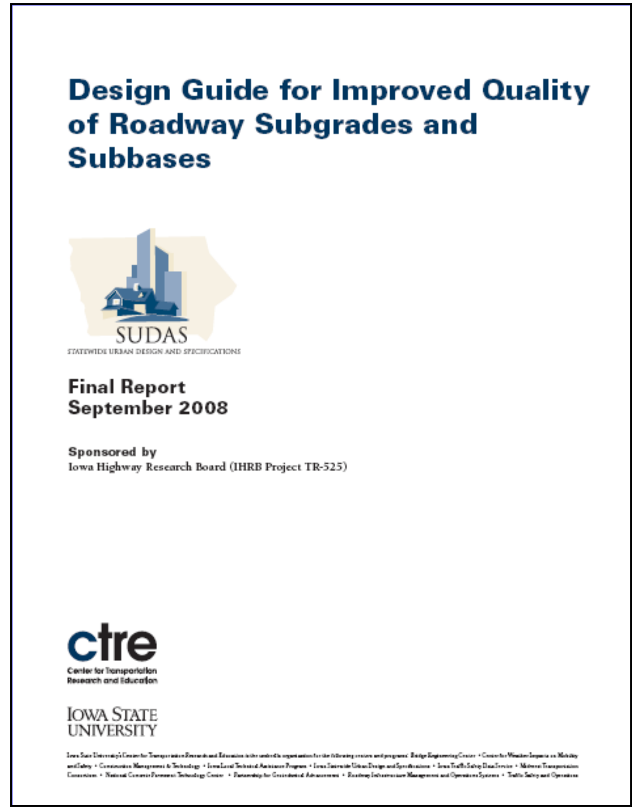
National Concrete Pavement Technology Center

IOWA STATE UNIVERSITY
Institute for Transportation

Sponsored by
Iowa Highway Research Board
(IHRB Project TR-640)
Iowa Department of Transportation
(InTrans Project 11-422)

Subbase Design Guidelines

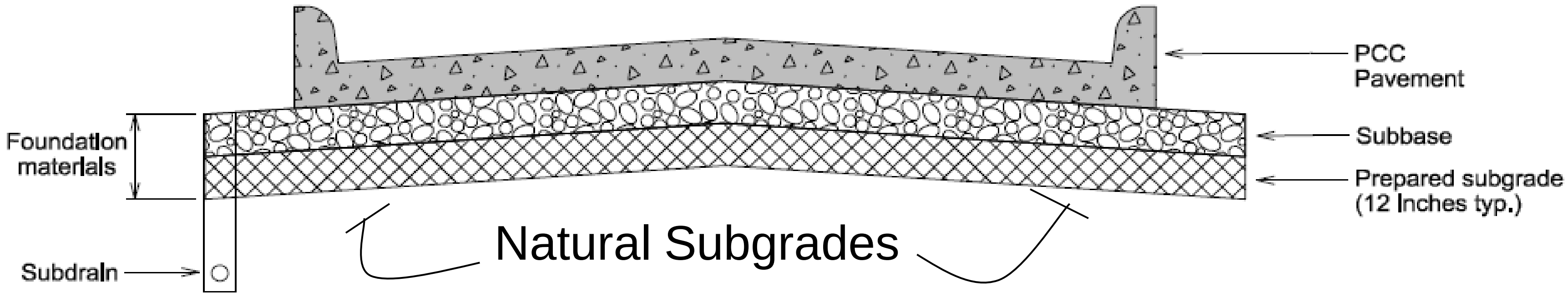




Subbase & Pavement Design

Good design applies these parameters:

- Actual soil characteristics (subgrade)
- Soil preparation
- Use of subbase/stabilization
- Traffic volumes including % trucks
- Design Life – 20 to 50 years
- Expected traffic growth per year over design life

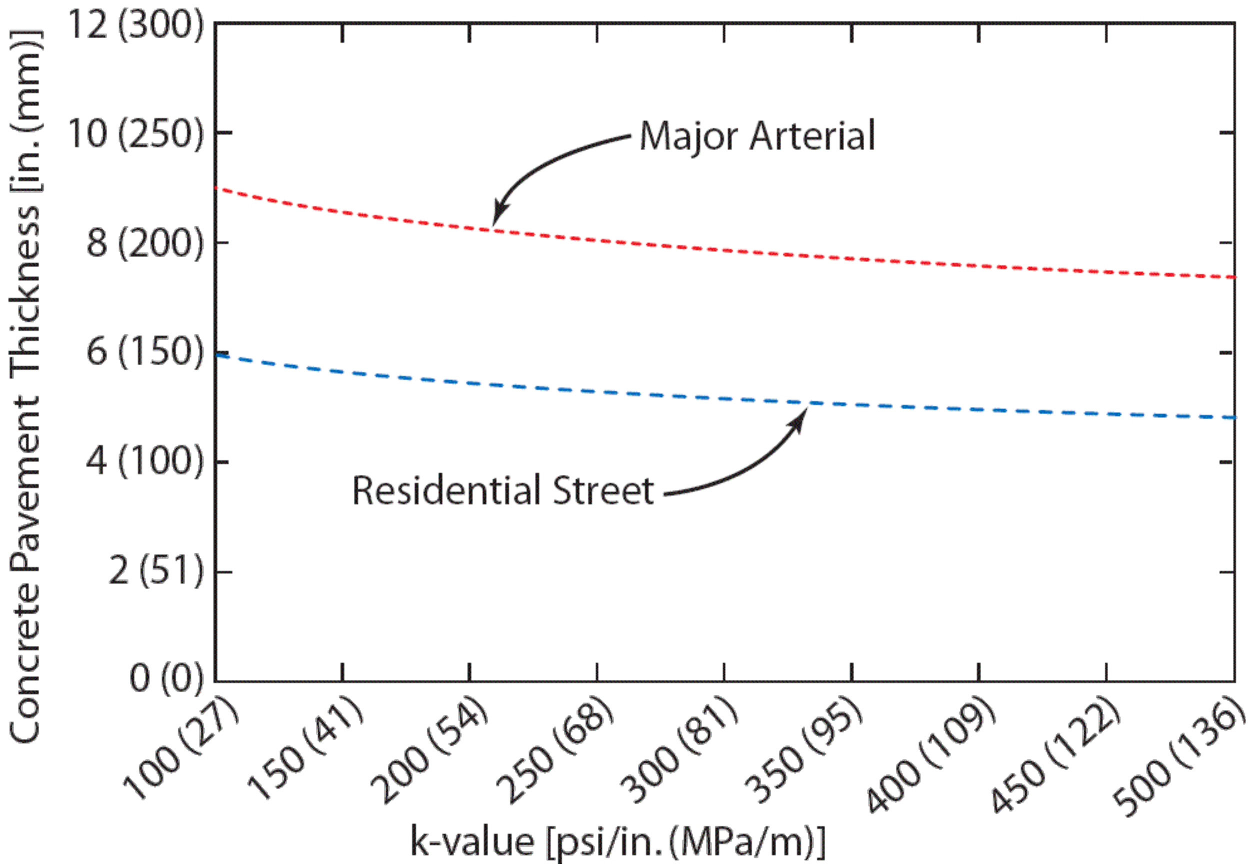


Why consider subbase?

+ Construction platform
+ Uniform support
+ Reduce delays
+ Drainability
+ Capillary cutoff
- Upfront cost

Subbases

- PCC thickness is not highly sensitive to support stiffness (k)
- Not always cost effective to increase subbase for structure



Tech Center

PCC Pavement Design Parameters

<u>AASHTO 93</u>

- Coefficient of Drainage, Cd
- Modulus of Subgrade Reaction, k
- Loss of Support, LOS
- Truck Traffic (quantity and type)

Tech Center

PCC Pavement Design Parameters

Table 5F-1.01: Summary of Design Parameters for Pavement Thickness

Section	Description	Flexible HMA	Rigid JPCP/JRCP
5F-1, B, 1	**Performance Criteria**		
	a. Initial Serviceability Index	X	X
	b. Terminal Serviceability Index	X	X
5F-1, B, 2	**Design Variables**		
	a. Analysis Period	X	X
	b. Design Traffic	X	X
	c. Reliability	X	X
	d. Overall Standard Deviation	X	X
5F-1, B, 3	**Material Properties for Structural Design**		
	a. Soil Resilient Modulus	X	
	b. Modulus of Subgrade Reaction		X
	c. Concrete Properties		X
	d. Layer Coefficients	X	
5F-1, B, 4	**Pavement Structural Characteristics**		
	a. Coefficient of Drainage	X	X
	b. Load Transfer Coefficients for Jointed		X
	c. Loss of Support		X

PCC Pavement Design Parameters

Serviceability – Ability to serve traffic (condition rating from 5 to 0)

- P_o Initial Serviceability
- P_t Terminal Serviceability

Table 5F-1.02: Terminal Serviceability Indexes (P_t) for Street Classifications

P_t	Classifications
2.00	Secondary Roads and Local Residential Streets
2.25	Minor Collectors, Industrial, and Commercial Streets
2.50	Major Collectors and Arterials

CP Tech Center

PCC Pavement Design Parameters

Reliability is the probability that the design will succeed for the life of the pavement.

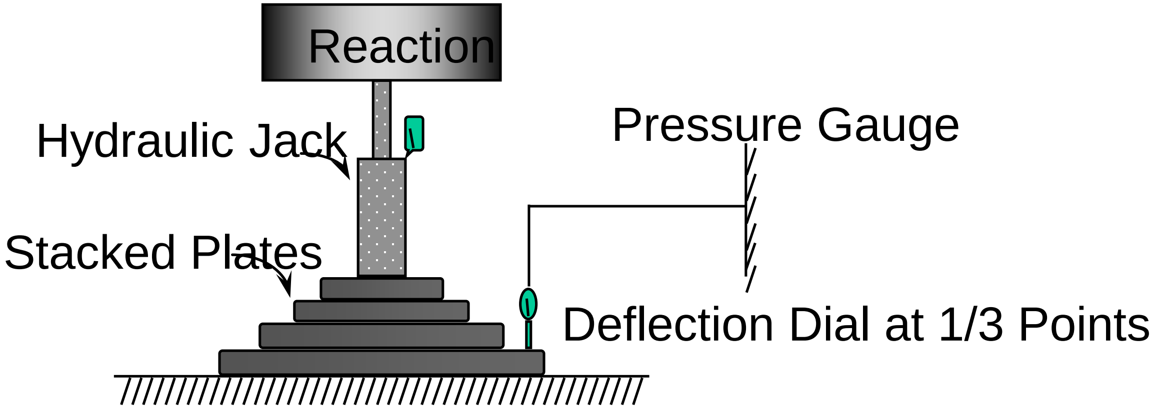
Table 5F-1.03: Reliability for Flexible and Rigid Pavement Design

Street Classification	Reliability
Local Streets	80%
Collector Streets	88%
Arterial Streets	95%

Tech Center

Pavement Thickness Design

- Use Modulus of Subgrade Reaction k
  - Concrete needs uniformity of support
  - Modulus of Subgrade reaction, $k = M_R / 19.4$
  - Composite Modulus of Subgrade Reaction = (k_c)
    - Strength corrected from subbase material



k (psi/in) = unit load on plate / plate deflection

Pavement Thickness Design

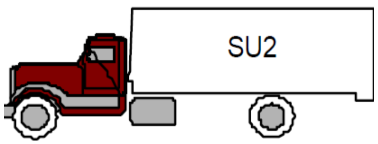
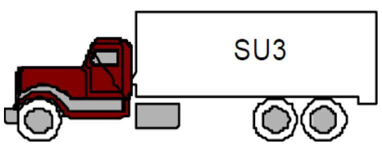
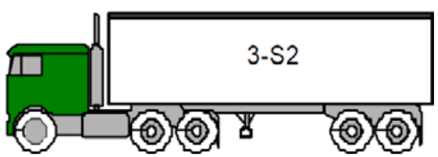
- Soil Resilient Modulus M_R
  - Stiffness or elasticity of soil under dynamic loading
  - Calculated based on California Bearing Ratio (CBR)

CBR Value	M_R Value
3	4120
5	5840
10	9400

  - $MR = 1941.488 \times CBR^{0.6844}$
    - Simple strength test comparing a given soil with well-graded crushed stone

CP Tech Center

Pavement Thickness Design

Vehicle Type		Percent of Total Trucks	Loading	Percent of Truck Type	Vehicle Weight (lbs)	Axle Type *S - Single* *TA - Tandem*	Axle Load (lbs)	ESAL Factor (per axle) Rigid	ESAL Factor (per axle) Flexible	LEF (by Vehicle) Rigid	LEF (by Vehicle) Flexible
	Single Unit (2 axles) (Class 5/6 Truck)	30%	Empty	30%	14,500	Front - S	7,000	0.019	0.024		
						Rear - S	7,500	0.025	0.032		
			Partial Load (50% Capacity)	50%	20,500	Front - S	8,000	0.033	0.041		
						Rear - S	12,500	0.212	0.242		
			Fully Loaded	20%	26,000	Front - S	9,000	0.053	0.066		
						Rear - S	17,000	0.785	0.799	*0.3033*	*0.3313*
	Dump Trucks - 3 axles (Class 7/8 truck) (doesn't address cheater axles)	10%	Empty	50%	22,000	Front - S	10,000	0.083	0.101		
						Rear - TA	12,000	0.026	0.018		
			Fully Loaded	50%	54,000	Front - S	20,000	1.558	1.52		
						Rear - TA	34,000	1.9	1.099	*1.7835*	*1.369*
	Semis (5 axles)	60%	Empty	20%	26,000	Front - S	12,000	0.178	0.206		
						Rear - TA	7,000	0.003	0.002		
						Trailer - TA	7,000	0.003	0.002		
			Partial Load (50% Capacity)	60%	53,000	Front - S	13,000	0.251	0.282		
						Rear - TA	20,000	0.208	0.138		
						Trailer - TA	20,000	0.208	0.138		
			Fully Loaded	20%	80,000	Front - S	20,000	1.558	1.52		
						Rear - TA	34,000	1.9	1.099		
						Trailer - TA	34,000	1.9	1.099	*1.5086*	*1.1204*
								Composite Load Equivalency Factor (LEF) for "Trucks"		**1.1745**	**0.90853**

Tech Center

SUDAS Ch. 5F-1 (High Volume)
ESAL factors for individual axles were determined from AASHTO Design Guide.
ESAL factors do not account for directional split. If 50/50 split, then divide ESAL factor in half.
2010 Iowa DOT traffic counts were used to develop this table.

Pavement Thickness Design

1993 AASHTO Rigid Pavement Structural Design

$$\log_{10}(W_{18}) = Z_R \times S_o + 7.35 \times \log_{10}(D+1) - 0.06 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.5-1.5}\right)}{1 + \frac{1.624 \times 10^7}{(D+1)^{8.46}}} + (4.22 - 0.32 p_t) \times \log_{10}\left[\frac{(S'_c)(C_d)(D^{0.75} - 1.132)}{215.63(J)\left(D^{0.75} - \frac{18.42}{\left(E_c/k\right)^{0.25}}\right)}\right]$$

Or use SUDAS Chapter 5F-1

SUDAS Design Values

★ Field Test
★ Calculated

Subbase:	Natural			4" Granular			6" Granular			8" Granular			10" Granular			12" Granular		
CBR Value:	3	5	10	3	5	10	3	5	10	3	5	10	3	5	10	3	5	10
Rigid Pavement Parameters																		
Initial Serviceability Index, P_o	4.5																	
Terminal Serviceability Index, P_t	Local Roads = 2.00 Collector Roads = 2.25 Arterials = 2.50																	
Reliability, R	Local Roads = 80% Collector Roads = 88% Arterial Roads = 95%																	
Overall Standard Deviation, S_o	0.35																	
Loss of Support, LS	1			0														
Soil Resilient Modulus, M_R Per NCHRP Project 128 $M_R = 1941.488 \times CBR^{0.6844709}$	4120	5840	9400	4120	5840	9400	4120	5840	9400	4120	5840	9400	4120	5840	9400	4120	5840	9400
Subbase Resilient Modulus, E_{SB} * Assumed	Not Applicable			30,000														
Modulus of Subgrade Reaction, k, and Composite Modulus of Subgrade Reaction, k_c Use AASHTO Chapter 3, Table 3.2 and Figures 3.3 - 3.6 to determine	252	327	469	263	332	455	284	354	477	308	379	504	332	406	535	356	433	566
Adjusted k or k_c for Loss of Support Use AASHTO Part 2, Figure 3.6	85	105	160	263	332	455	284	354	477	308	379	504	332	406	535	356	433	566
Coefficient of Drainage, C_d	1.00			1.10														
Modulus of Rupture, S'_c $S'_c = 2.3 \times f_c^{0.667}$ * Assumed 4,000 psi concrete	580																	
Modulus of Elasticity, E_c $E_c = 6{,}750 \times S'_c$ * Assumed 4,000 psi concrete	3,915,000																	
Load Transfer, J	J = 3.1 (Pavement Thickness < 8") J = 2.7 (Pavement Thickness ≥ 8")																	

Parameter Values
Design & Actual

		TR640 Field Tests	
	SUDAS	**Subgrade**	**Subbase**
Loss of Support	1 (subgrade) 0 (subbase)	1.8 to 2.5	1.3 to 2.0
CBR SG	10	1.4 to 56	
CBR SB	55*		20-111
Modulus of Subgrade Reaction	k_c 284- 477 (6”) k 252-469**	k=50 to 133	k_c=66 to 222
Coefficient of Drainage, C_d	1.0 (subgrade) 1.1 (subbase)	0.71 to 0.93	0.70 to 0.99

* Based on 30,000 M_R
** Per SUDAS, k is adjusted by reducing 200 to 300 if no subbase is used (due to loss of support)

TR640 Summary

What did we find out about Loss of Support with TR 640 testing?

- $k_{c\text{-}fwd}$ were on average of 4 to 10 times lower than $k_{c\text{-}dcp}$
- $k_{c\text{-}fwd}$ values provide a direct measure of stiffness while $k_{c\text{-}dcp}$ is empirically estimated

Tech Center

TR640 Summary

- The $k_{c\text{-}dcp}$ values do not account for loss of support under pavements in situ while the $k_{c\text{-}fwd}$ values do
- Loss of support factors were within AASHTO recommended design, but higher than SUDAS suggested values
  (1 for natural subgrade, 0 for subbase)

Tech Center

What are the implications?

- Found variable parameter values
- Further analysis of TR640 test results
- How reliable are our pavements?

Tech Center

Concrete and Asphalt Design Inputs

Concrete Pavement Design/Analysis Inputs

Concrete Thickness	7.75	inches
Total Rigid ESALs	7.461309	
Reliability	50	%
Overall Standard Deviation	0.35	
Flexural Strength	500	psi
Modulus of Elasticity	3,400,000	psi
Load Transfer Coefficient	2.8	
Modulus of Subgrade Reaction	67	psi/in.
Drainage Coefficient	0.70	
Initial Serviceability	4.50	
Terminal Serviceability	2.00	

Concrete Pavement Design/Analysis

Reliability Solve For

Save and Close

Help

Asphalt Pavement Design/Analysis Inputs

WinPAS12
Solve for Reliability

- Lower reliability = Lower performance
- Higher maintenance costs

TR640 Data

Street Name	Age	PCC Thickness (in.)	AADT	Percentage of Trucks	Number of Trucks (2way)	PCI - Test Site Only	PCI- from IPMP	Reliability (using WinPAS 12 AASHTO 93)	Reliability Design Value - SUDAS
NW Greenwood St	23	8.5	2000	1.5%	30	83	*75	83%	80%
NW Greenwood St	36	8.25	2000	1.5%	30	38	*40	82%	80%
E63	22	8.5,8.0	1040	5.0%	52	46	81	93%	88%
Riverside Rd.	18	11.0	2910	20.0%	582	79	65	86%	88%
E23	26	6.75,6.75	150	5.0%	8	55	-	92%	88%
SW Westlawn Dr.	4	9.0,7.25	1000	1.0%	10	85	-	90%	80%
SW Logan St.	0	7.5	500	1.0%	5	100	-	99%	80%
West Main St.	5	7.0,7.5	500	3.0%	15	99	78	99%	80%
South 5th St.	3	8.0,8.0	680	2.0%	14	98	74	100%	80%
Valley View Dr.	15	9.75,9.0	8900	8.0%	712	77	72	50%	88%
9th Ave.	23	7.75	7600	5.0%	380	54	41	50%	88%
Cliff Rd.	19	7.75	1120	5.0%	56	78	67	92%	80%
Cliff Rd.	19	6.5,6.75	1120	5.0%	56	87	67	53%	80%
Meadowbrook Dr.	18	6.5	300	1.5%	5	97	-	99%	80%
W38 Locust Rd.	16	7.5,7.0	660	6.0%	40	92	76	90%	88%
175th Street	42	6.0,6.0	560	3.0%	17	35	-	50%	88%

Life Cycle Cost

- How can we predict when maintenance is needed?

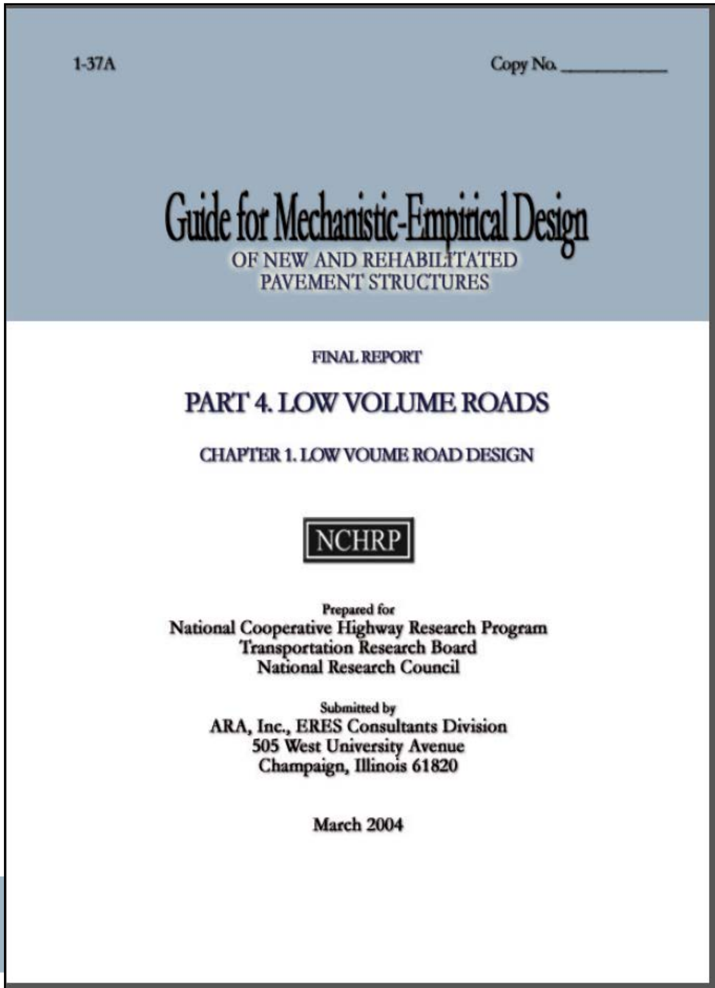
- How much maintenance and what will it cost?

Tech Center

Life Cycle Cost

MEPDG (Mechanistic Empirical Pavement Design Guide)

- Determines loading directly from axle configurations and weights (No ESALs)
- More precise characterization of traffic but relies on the same input data used to calculate ESALs
- Costly Program


1-37A Copy No. ____________

Guide for Mechanistic-Empirical Design
OF NEW AND REHABILITATED PAVEMENT STRUCTURES

FINAL REPORT

PART 4. LOW VOLUME ROADS

CHAPTER 1. LOW VOUME ROAD DESIGN

NCHRP

Prepared for
National Cooperative Highway Research Program
Transportation Research Board
National Research Council

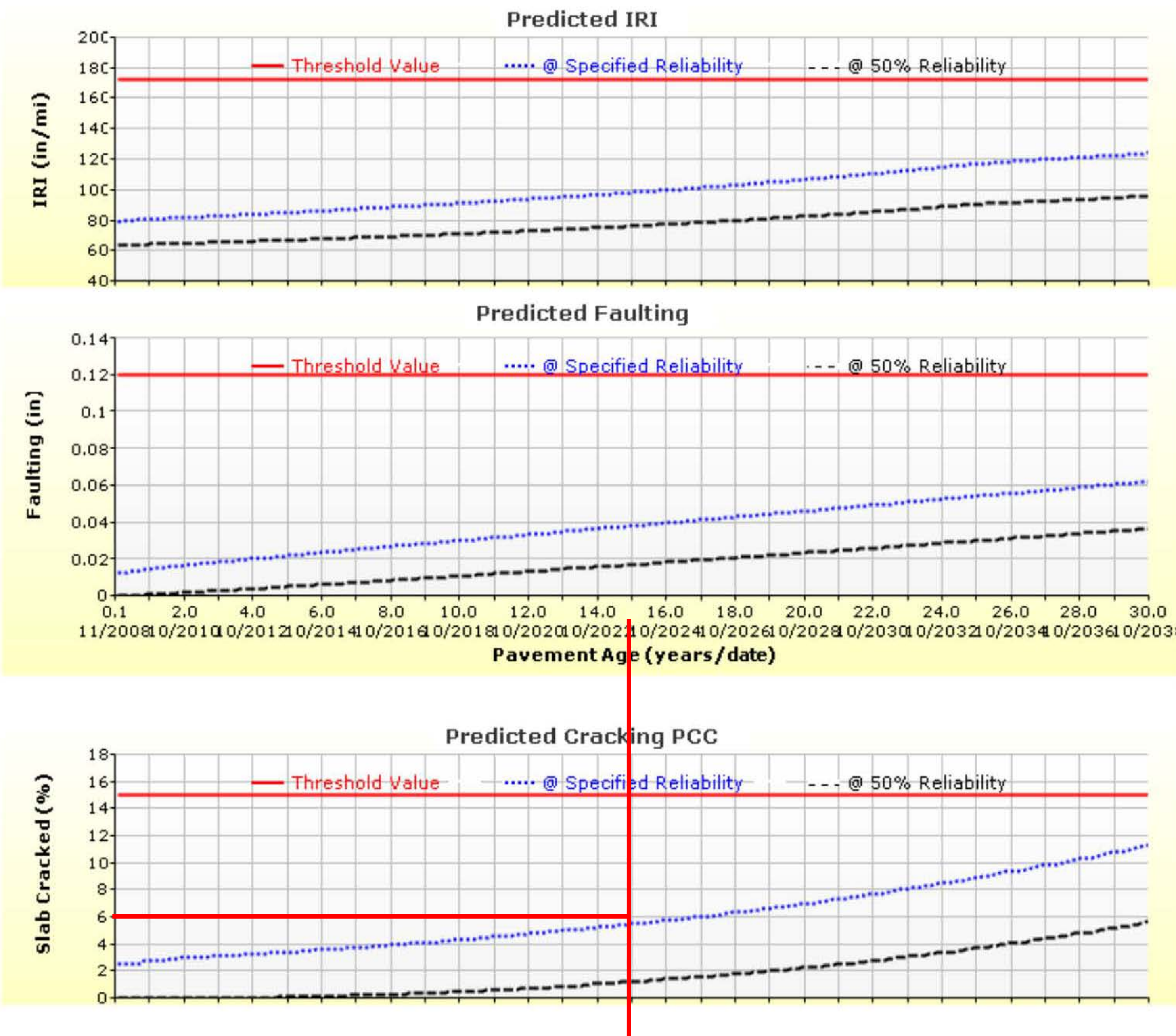
Submitted by
ARA, Inc., ERES Consultants Division
505 West University Avenue
Champaign, Illinois 61820

March 2004

Tech Center

MEPDG

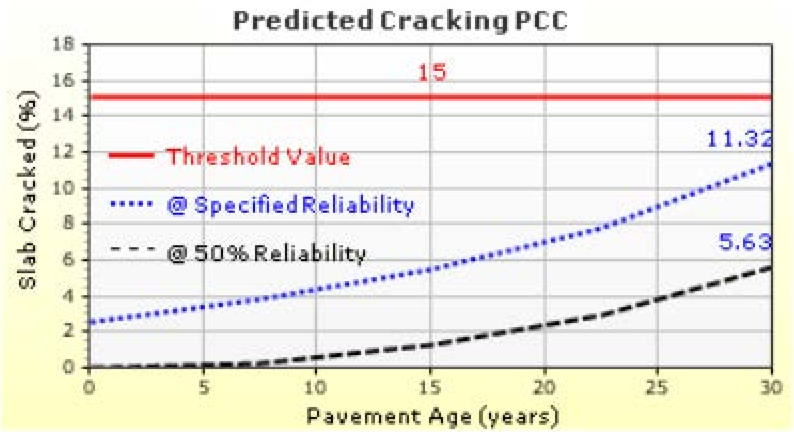
Analysis Output Charts

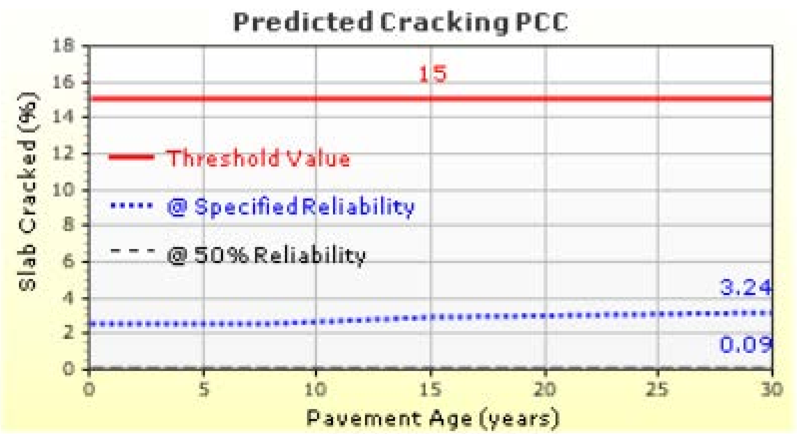


Tech Center

Life Cycle Cost

- Study two equal pavements - one w\subbase, one without
- Run MEPDG
- Then complete a life cycle cost estimate
- And the winner is…….





Life Cycle Cost

New Construction	Costs
Subgrade Preparation	$2 per square yard
Subdrain	$11 per lineal foot
Subbase (8” thickness)	$10 per square yard
Fly-Ash Treated Subgrade	$8 - $10 per square yard
Cement Treated Subgrade	$8 - $10 per square yard
Geosynthetics	$2 - $5 per square yard
PCC Pavement (7”)	$40 per square yard

Tech Center

Life Cycle Cost

Rehabilitation	**Costs**
Partial Depth Patching**	$25-$30 per square foot
Full Depth Patching (M Mix)	$65 - 80 per square yard
Joint & Crack Cleaning, Routing & Sealing*	$2.00 per lineal foot
Joint & Crack Cleaning & Sealing*	$1.25 per lineal foot
Diamond Grinding	$1.70 - $6.70 per square yard
Dowel Bar Retrofit	$25 - $35 per dowel bar

*If silicones are used, cost is approximately 2 times more than hot pour sealants.
** Cost on Major Quantities of Longitudinal patching can be $12-$20 per square foot. Cost on night work can be as high as $55 per square foot.

What have we learned?

•Soil modulus (M_R) varies during seasons and throughout life

•Distress related to Loss of Support

•Stabilization provides long term freeze thaw durability & stiffness

•Subbase isn't the only answer - treat the subgrade

•Factors critical in pavement design

Truck Traffic, C_d, k & k_c

Where do we go from here?

- Consider range of LOS values
- Use realistic design parameters or consider mitigation
- Pay attention to the subgrade
- Continued testing
  - Spring conditions
  - Re-visit same sites
- TR 640 Design Guide

Thank You

David J. White, Ph.D., P.E.
Associate Professor
Director CEER
djwhite@iastate.edu
515-294-1463

Jerod Gross, PE, LEED AP
Project Manager
jgross@snyder-associates.com
515-964-2020

Tech Center