NC STATE UNIVERSITY

Multi-level FWD Load Analysis for Remaining Life Prediction of Asphalt Pavements

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Presented at the Winter School 2022
Moena, Italy
Dec. 19, 2022

Outline

- Background information
- Findings from the NCHRP 10-48 project on layer condition assessment for flexible pavements using 40 kN FWD load
- Conclusions from the NCHRP 10-48 study
- Remaining life prediction using multi-level FWD loads
- Conclusions on remaining life prediction

Components of Nondestructive Evaluation

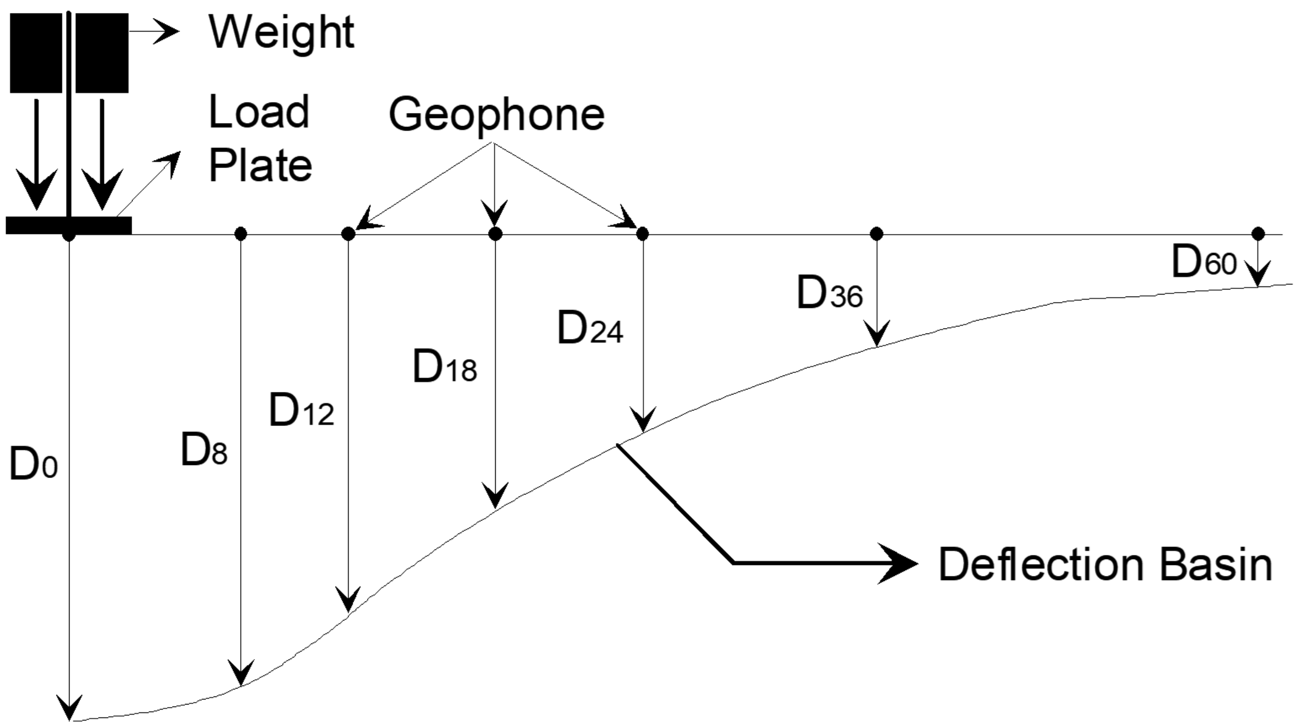
- Experiment: Input vs. response
  - Disturb a system at a location and monitor the response at some other points
- Forward Model
  - Formulation of the … response and/or between responses usi… system
- Backward Search or System Identification
  - Identification of the system parameters by ma… measurements and calculated responses

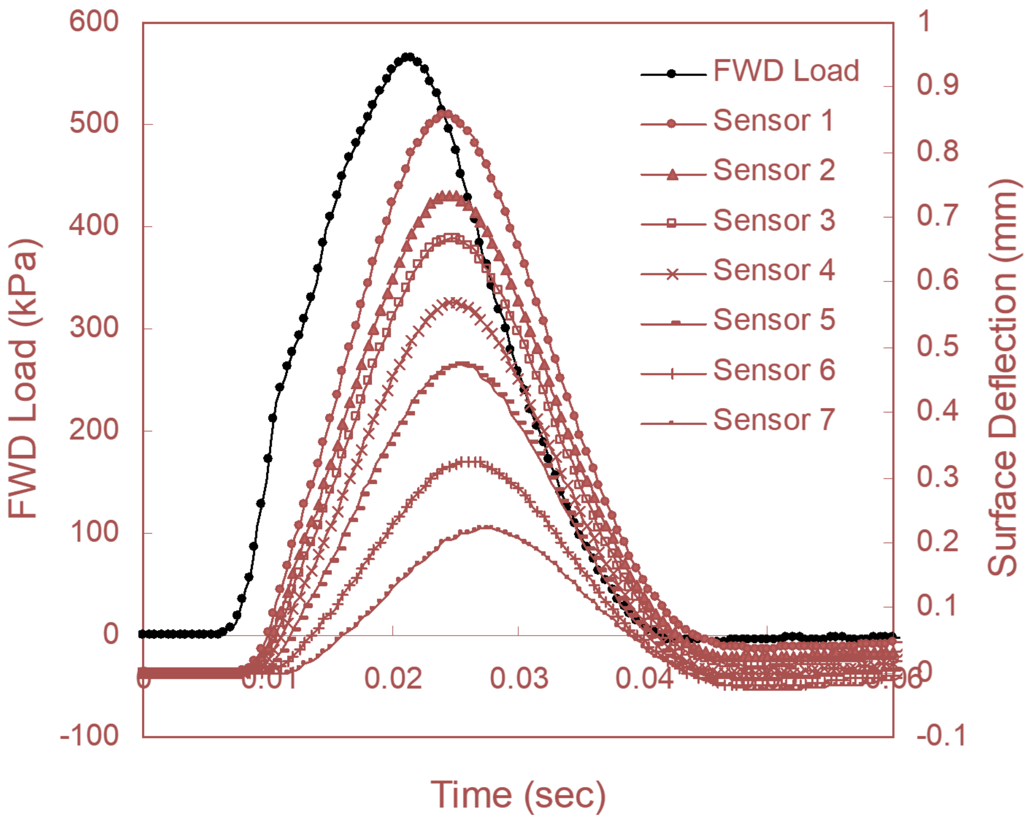
Falling Weight Deflectometer

Dynamic, Nonlinear Elastic FEM, High Performance Computing

Artificial Neural Network, Regression Equations

Falling Weight Deflectometer

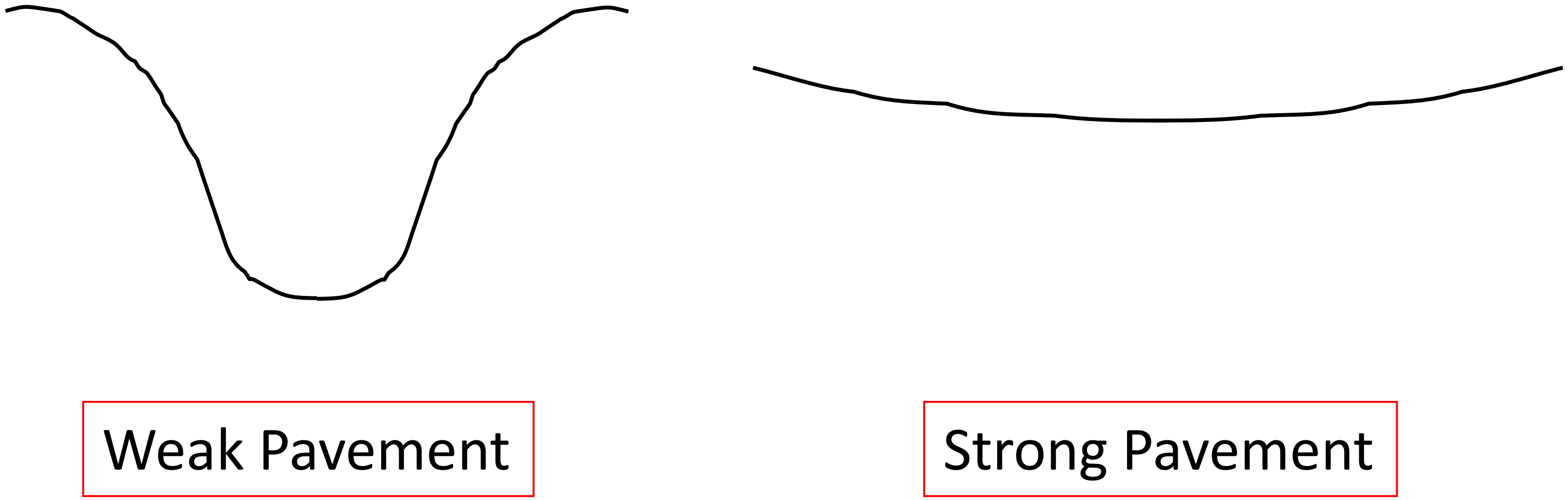




FWD Analysis Methods

- Backcalculation of Layer Moduli Using Optimization Techniques
  - Static, linear elastic: WESDEF, BOUSDEF, ELMOD, EVERCALC, FPEDD1, MODULUS, ADAM, EFROMD2
  - Static, quasi nonlinear elastic: MODCOMP3, EMOD, ISSEM4, PADAL
  - Static, finite element nonlinear elastic: ILLIPAVE, MICHBACK, FINLAP, 2DB, UZAN
  - Dynamic, linear viscoelastic: UT, SCALPOT, UZAN
  - Dynamic, linear elastic: SASWOPR, Nazarian
  - Dynamic, finite element nonlinear elastic, ANN based: APLCAP
- Deflection Basin Parameter Approach
  - Easy to calculate and practical to implement

Deflection Basin Parameters



- Deflection magnitude
- Slope
- Deflection difference
- Radius
- Area
- Deflection ratio

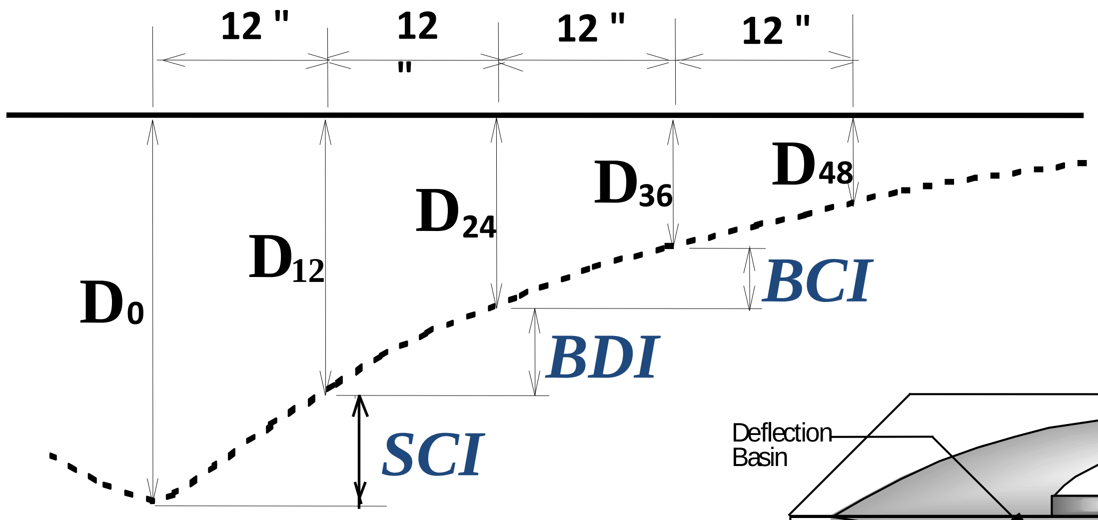
Deflection Basin Parameters

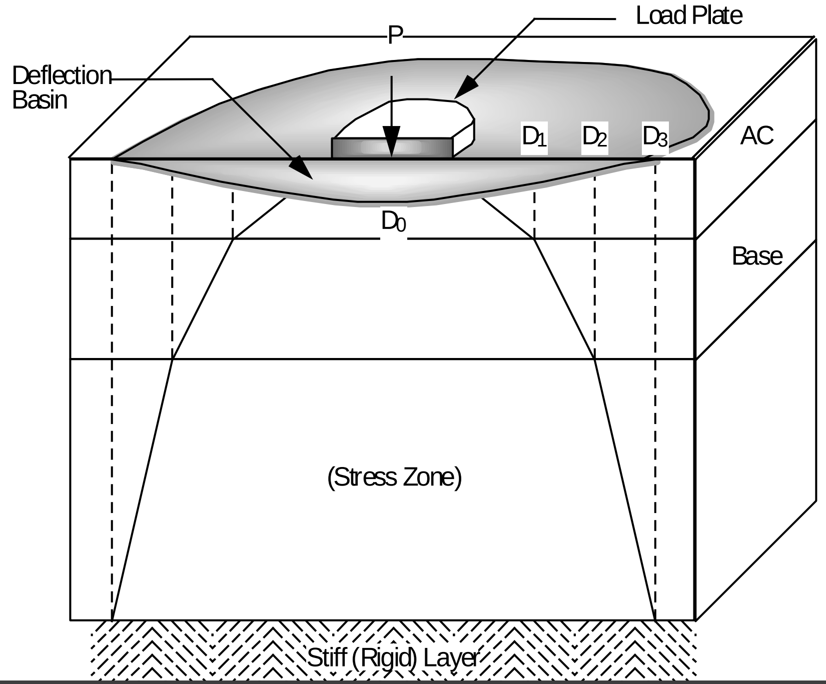
NCHRP 10-48

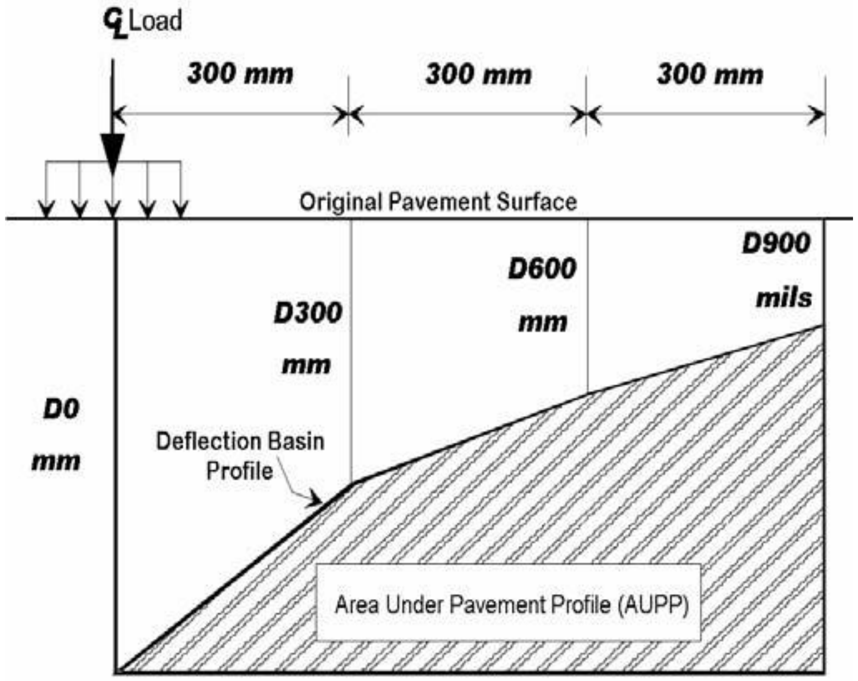
Deflection Parameter	Formula	Measuring Device	Reference
Area	$AREA = \frac{6(D_0 + 2D_{12} + 2D_{24} + D_{36})}{D_0}$	FWD	Hoffman 1981
Add. Areas	$AREA_2 = \frac{6(D_{12} + 2D_{18} + D_{24})}{D_0}$ $AREA_3 = \frac{6(D_{24} + 2D_{36} + D_{48})}{D_0}$	FWD	
Area Indexes	$AI_1 = \frac{D_0 + D_{12}}{2D_0}$ $AI_2 = \frac{D_{12} + D_{24}}{2D_0}$ $AI_3 = \frac{D_{24} + D_{36}}{2D_0}$ $AI_4 = \frac{D_{36} + D_{48}}{D_0}$	FWD	
Area Under Pavement Profile	$AUPP = \frac{5D_0 - 2D_{12} - 2D_{24} - D_{36}}{2}$	FWD	Hill & Thompson
Base Curvature Index	$BCI = D_{60} - D_{48}$ or $BCI = D_{24} - D_{36}$	Dynaflect FWD	Peterson 1972
Base Damage Index	$BDI = D_{12} - D_{24}$	RR & FWD	

Bending Index	$BI = D_0 / a$	BB	Hveem 1954
Deflection Ratio	$DR = D_r / D_0$	FWD	Classen 1976
Load Spreadability Index	$LSI = (D_{48} / D_{24})xF$	FWD	Wimsatt 1995
Maximum Deflection	D_0	BB Dynaflect	Shrivner 1968
Radius of Curvature	$R = \frac{r^2 *}{(2D_0(D_0 / D_r - 1))}$	CM & BB	Dehlen 1962
Radius of Influence	$RI = x / D_0$	BB	Ford 1962
Shape Factors	$F_1 = (D_0 - D_{24}) / D_{12}$ $F_2 = (D_{12} - D_{36}) / D_{24}$	FWD	Hoffman 1981
Add. Shape Factor	$F_3 = (D_{24} - D_{48}) / D_{36}$	FWD	
Slope of Deflection	$SD = \tan^{-1}[(D_0 - D_r) / r]$	BB	Kung 1967
Spreadability	$S = \frac{25(D_0 + D_{12} + D_{24} + D_{36})}{D_0}$	Dynaflect RR FWD	Vaswani 1971
Structural Strength Index	$SSI = A_x / (X_{min} x E_{min})$	FWD	Jung 1992
Structural Integrity Index	$SII = A_x / (X_s x E_m)$	FWD	Jung 1992
Surface Curvature Index	$SCI = D_0 - D_{12}$	BB RR Dynaflect FWD	Shrivner 1968
Tangent Slope	$TS = (D_0 - d_x) / x$	FWD	Stock 1984

Stress Bulb in Pavements







Layer Condition Assessment Using FWD
NCHRP 10-48 Project

Synthetic Database

- ABAQUS axisymmetric, dynamic, linear and nonlinear elastic finite element analysis with UMAT
- Linear elastic database: 10,000 pavements
- Nonlinear elastic database: 14,000 pavements
- Wide range of layer moduli
- Thickness ranges from DataPave (LTPP database)

Nonlinear Elastic Model

- Uzan’s universal model

$$E = K_1(\theta)^{K_2}(\sigma_d)^{K_3}$$

  - Granular materials: K_1, K_2, K_3 are all non-zero
  - Cohesive materials: $K_2 = 0$
  - Linear elastic materials: $K_2 = K_3 = 0$

- Nonlinear model coefficients from Santha, Thompson, and Garg

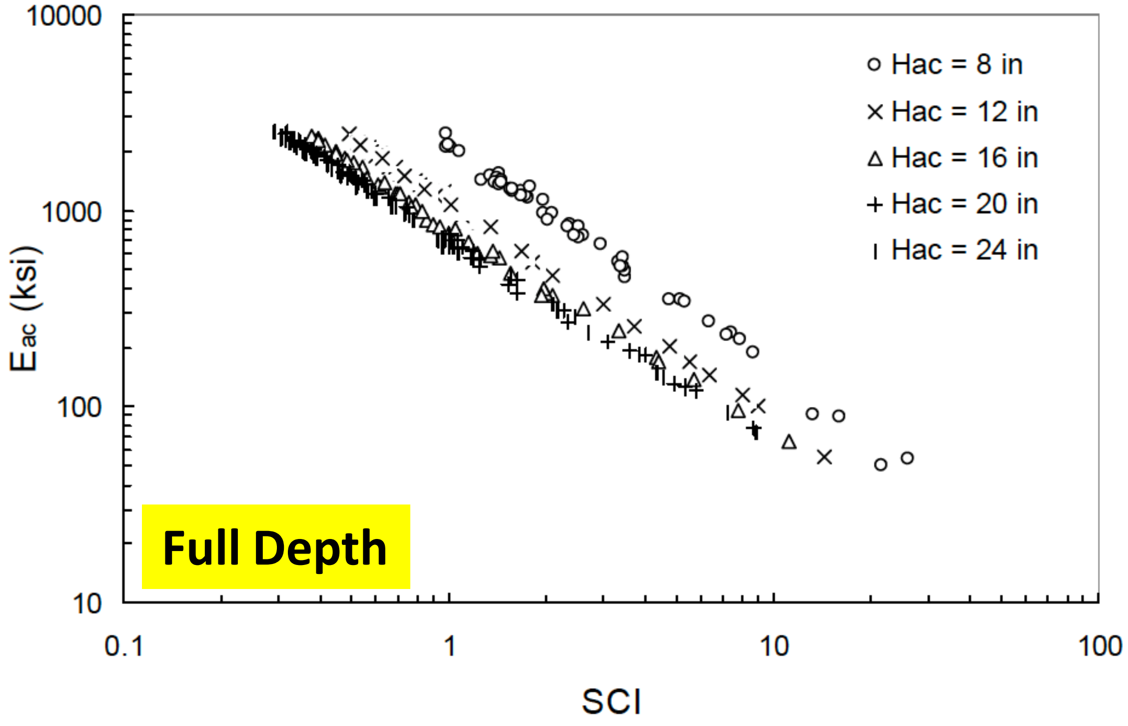
Layer Condition Indicators

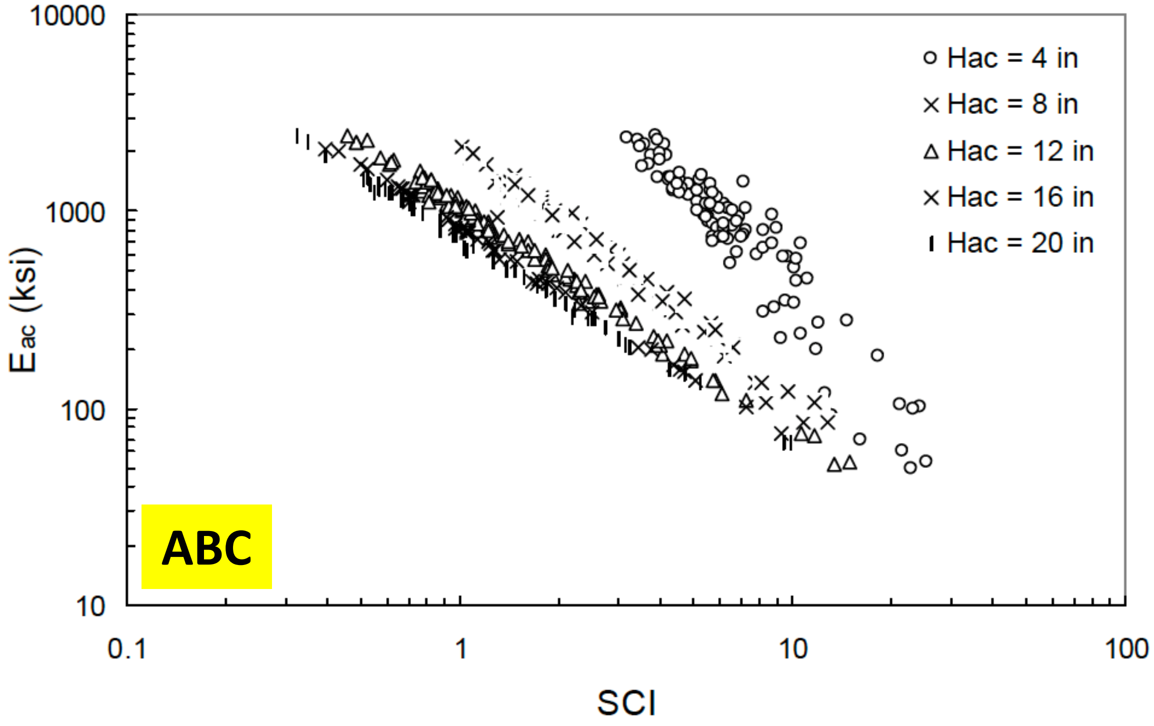
Pavement	Layer	Layer Condition	Condition Indicator
Aggregate Base Pavement	Asphalt Layer	Cracking, Stripping	ε_{ac}, E_{ac}
	Aggregate Base	Rutting	BDI, ε_{abc}
	Subgrade	Rutting	BCI, SSR, ε_{sg}, E_{sg}
	Stiff Layer	Depth	Depth
Full Depth Pavement	Asphalt Layer	Cracking, Stripping	ε_{ac}, E_{ac}
	Subgrade	Strength (Rutting Potential)	BDI, BCI, SSR, ε_{sg}, E_{sg}
	Stiff Layer	Depth	Depth

Xu, B., S.R. Ranjithan, and Y.R. Kim (2002). New Relationships between Falling Weight Deflectometer Deflections and Asphalt Pavement Layer Condition Indicators, Transportation Research Record, 1806, 48-56.

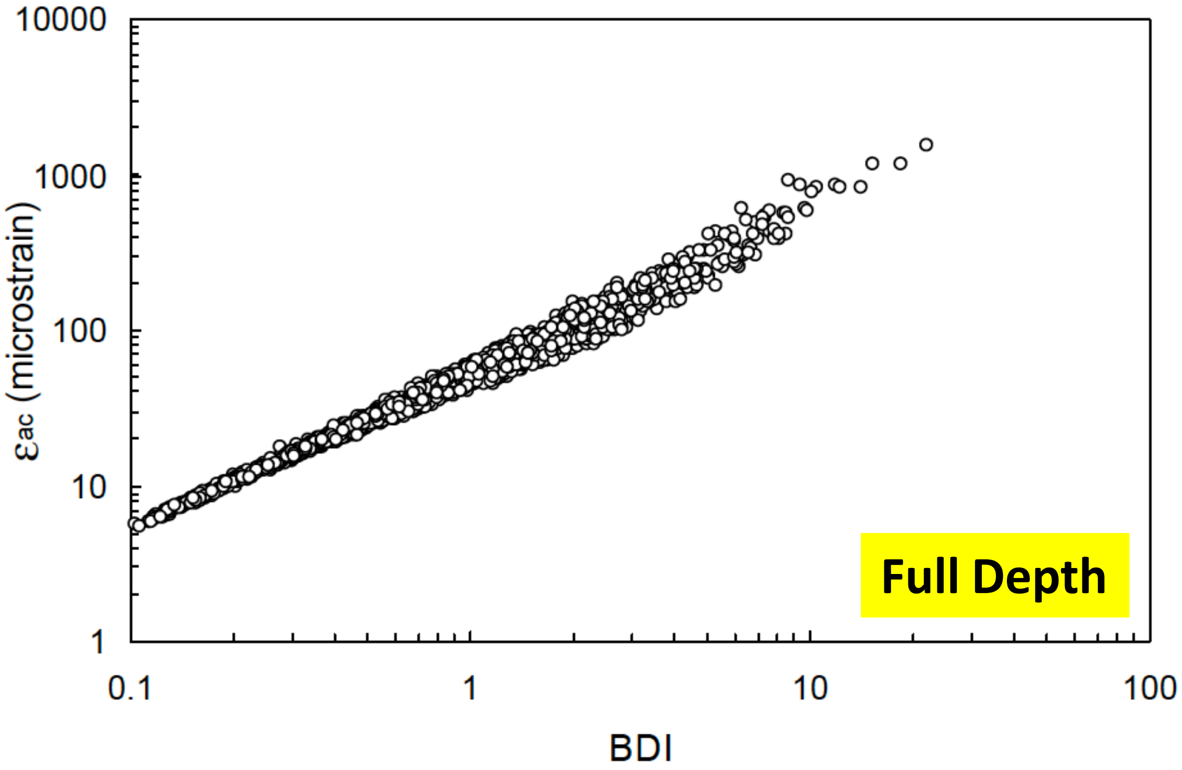
Xu, B., S.R. Ranjithan, and Y.R. Kim (2002). "New Condition Assessment Procedure for Asphalt Pavement Layers, Using Falling Weight Deflectometer Deflections," Transportation Research Record, 1806, 57-69.

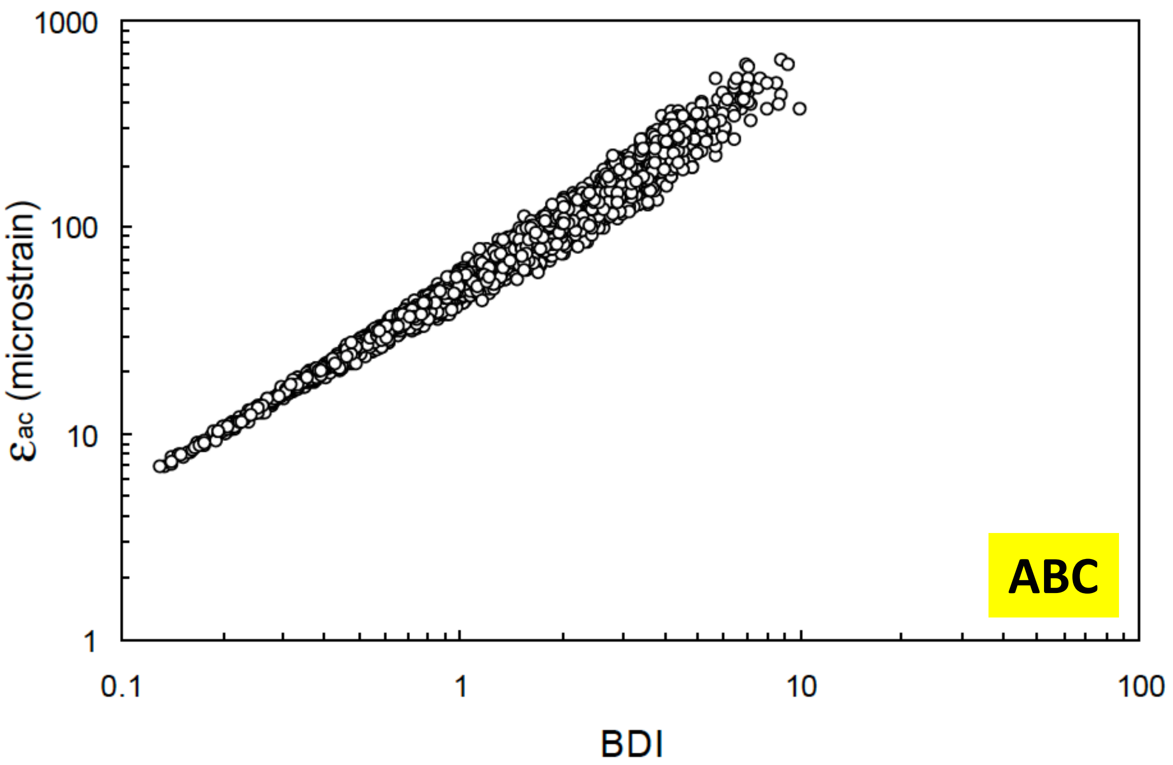
Asphalt Modulus As a Function of SCI



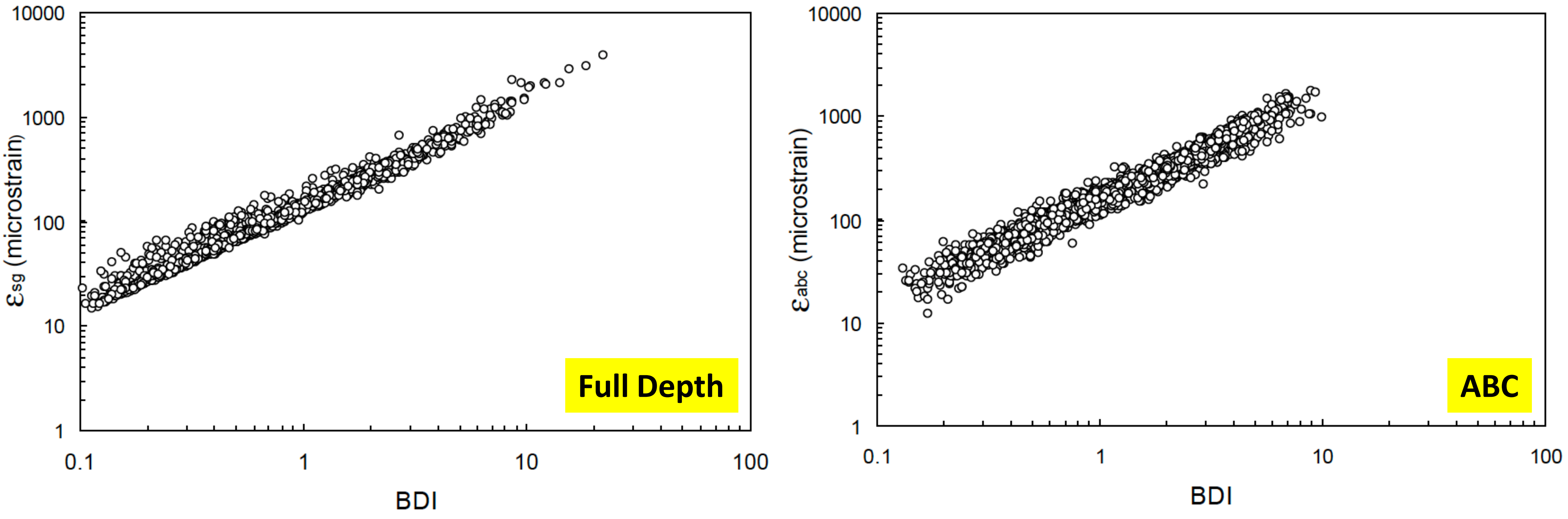


ε_{ac} As a Function of BDI





ε_{sg} and ε_{abc} As a Function of BDI



Predictive Equations for Condition Indicators

Aggregate Base Pavement	
Hac < 6 inches	Hac > 6 inches
$\log(E_{ac}) = -1.7718 * \log(SCI) + 0.8395 * \log(BDI) - 2.5124 * \log(H_{ac}) + 0.0756 * H_{ac} + 4.8888$	
$\log(\varepsilon_{ac}) = 0.7798 * \log(SCI) + 0.2279 * \log(BDI) + 0.5736 * \log(H_{ac}) + 0.0410 * \log(H_{abc}) + 1.1604$	$\log(\varepsilon_{ac}) = 0.3898 * \log(SCI) + 0.5930 * \log(BDI) + 0.6935 * \log(H_{ac}) - 0.0328 * H_{ac} + 1.3347$
$\log(\varepsilon_{abc}) = 0.7357 * \log(SCI) + 0.1043 * \log(BDI) + 0.1240 * \log(H_{ac}) + 0.0648 * \log(H_{abc}) + 2.073$	$\log(\varepsilon_{abc}) = 0.4976 * \log(SCI) + 0.2910 * \log(BDI) + 0.5316 * \log(H_{ac}) - 0.0442 * H_{ac} + 2.1346$
$\log(\varepsilon_{sg}) = 0.8835 * \log(BDI) + 0.1526 * \log(BCI) - 0.0995 * \log(H_{ac}) - 0.0185 * H_{abc} + 2.2461$	$\log(\varepsilon_{sg}) = 0.2811 * \log(BDI) + 0.6788 * \log(BCI) - 0.0135 * \log(H_{ac}) - 0.0123 * H_{abc} + 2.2083$
Full Depth Pavement	
$\log(E_{ac}) = -1.0831 * \log(SCI) - 2.6210 * \log(H_{ac}) + 0.0482 * H_{ac} + 5.2961$	
$\log(\varepsilon_{ac}) = 0.9977 * \log(BDI) + 1.7142$	
$\log(\varepsilon_{sg}) = 0.9823 * \log(BDI) + 2.1460$	

Case Studies

- Danish Road Test Machine (RTM) pavement with known tensile strain at the bottom of AC layer
- Cold Regions Research & Engineering Laboratory (CRREL) pavement with known compressive strains in aggregate base and subgrade
- LTPP SPS pavements with deflections measured at different seasons
- MnROAD pavements with various fatigue cracking and rutting performance
- Flexible pavements in Davidson County, NC with measured CBR for subgrade
- US 264 pavements in Hyde Country, NC with DCP test results (CBR_{abc} = 60-80, very weak subgrade)

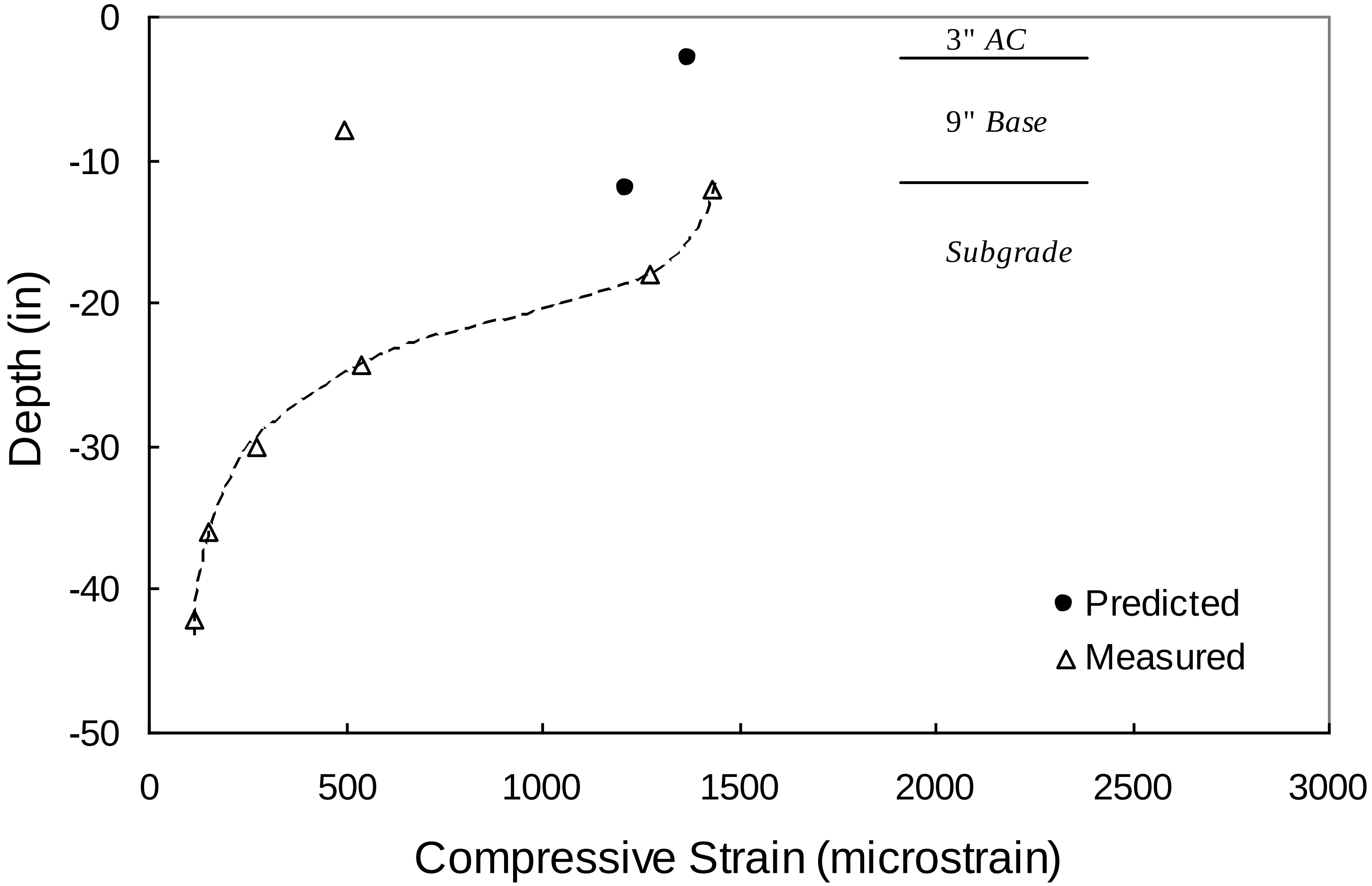
ε_{ac} Prediction

RTM

Load (lbs)	D_0 (mils)	D_{12} (mils)	D_{24} (mils)	H_{ac} (in.)	H_{abc} (in.)	SCI (mils)	BDI (mils)	Measured ε_{ac}	Predicted ε_{ac} (% error)
8,755	22.4	13.0	4.2	3.3	5.5	9.6	9.0	282 με	289 με (2%)

Compressive Strain Prediction in Unbound Layers

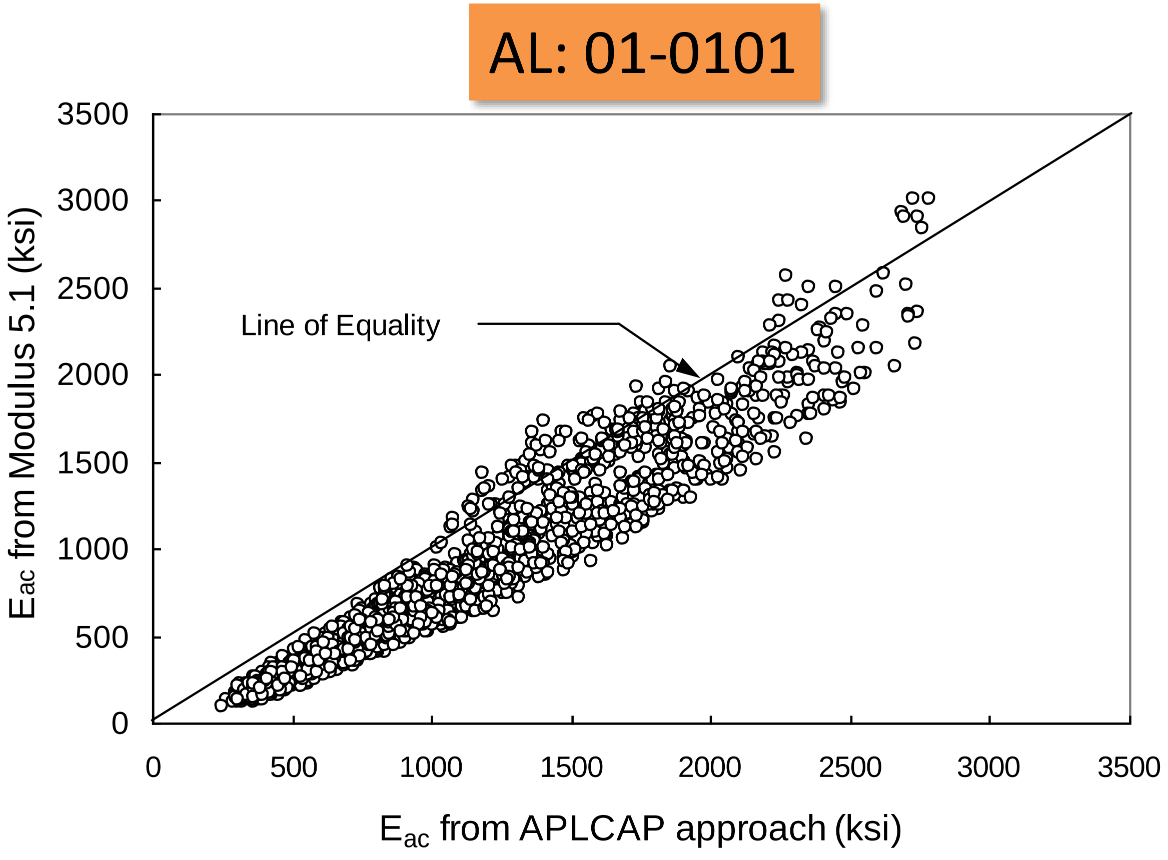
CRREL Pavement

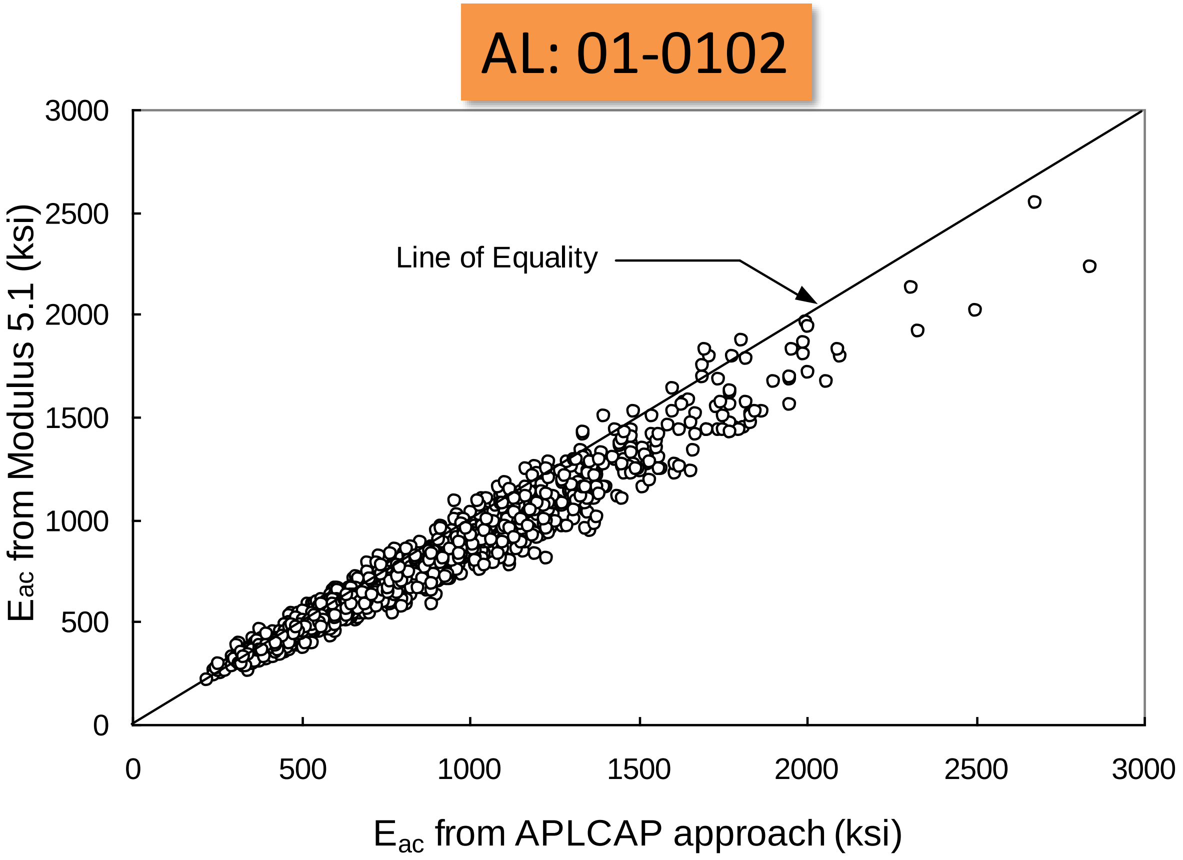


LTPP SPS Pavements

State Code	SHRP ID	H_{ac} (in.)	H_{abc} (in.)	Asphalt Type	Climate Region
AL (01)	0101	6.6	7.9	AC-20	Wet-No Freeze
AL (01)	0102	3.9	11.9	AC-20	Wet-No Freeze
VA (51)	0113	4.0	13.9	AC-20	Wet-No Freeze
VA (51)	0114	6.8	17.9	AC-20	Wet-No Freeze
DE (10)	0102	5.5	50.8	AC-20	Wet-Freeze
AZ (04)	0113	4.2	7.5	AC-30	Dry-No Freeze
AZ (04)	0114	7.1	12.0	AC-30	Dry-No Freeze
NV (32)	0101	7.1	31.3	AC-20	Dry-Freeze

E_{ac} from Regression Eqn. and MODULUS 5.1

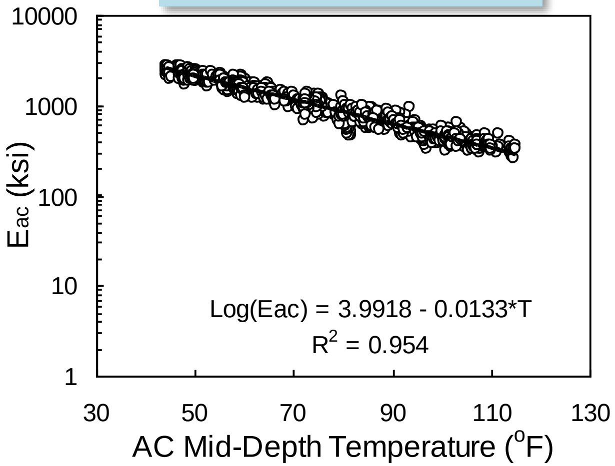


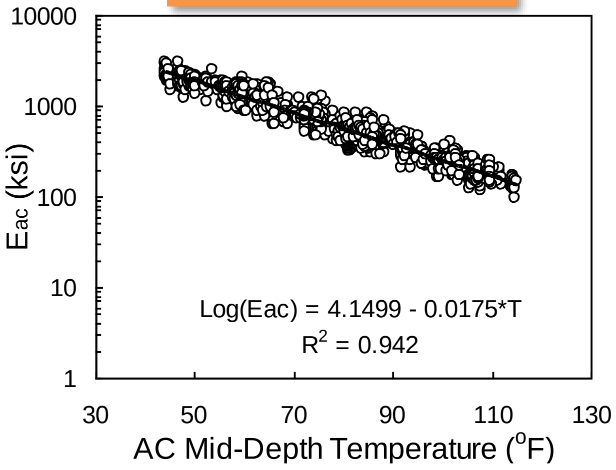


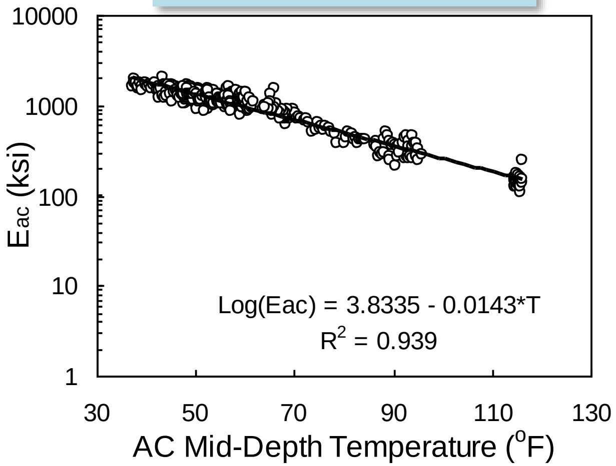
E_{ac} vs. Temp. from Regression Eqn. and MODULUS 5.1

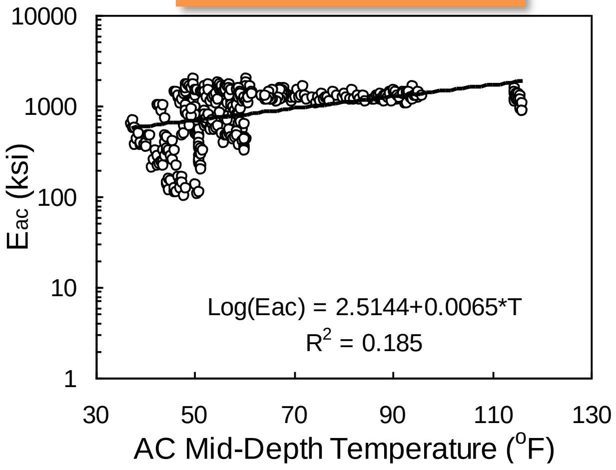
Wet-No Freeze Region

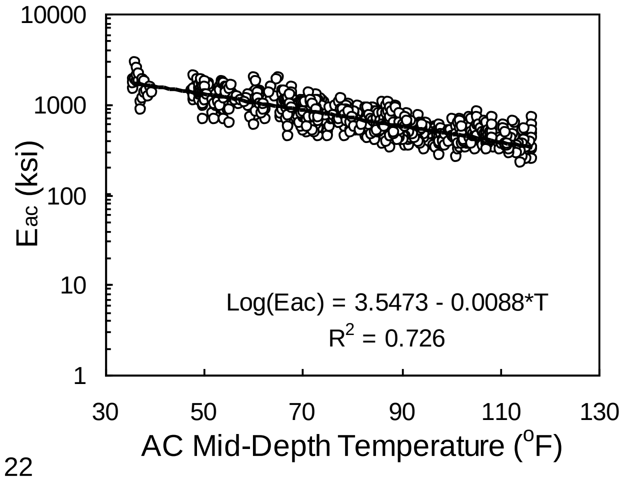
Regression Eqn. | MODULUS 5.1 | Regression Eqn. | MODULUS 5.1

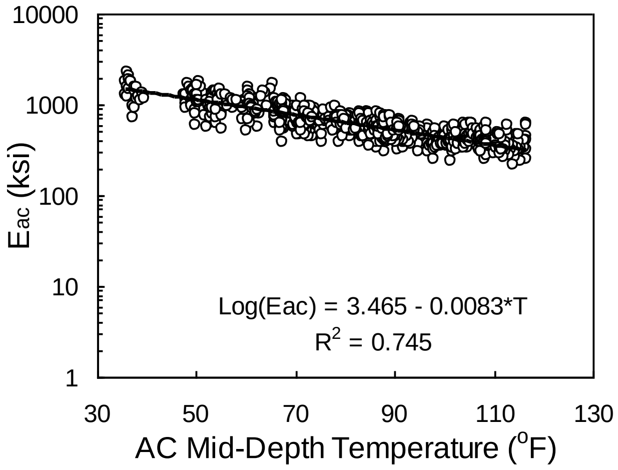


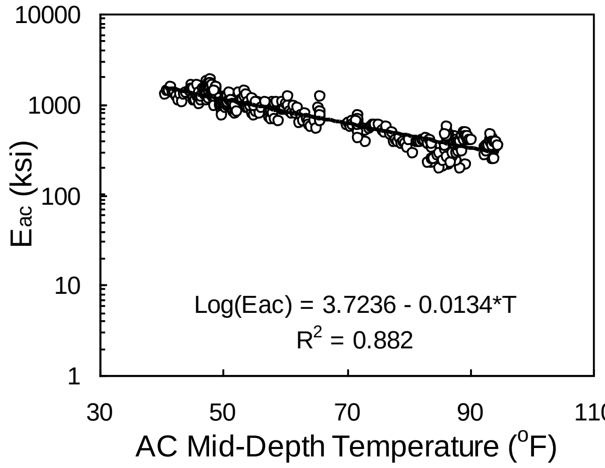


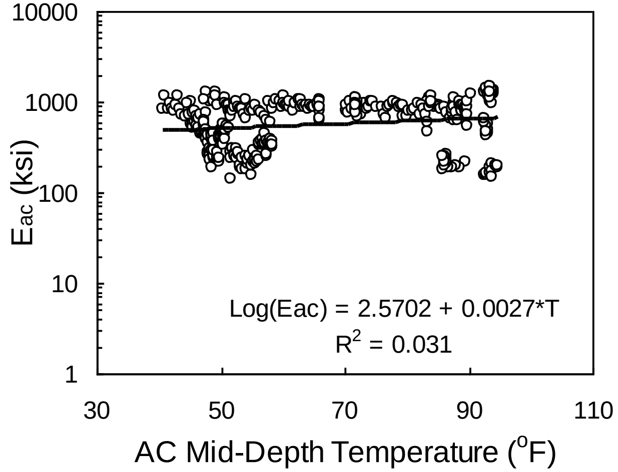












Eac vs. Temp. from Regression Eqn. and MODULUS 5.1

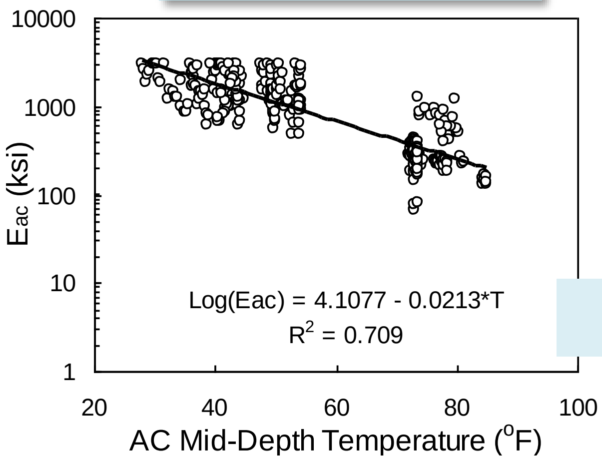
Other Regions

Regression Eqn.

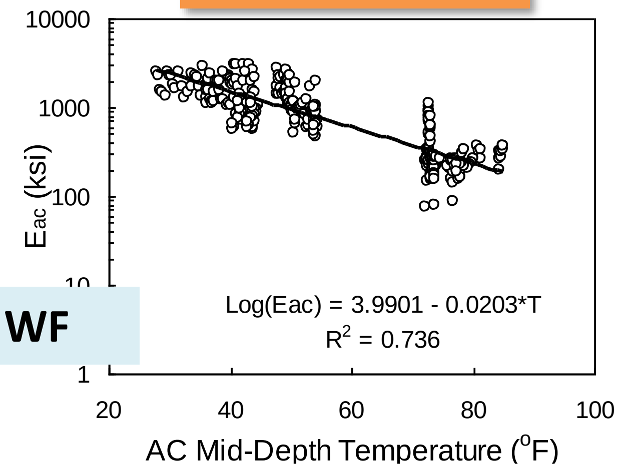
MODULUS 5.1

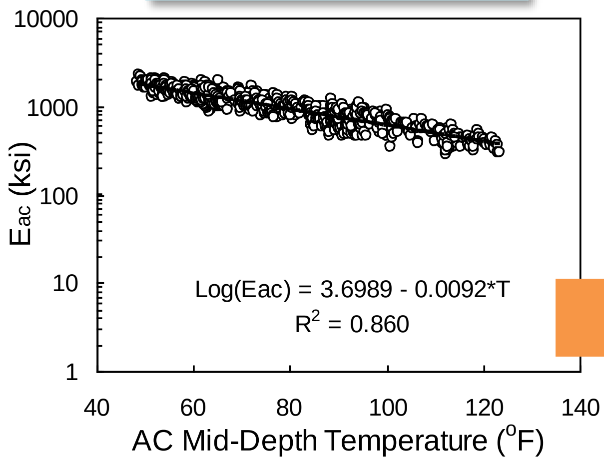
Regression Eqn.

MODULUS 5.1

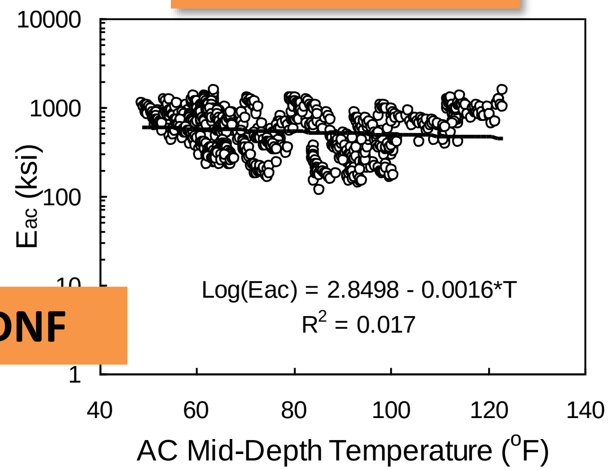


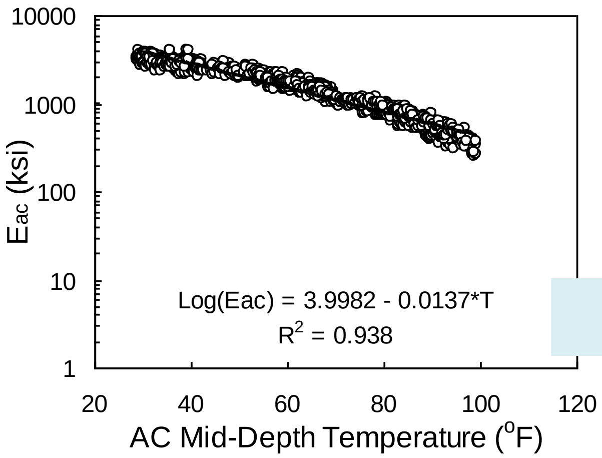
WF



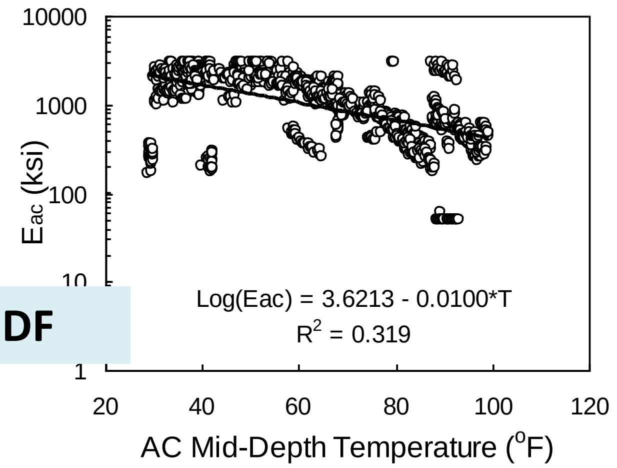


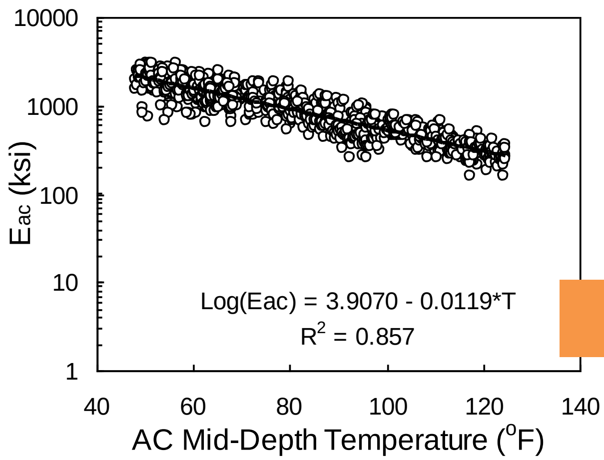
DNF



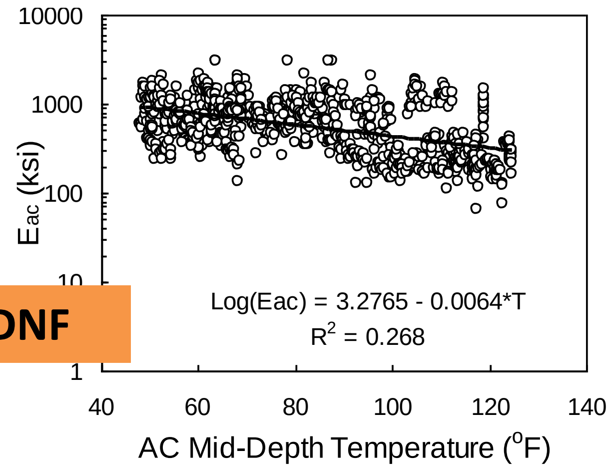


DF



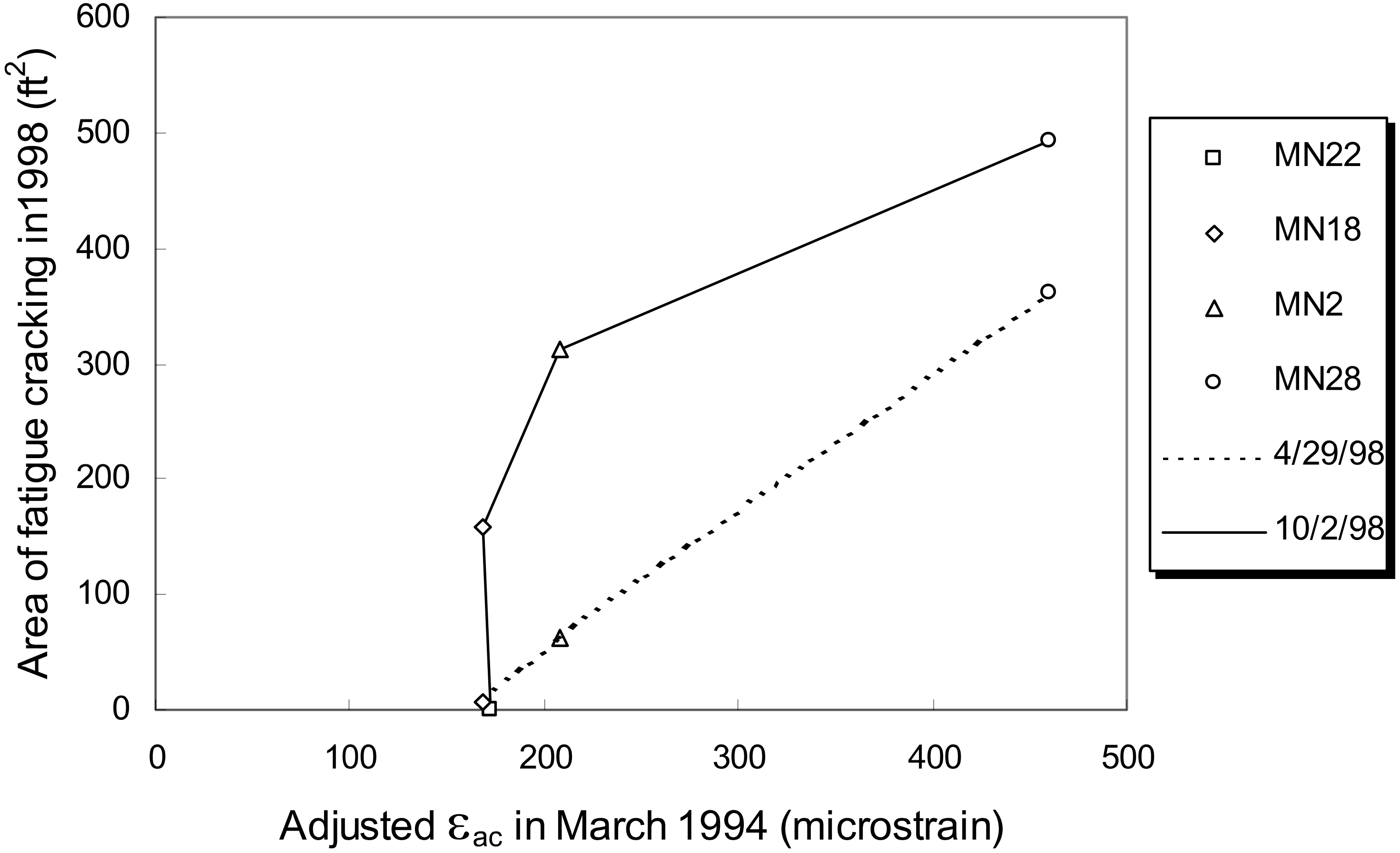


DNF



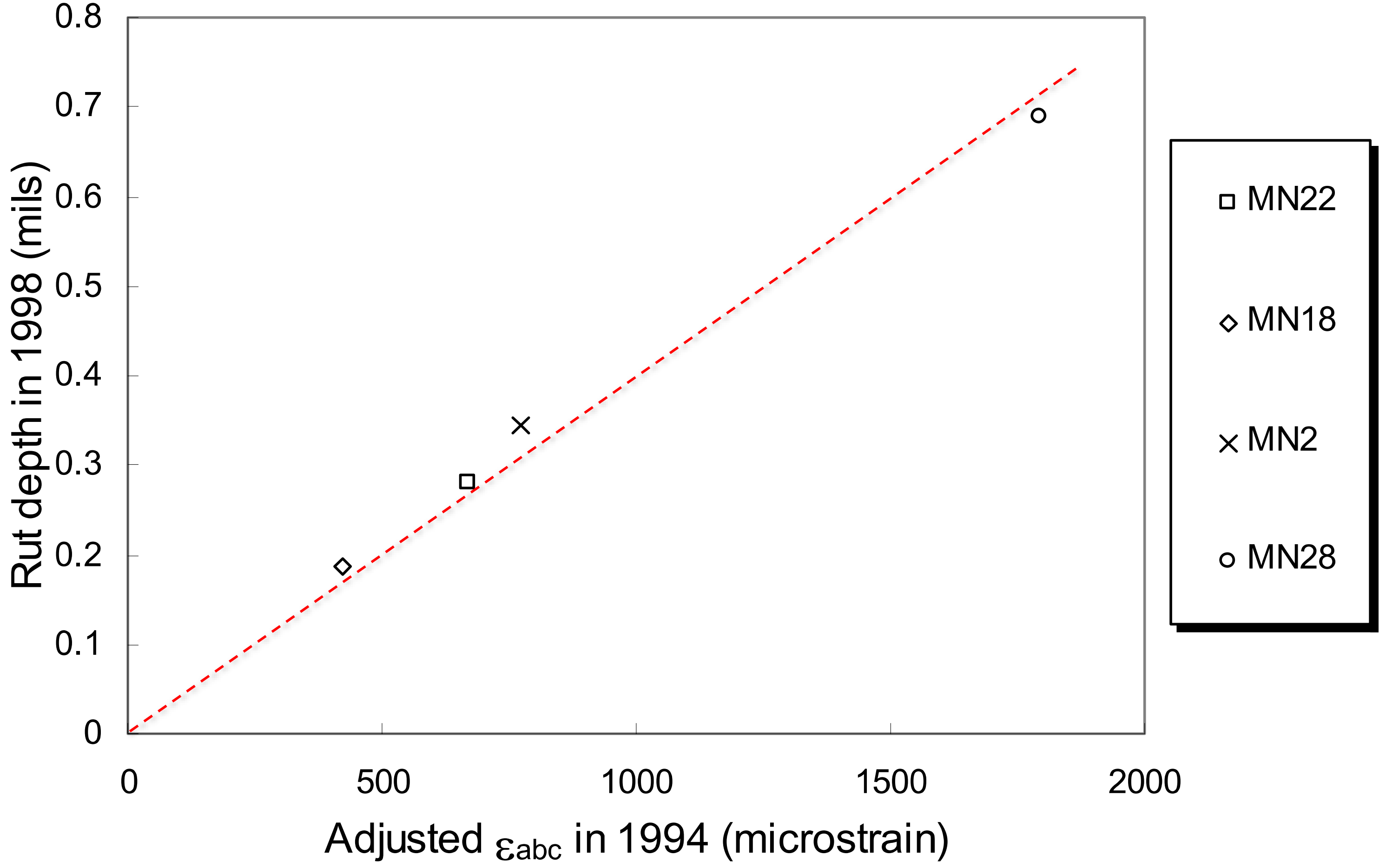
ε_{ac} for Cracking Indicator

MnROAD



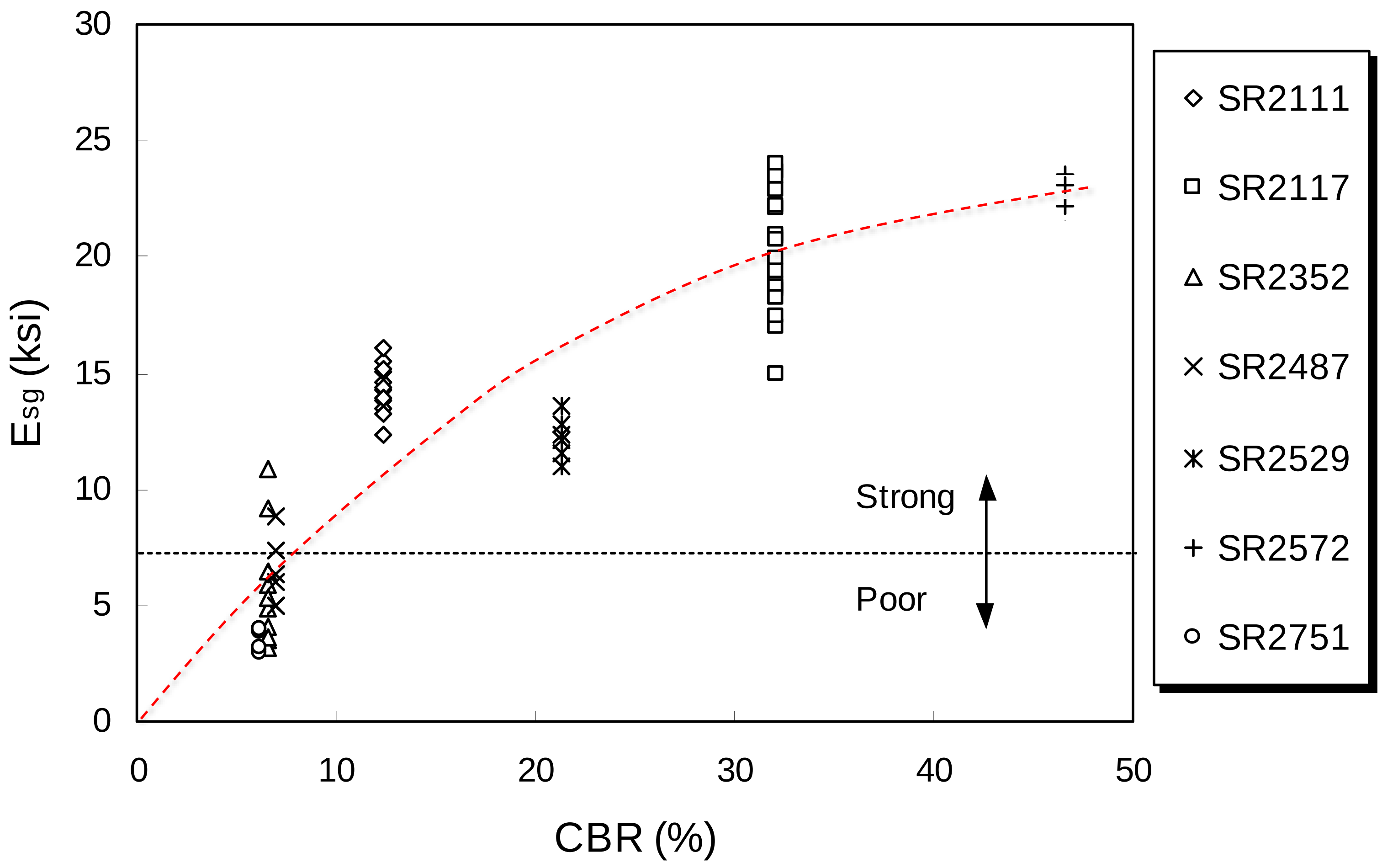
ε_{abc} for Rutting Indicator

MnROAD



E_{sg} vs. CBR

Davidson County, NC

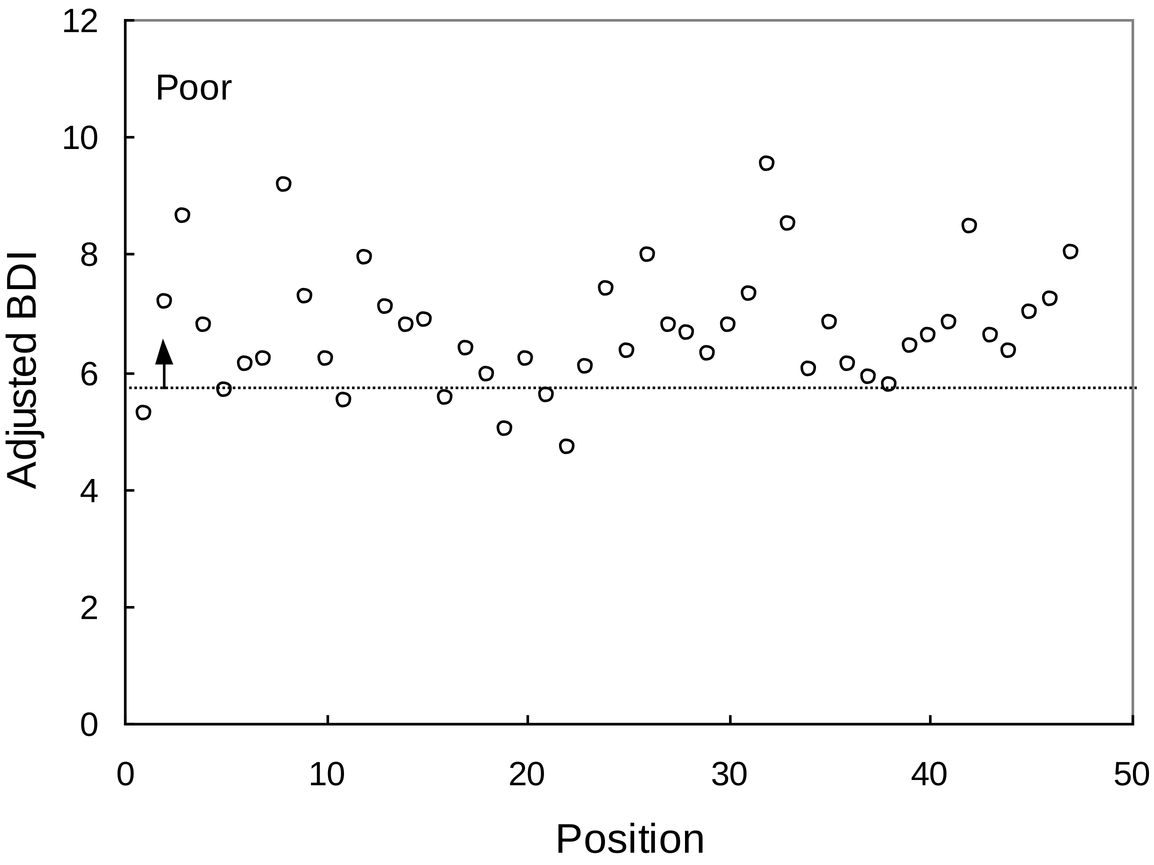


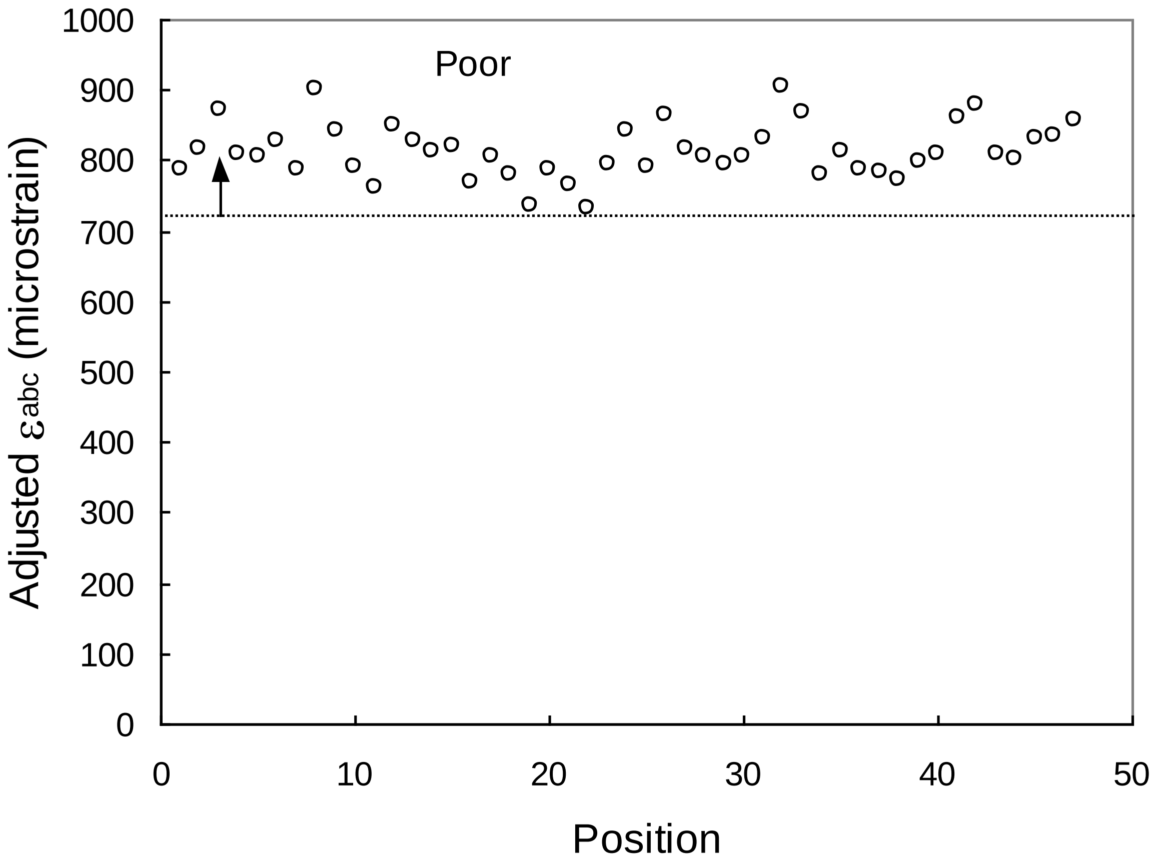
Unbound Layer Condition Evaluation Criteria

Pavement Type	Layer	Indicator*	Criteria
Aggregate Base Pavement	Base	*BDI*	*BDI* ≥ 5.8 mils
		ε_{abc}	ε_{abc} ≥ 720 micro.
	Subgrade	*BCI*	*BCI* ≥ 3.2 mils
		ε_{sg}	ε_{sg} ≥ 620 micro.
		SSR	*SSR* ≥ 0.4
		E_{sg}	E_{sg} ≤ 7 ksi
Full-Depth Pavement	Subgrade	*BDI*	*BDI* ≥ 3.4 mils
		BCI	*BCI* ≥ 3 mils
		ε_{sg}	ε_{sg} ≥ 470 micro.
		SSR	*SSR* ≥ 0.38
		E_{sg}	E_{sg} ≤ 7 ksi

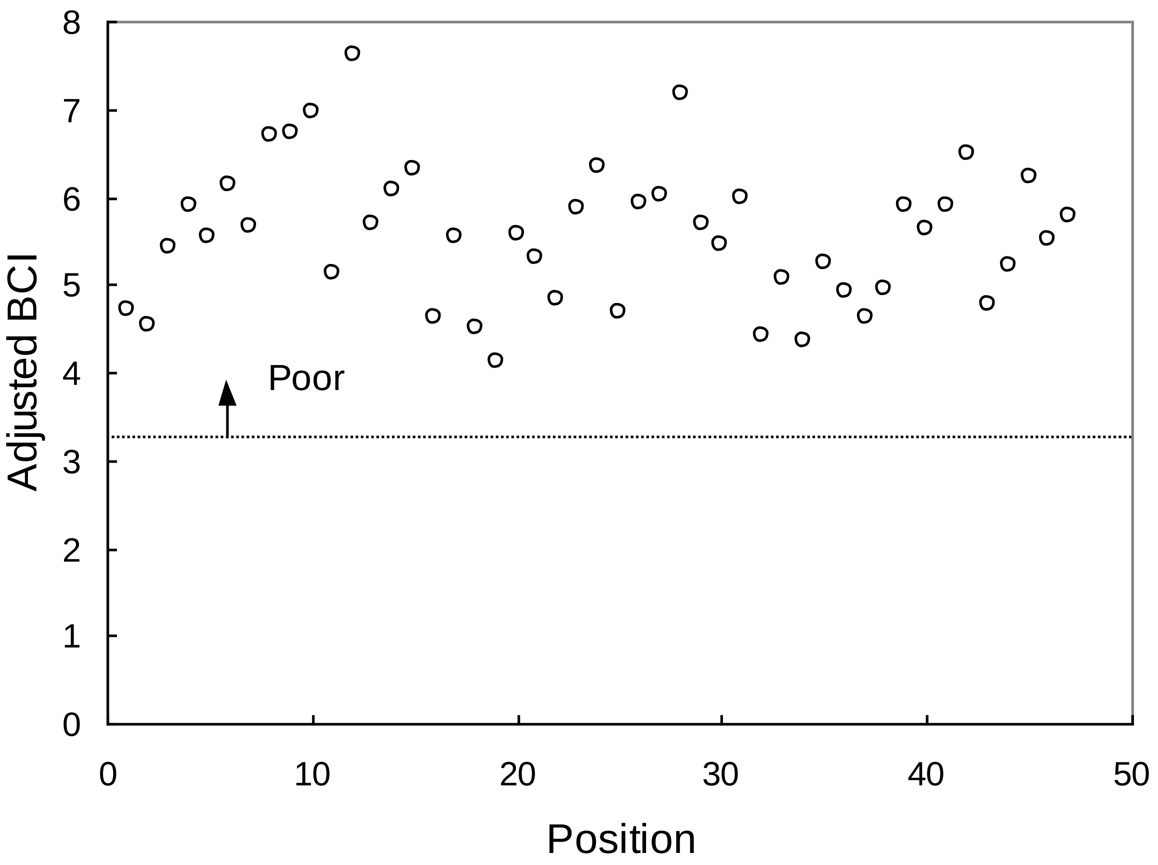
Note: *After structural adjustment

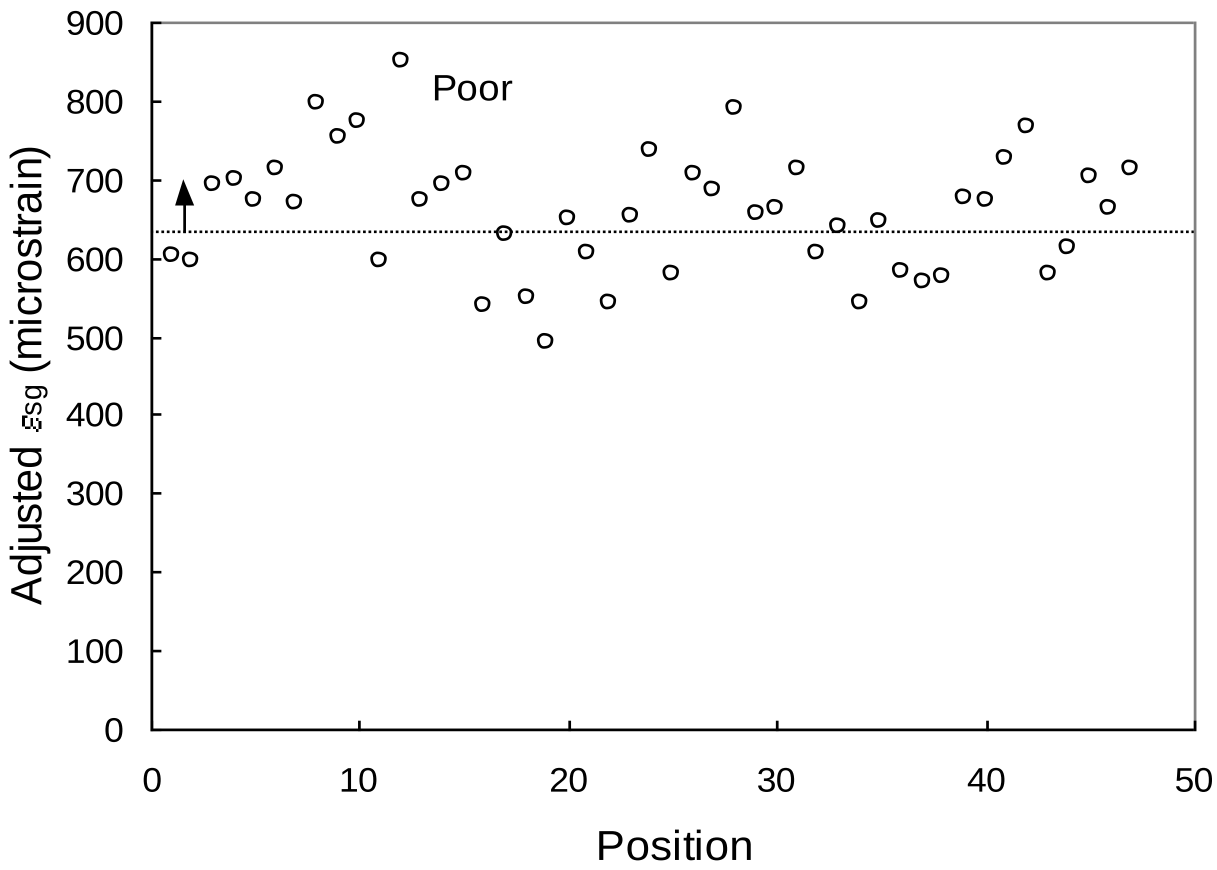
BDI and ε_{abc} for US 264



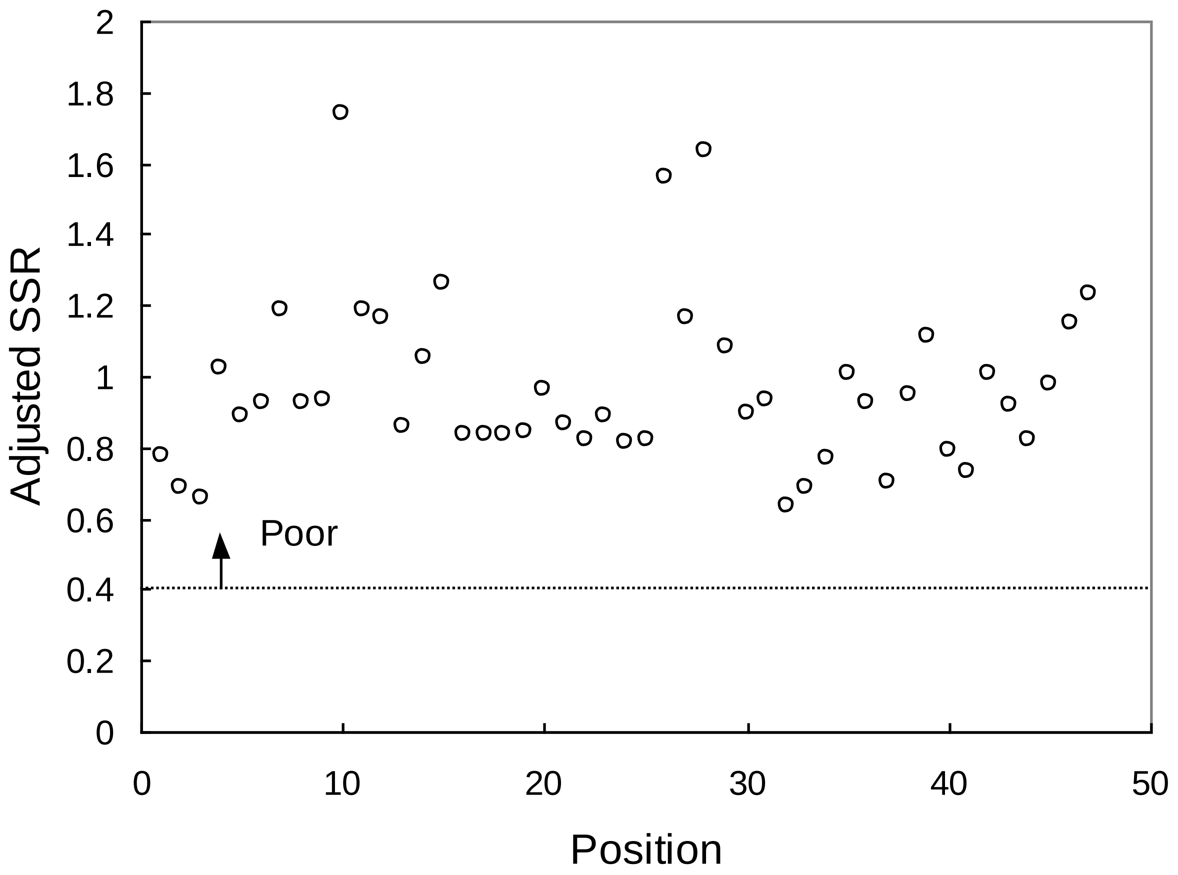


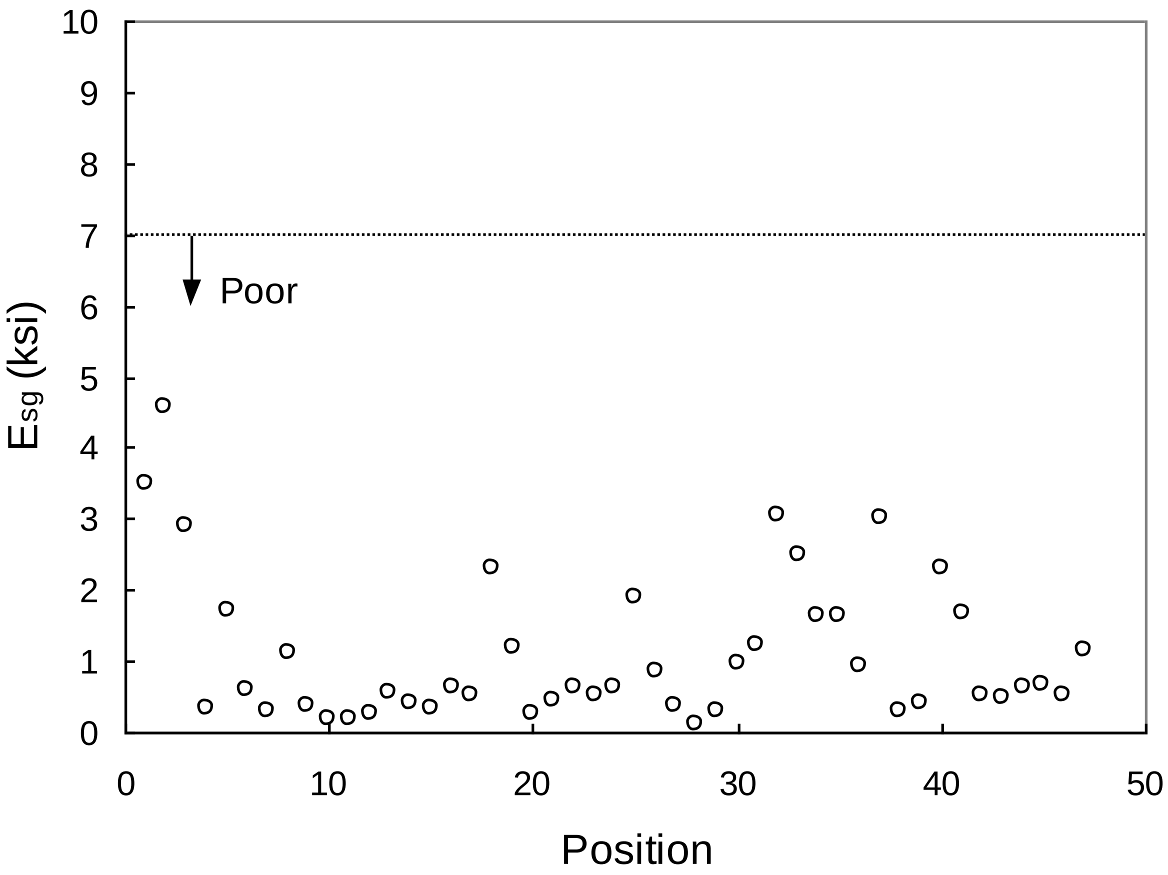
BCI and ε_{sg} for US 264





SSR and ε_{sg} for US 264



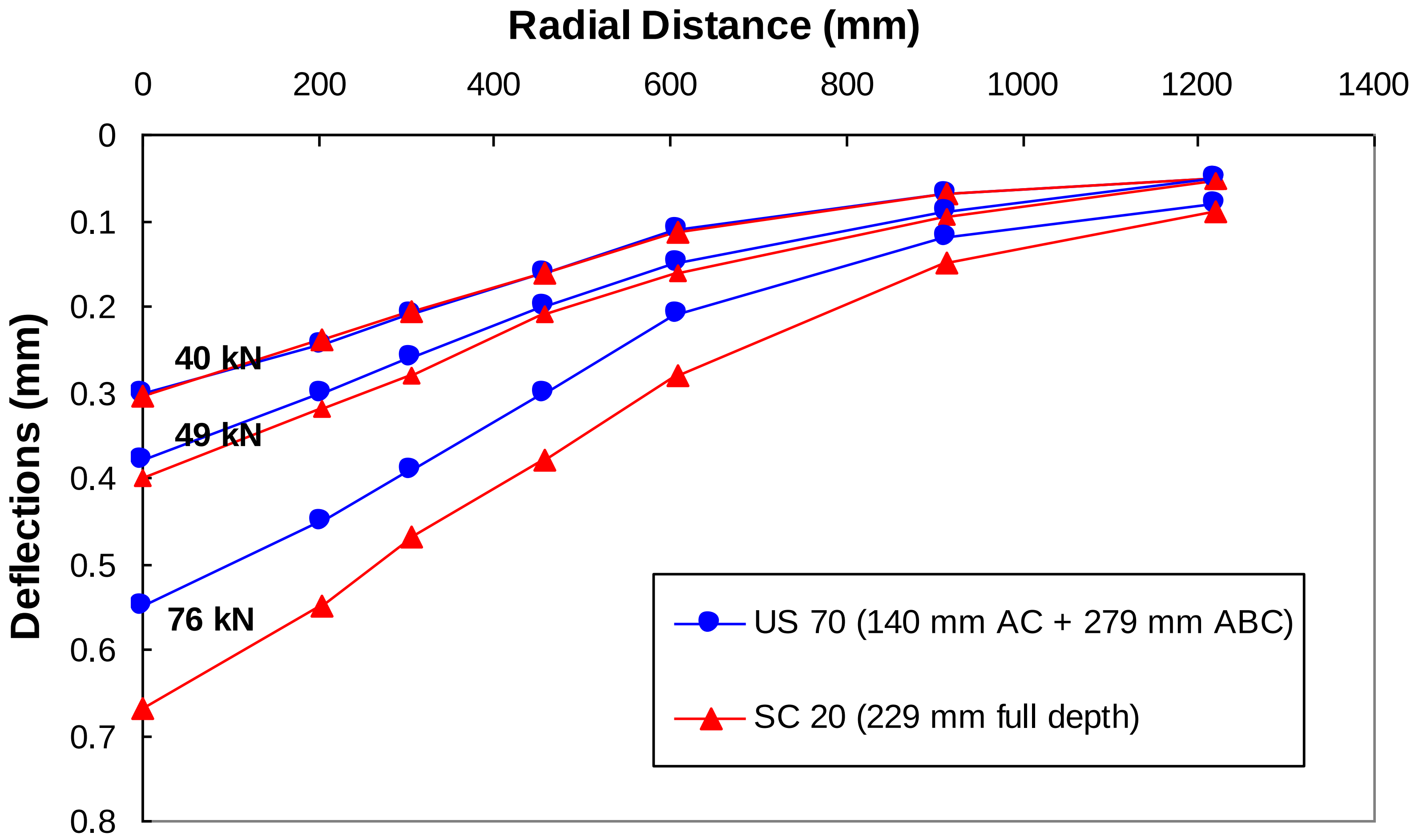


Conclusions from the NCHRP 10-48 Study

- AC moduli predicted by the NCHRP 10-48 algorithms are slightly higher than those predicted from Modulus 5.1 based on linear, static analysis.
- AC moduli predicted by the NCHRP 10-48 algorithms show much more consistent relationships with the measured mid-depth temperatures than those predicted from Modulus 5.1.
- The predicted critical strains from NCHRP 10-48 algorithms match reasonably well with the measured values in CRREL and RTM pavements, except the compressive strain on the top of the aggregate base layer.
- In general, the layer condition indicators predicted from deflection basin parameters and regression equations that were developed from NCHRP 10-48 predict the layer conditions of the selected flexible pavements reasonably well.

Remaining Life Prediction Using Multi-Level FWD Loads

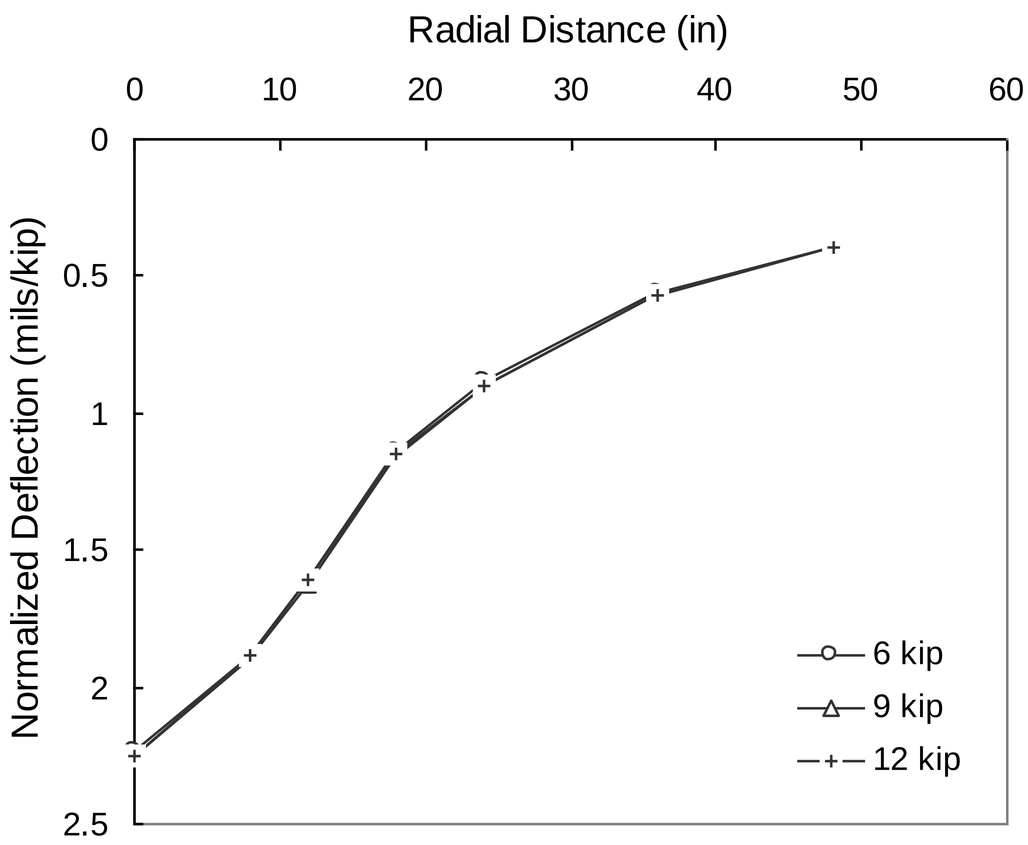
Same Overlay Design?



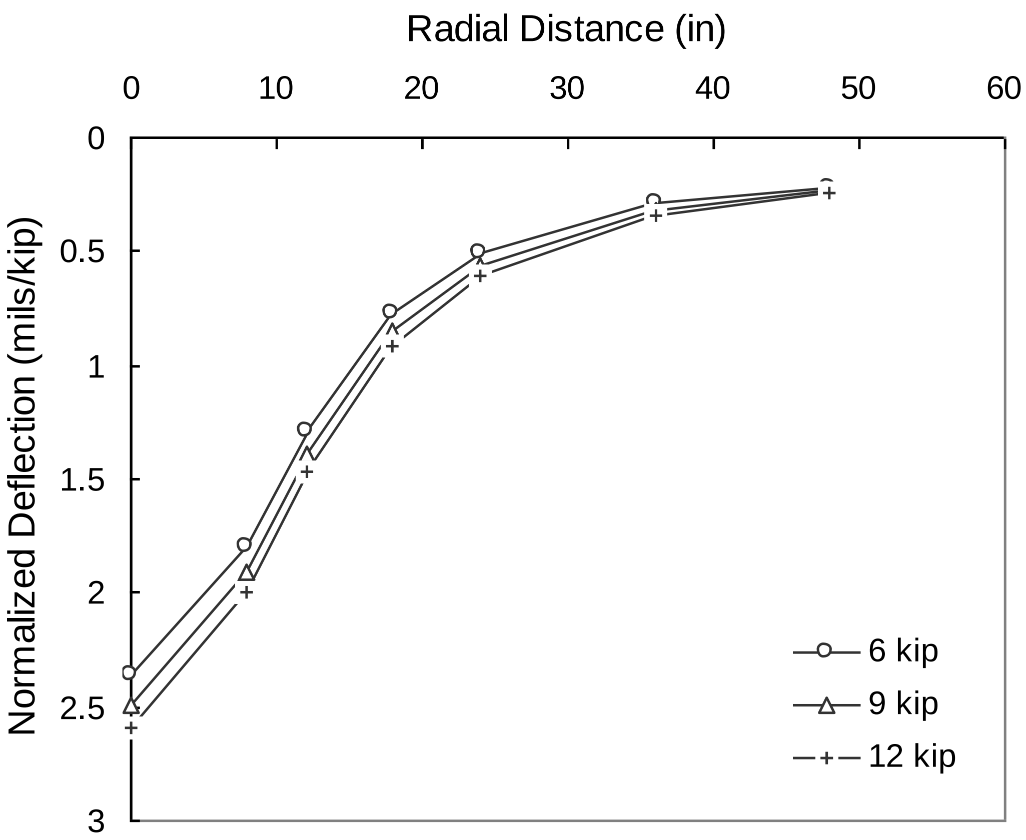
Objectives

- Develop a mechanistic-empirical analysis method for predicting remaining life of pavements using FWD multi-load level deflection data.

Normalized Deflection for Nonlinearity Check



SR 1125 with 4.9 in. AC



SR 1706 with 3.2 in. AC

Stress-Dependent Behavior of Subgrade Soils

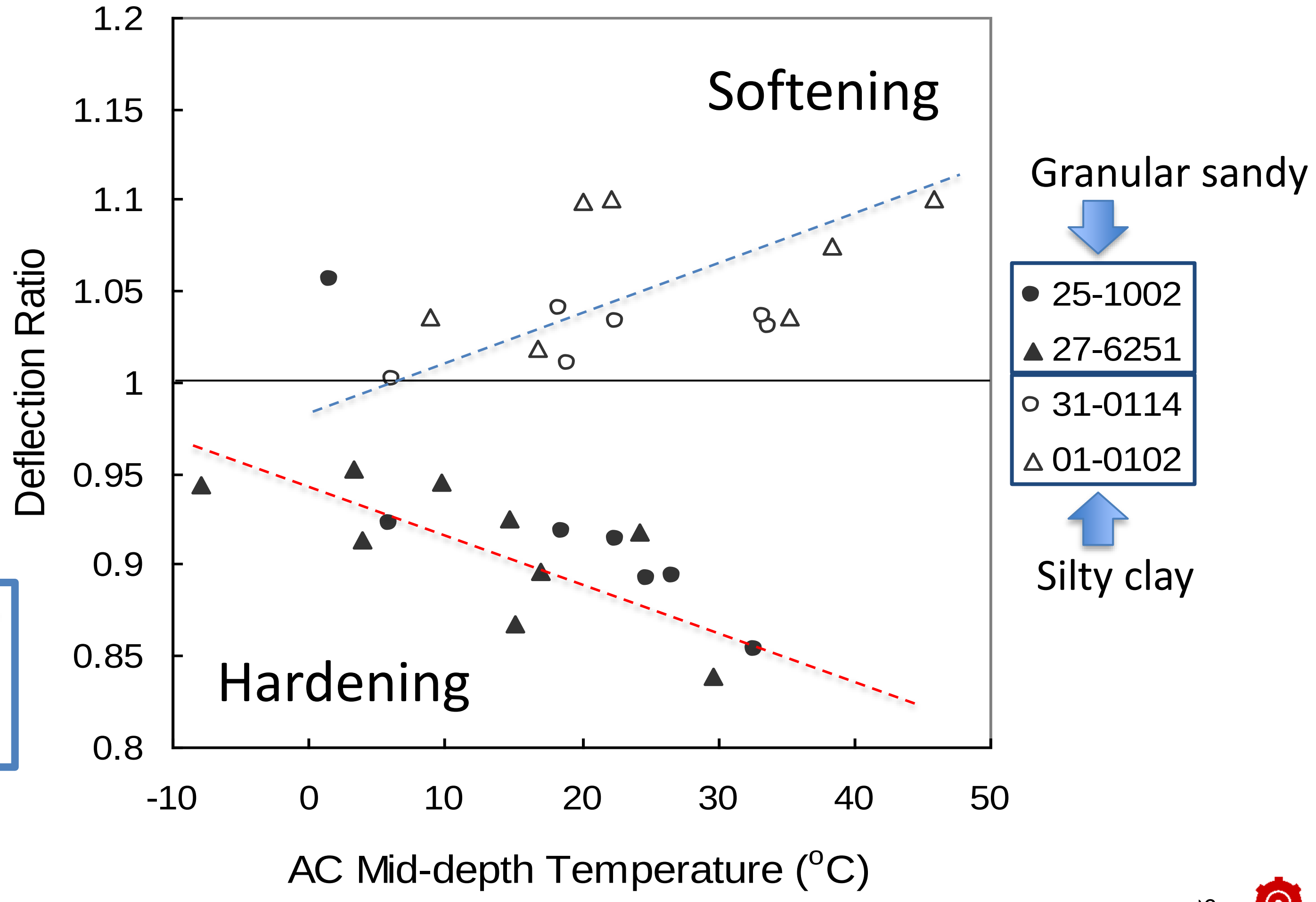
$$Def.Ratio = \frac{\delta_{71.2\ kN}}{\delta_{26.7\ kN}}$$

$$M_r = k_1(\theta)^{k_2}(\sigma_d)^{k_3}$$

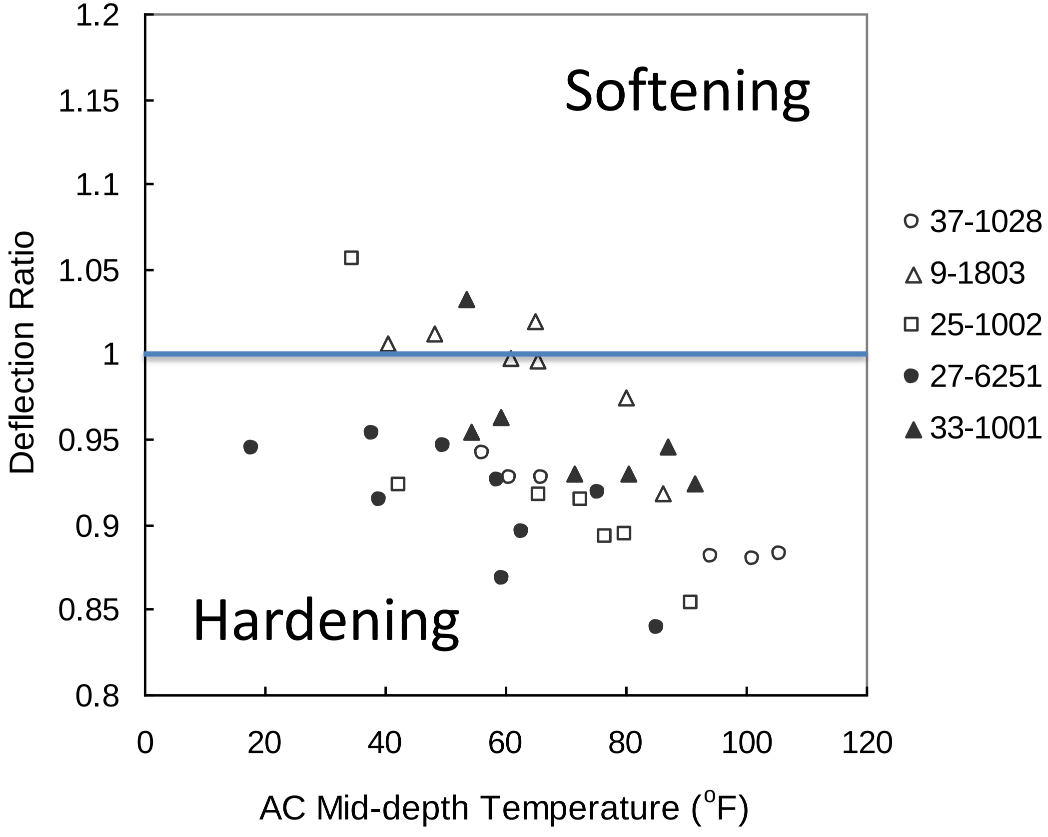
+ (k_2)   - (k_3)

T ↑ σ_d ↑ $(\sigma_d)^{k_3}$ ↓ Mr ↓ Deflection ↑ Def. Ratio ↑

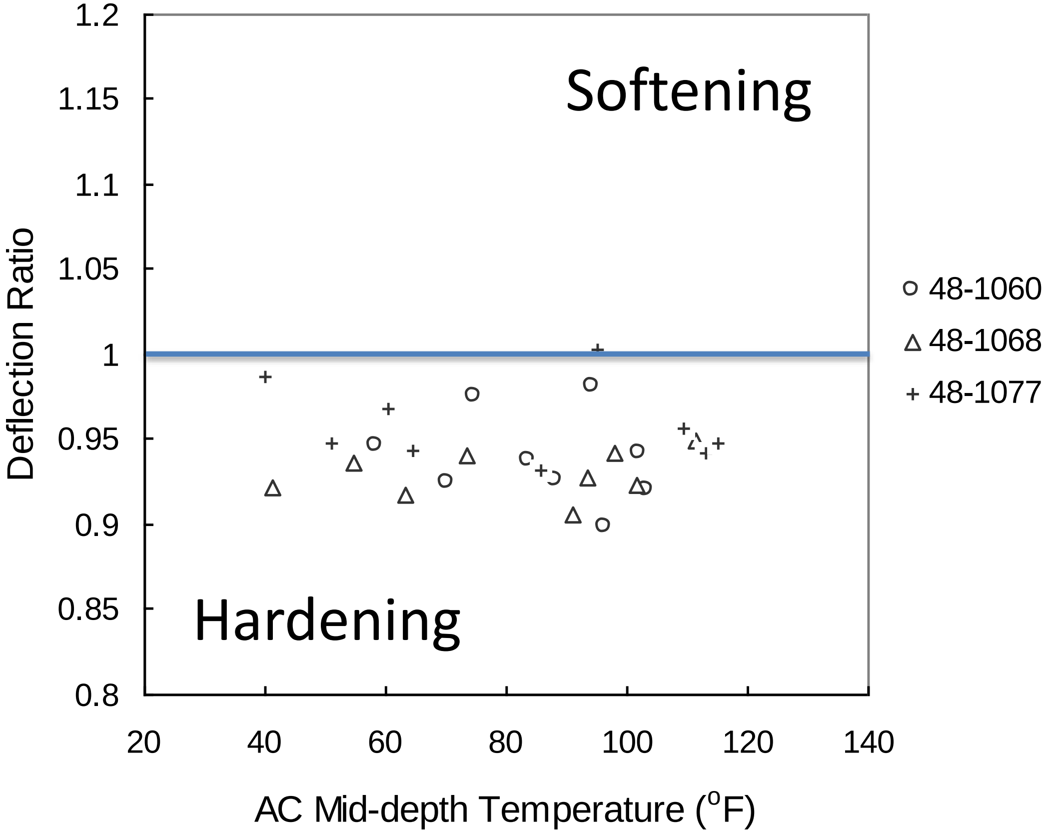
T ↑ θ ↑ $(\theta)^{k_2}$ ↑ Mr ↑ Deflection ↓ Def. Ratio ↓



Stress-Dependent Behavior of Aggregate Base



Gravel Base



Crushed Stone Base

Synthetic Database for Remaining Life

- Dynamic, nonlinear elastic finite element analysis using ABAQUS
- Universal soil model with aggregate properties from Garg and Thompson (1998) and subgrade properties from Santha (1994)
- 40, 53.3, and 66.7 kN (9, 12, and 15 kips) of FWD load
- 2,000 and 8,000 cases for full-depth (FD) and aggregate base (AB) pavements, respectively
- Pavement responses
  - Tensile strain at the bottom of AC layer for fatigue cracking
  - Vertical compressive strains in the AC layer, on top of the base layer, and on top of the subgrade for rutting

Parametric Sensitivity Analysis – AB Pavement

Distress Type	Critical Response	DBP's	R2
Fatigue Cracking	Tensile Strain at Bottom of AC layer	**BDI**	**0.9808**
		AUPP	**0.9319**
		BCI	0.9302
		SCI	0.8458
Rutting	Average Compressive Strain in AC layer	**SCI**	**0.911**
		AUPP	0.7476
		BDI	0.5206
		BCI	0.4182
	Compressive Strain on Top of Base Layer	**BDI**	**0.9675**
		BCI	0.908
		AUPP	0.8824
		SCI	0.783
		D_{36}-D_{60}	0.5155
	Compressive Strain on Top of Subgrade	**BCI**	**0.7461**
		BDI	0.7157
		D_{36}-D_{60}	0.624
		SCI	0.532
		AUPP	0.4977

Predictive Equations for AC Modulus and Critical Strains

Aggregate Base Pavement (Multi-Level FWD Load)
$\log(E_{ac}) = -1.183 \log(H_{ac}) - 1.103 \log(SCI) + 5.096$
$\log(\varepsilon_{ac}) = 1.078 \log(BDI) + 0.180 \log(H_{ac}) + 2.772$
$\log(\varepsilon_{cac}) = 1.076 \log(SCI) + 1.122 \log(H_{ac}) + 0.315$
$\log(\varepsilon_{abc}) = 0.938 \log(BDI) - 0.079 \log(H_{ac}) + 0.045 \log(H_{base}) + 3.826$
$\log(\varepsilon_{sg}) = 1.017 \log(BCI) - 0.042 \log(H_{ac}) - 0.494 \log(H_{base}) + 5.072$

Pavement Performance Models

Fatigue Cracking (Asphalt Institute)

$$N_f = 0.0796\varepsilon_t^{-3.291}\left|E^*\right|^{-0.854} P^{-0.3}$$

Rutting (VESYS Model)

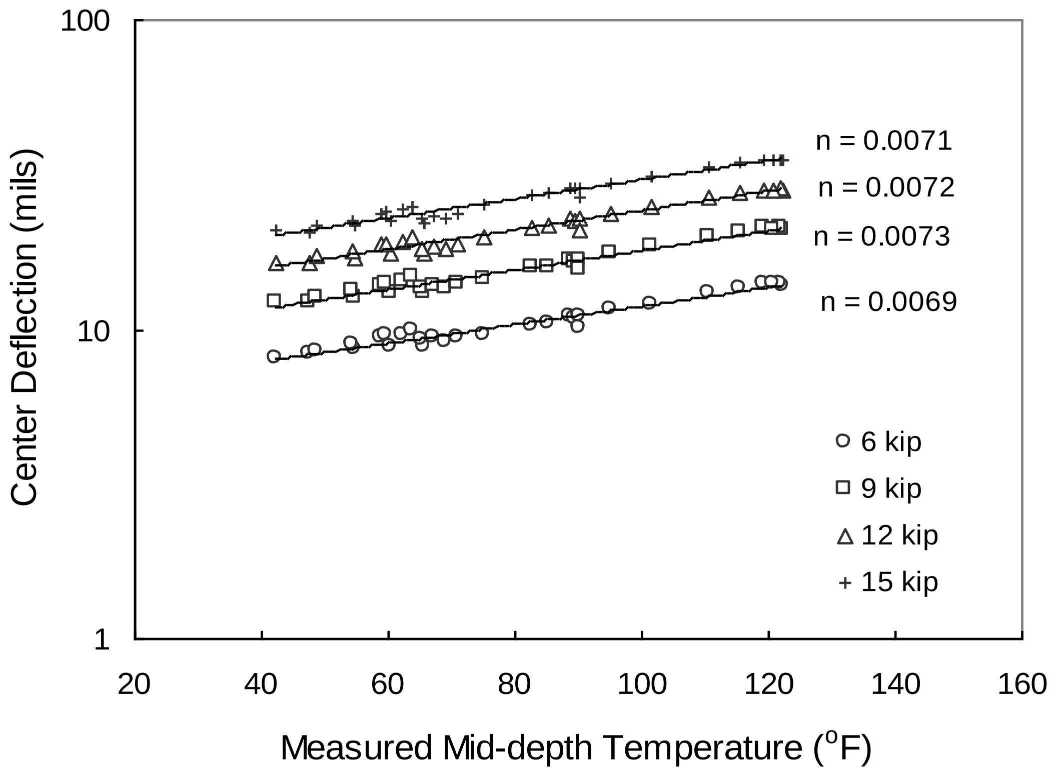
$$RD(N) = \sum_{i=1}^{n}\left[\int_0^N \mu_i N^{-\alpha_i} dN \int_{d_{i-1}}^{d_i} \varepsilon_c(z)dz\right] = \sum_{i=1}^{n}\left[\frac{\mu_i N^{1-\alpha_i}}{1-\alpha_i}\int_{d_{i-1}}^{d_i} \varepsilon_c(z)dz\right]$$

Traffic Consideration

- The LTPP database contains the number of axles corresponding to a particular axle load for a given period.
- Estimate the Equivalent Axle Load Factor (EALF) for each load level based on the results of AASHTO Road.
- Determine the Equivalent Single Axle Load (ESAL) for the axle load of interest during the given period. => $P_{i,j}$

Temperature Consideration

- Temperature correction procedures for FWD deflections are based on a 40 kN (9 kip) load level.
- Deflections under multi-level FWD loads were measured from US 264 at different times of day and different seasons.
- The slopes of deflection-AC mid-depth temperature in semi-log scale are relatively the same at all load levels.
- The temperature correction procedure for FWD deflections developed by Lukanen et al. (2000) using LTPP data was adopted.



Remaining Life Prediction Method

- Cumulative damage concept based on Miner's hypothesis
- Damage factor = damage per pass caused to a specific pavement system by the load in question

$\log(E_{ac}) = -1.183 \log(H_{ac}) - 1.103 \log(SCI) + 5.096$

$$DF_i = \frac{1}{N_{f,i}} \Leftarrow N_f = 0.0796\varepsilon_t^{-3.291}\left|E^*\right|^{-0.854} P^{-0.3}$$

$\log(\varepsilon_{ac}) = 1.078 \log(BDI) + 0.180 \log(H_{ac}) + 2.772$

- Total damage, S

$$S = \sum_{i=1}^{n}\sum_{j=1}^{m}\left(P_{i,j} \times DF_{i,j}\right)\times Y$$

where $P_{i,j}$ = number of repetitions of the i^{th} load group during the j^{th} season,
$DF_{i,j}$ = damage factor due to the i^{th} load group during the j^{th} season,
Y = number of years, and
n, m = number of load groups and seasons, respectively.

Verification

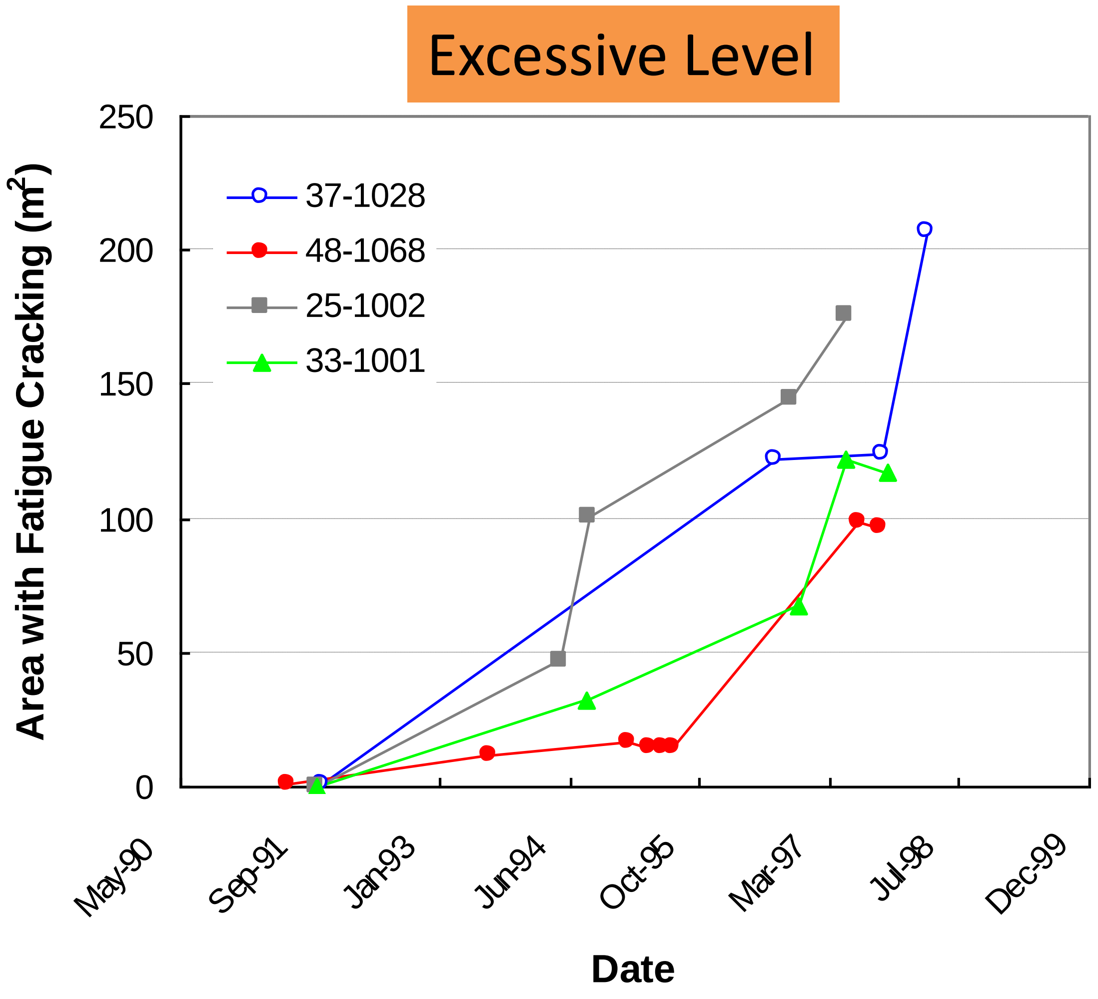
- LTPP sections from the Seasonal Monitoring Program (SMP)
- Wet freeze and wet no-freeze regions
- Data include:
  - Temperature measurements within the AC layer
  - Traffic monitoring data
  - Multiload level FWD deflection data
  - Distress survey results

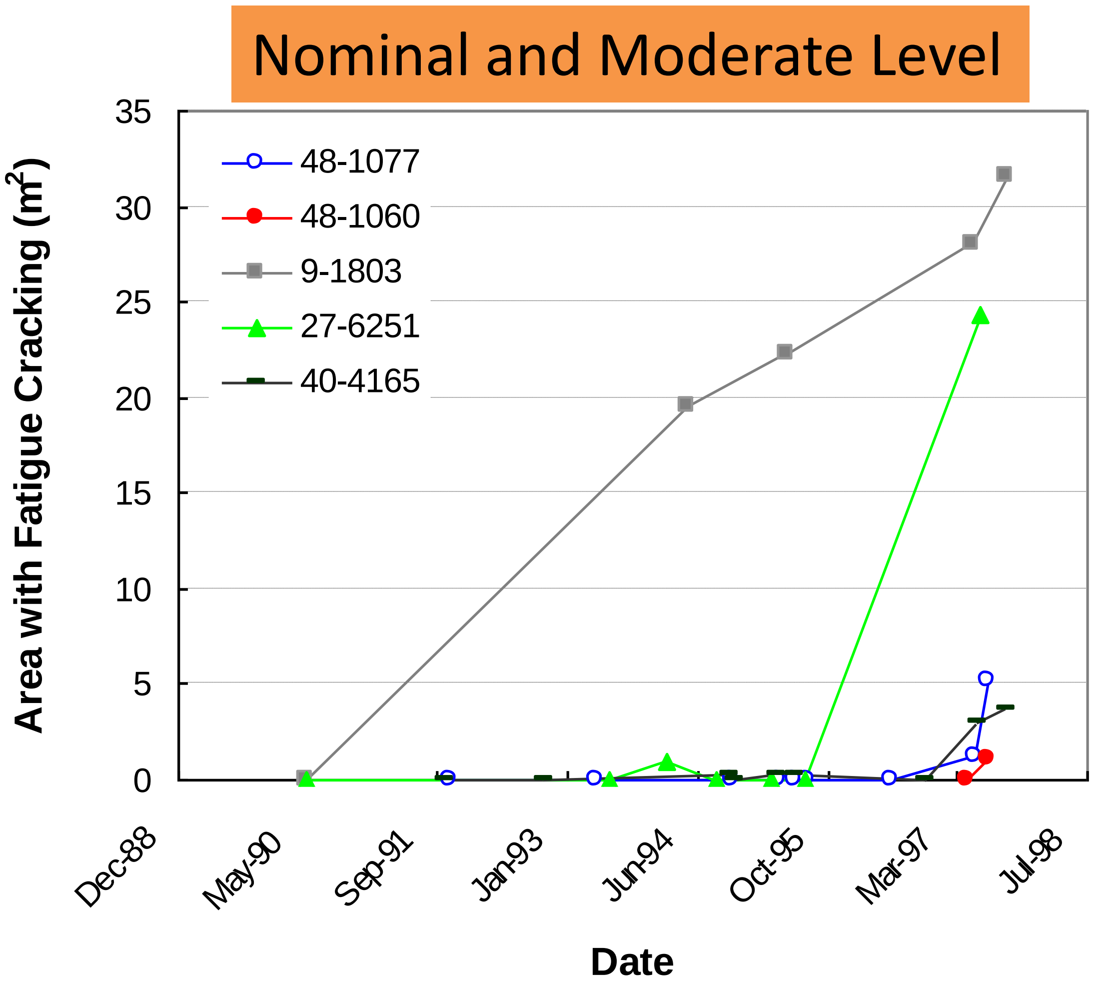
Characteristics of LTPP SMP Sections

State	SHRP ID	Thickness (mm)			Material Type		
		AC	Base	Subbase	Base	Subbase	Subgrade
NC (37)[1]	1028	266.7	139.7	-	Silty Sand	-	SM
TX (48)[1]	1077	129.5	264.2	-	Cr. Stone	-	ML
TX (48)[1]	1068	276.9	152.4	203.2	Cr. Stone	Lime-Treated Soil	CL
TX (48)[1]	1060	190.5	312.4	152.4	Cr. Stone	Lime-Treated Soil	SM
CT (9)[2]	1803	182.9	304.8	-	Gravel	-	ML
MA (25)[2]	1002	198.1	101.6	213.4	Cr. Gravel	Soil Aggregate	SP
MN (27)[2]	6251	188.0	259.1	-	Gravel	-	SP
NH (33)[2]	1001	213.4	490.2	365.8	Gravel	Soil Aggregate	SP
OK (40)[2]	4165	68.6	137.2	-	HMAC	-	SM

[1]Wet no freeze region; [2]Wet freeze region

Extent of Fatigue Cracking

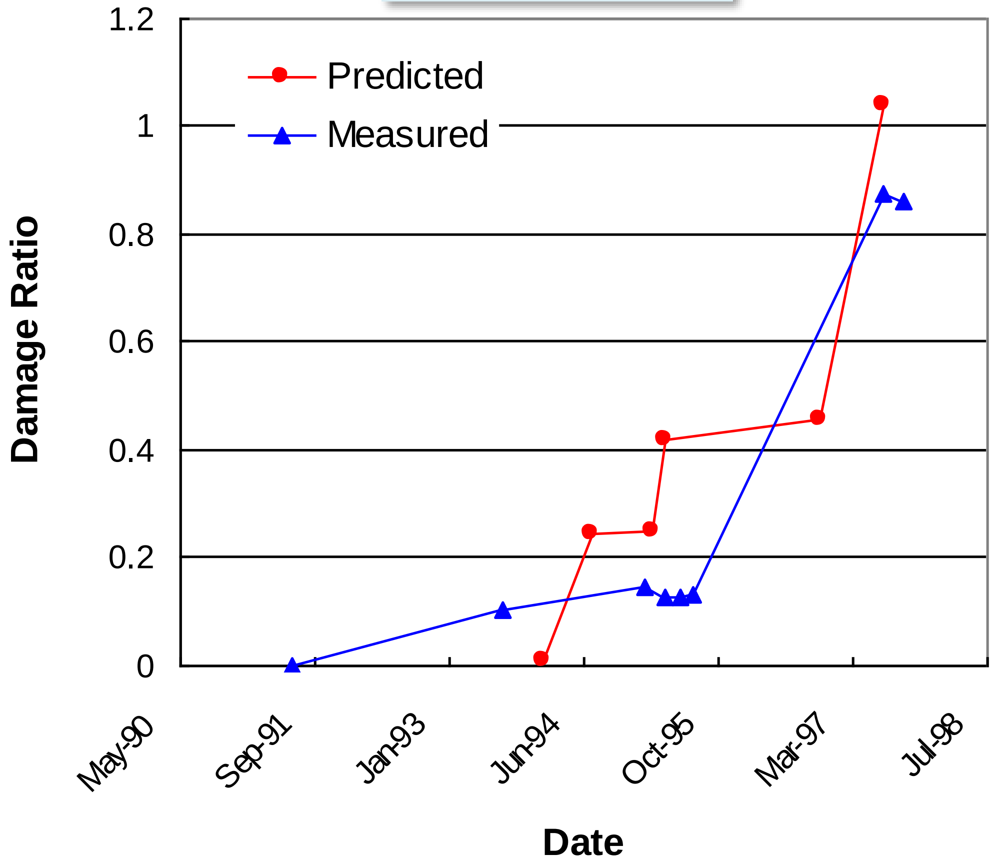




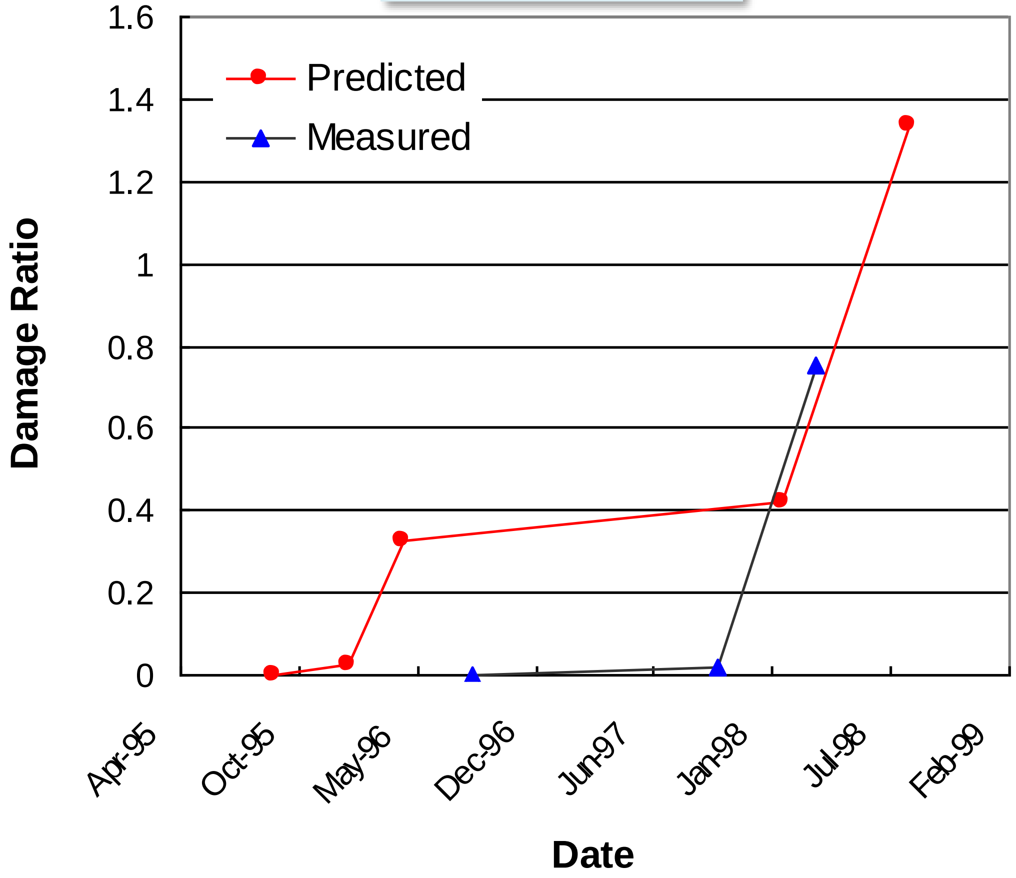
Fatigue Cracking Prediction

Wet-No Freeze

TX: 48-1068



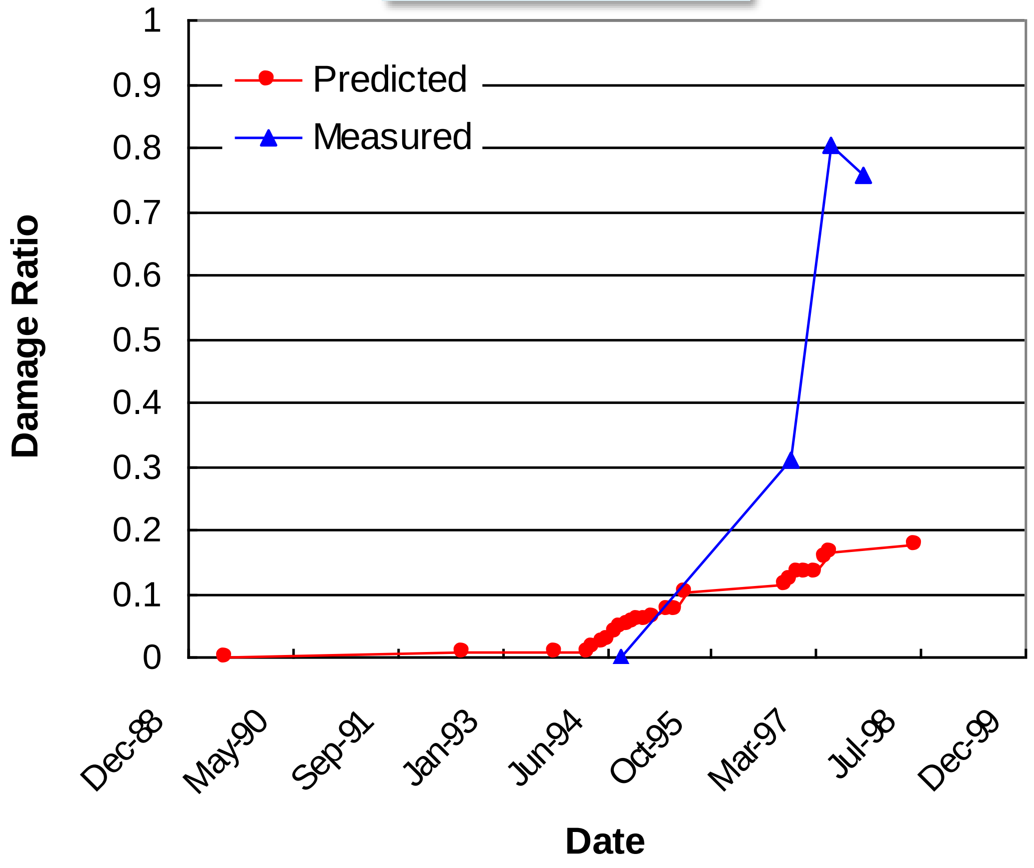
NC: 37-1028



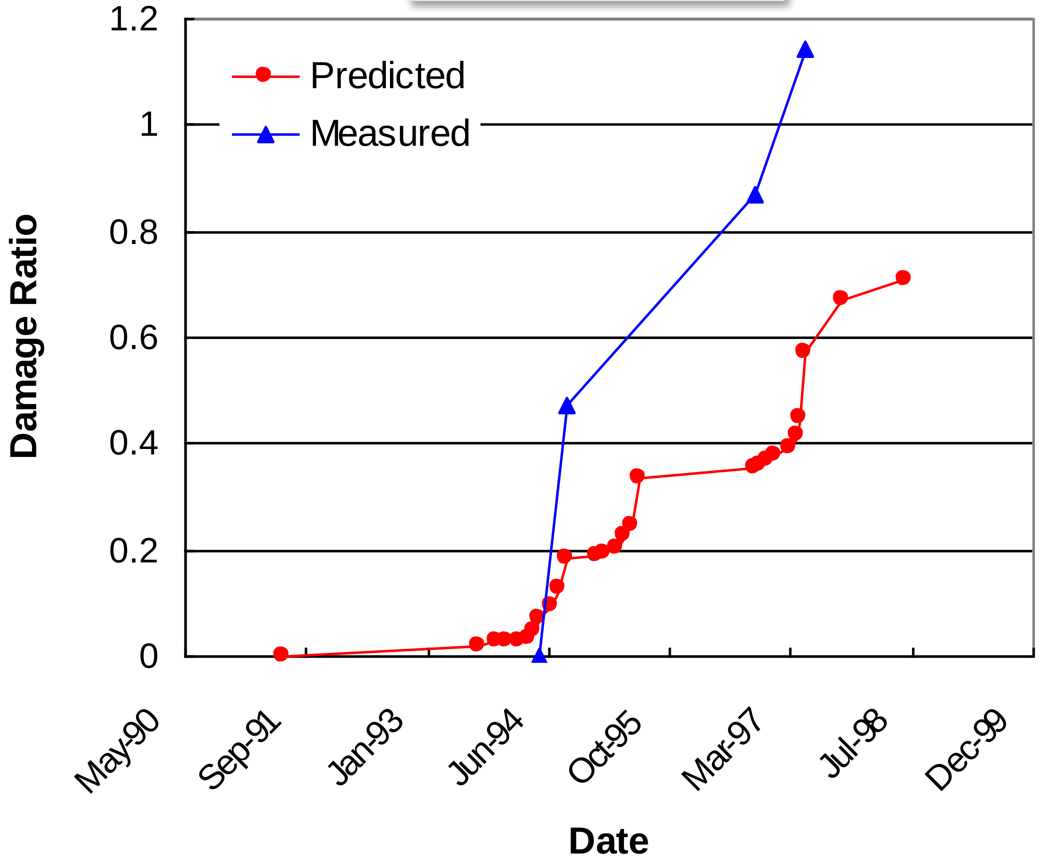
Fatigue Cracking Prediction

Wet Freeze – Severe Cracking

NH: 33-1001



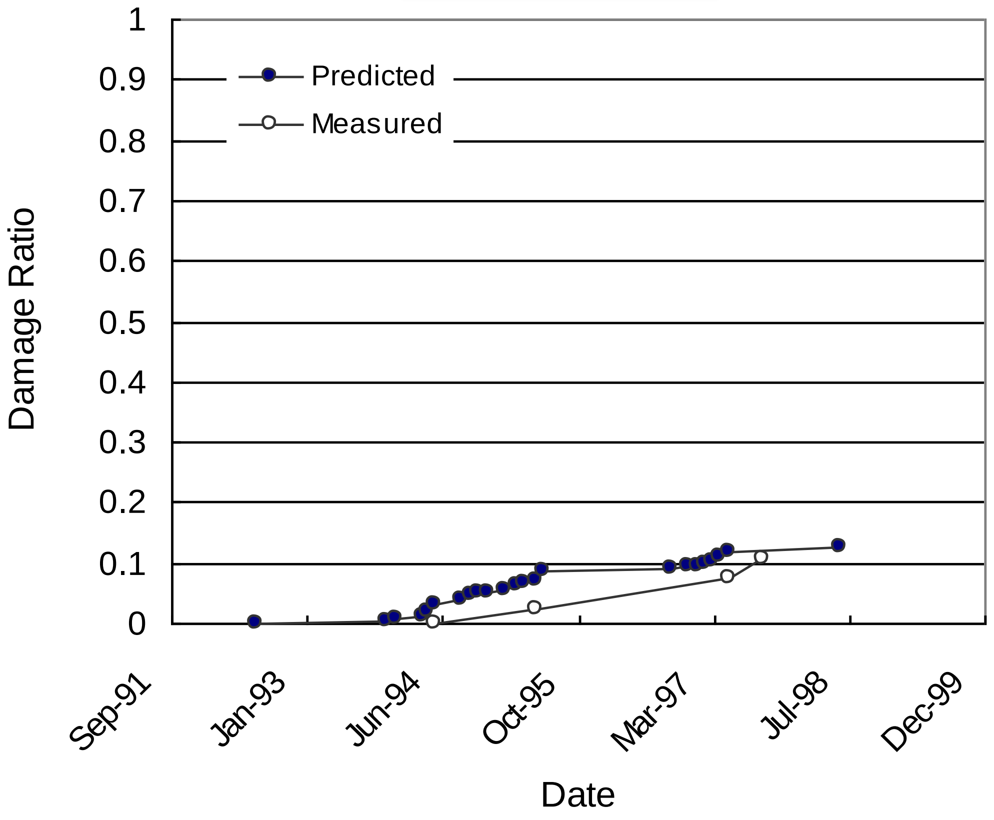
MA: 25-1002



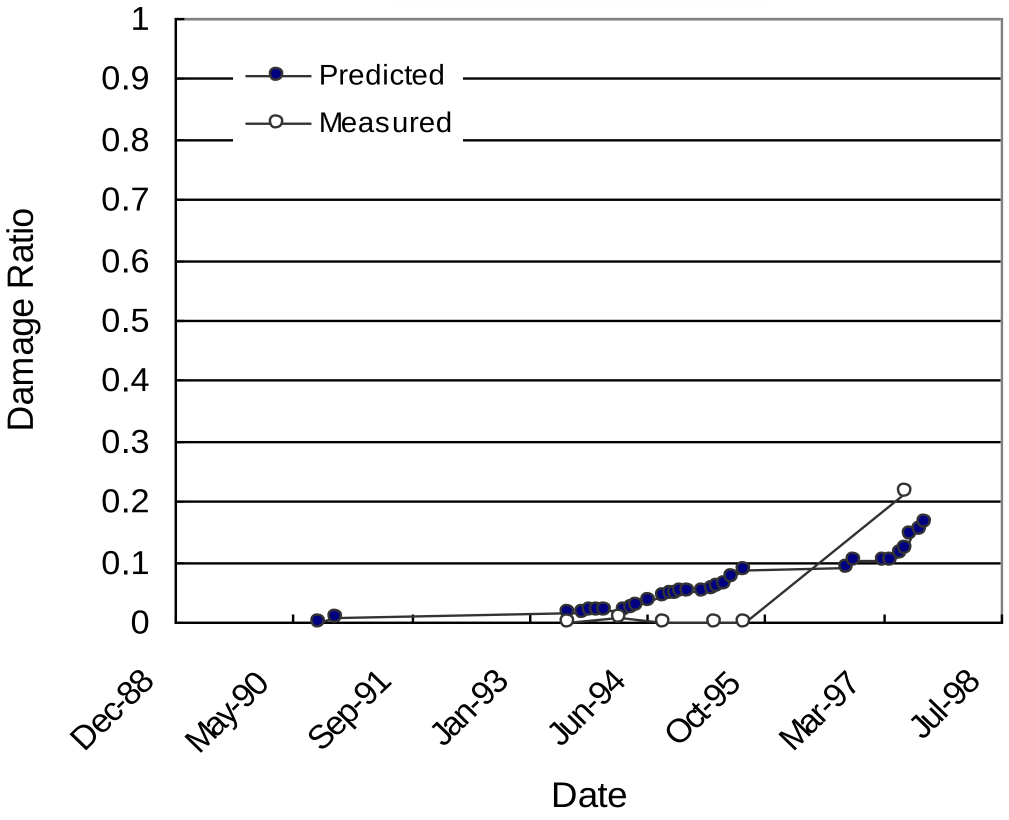
Fatigue Cracking Prediction

Wet Freeze – Nominal and Moderate Cracking

CT: 9-1803



MN: 27-6251

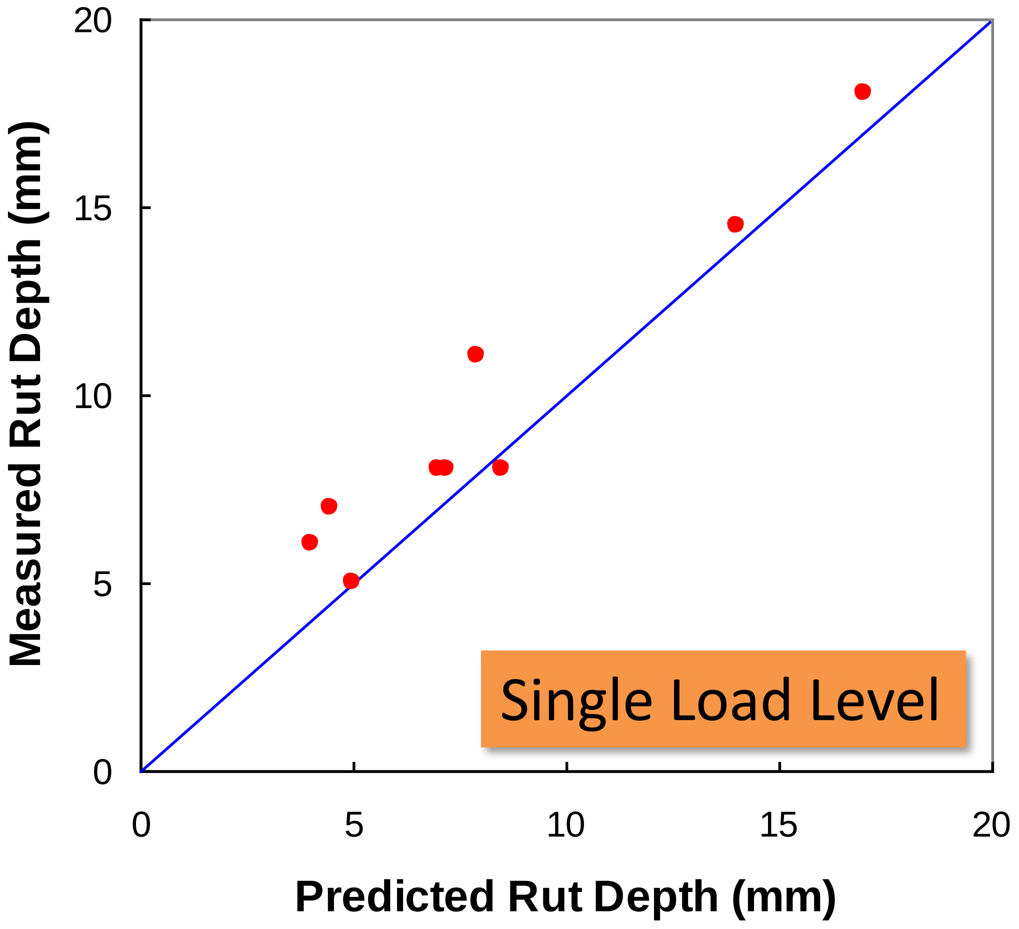


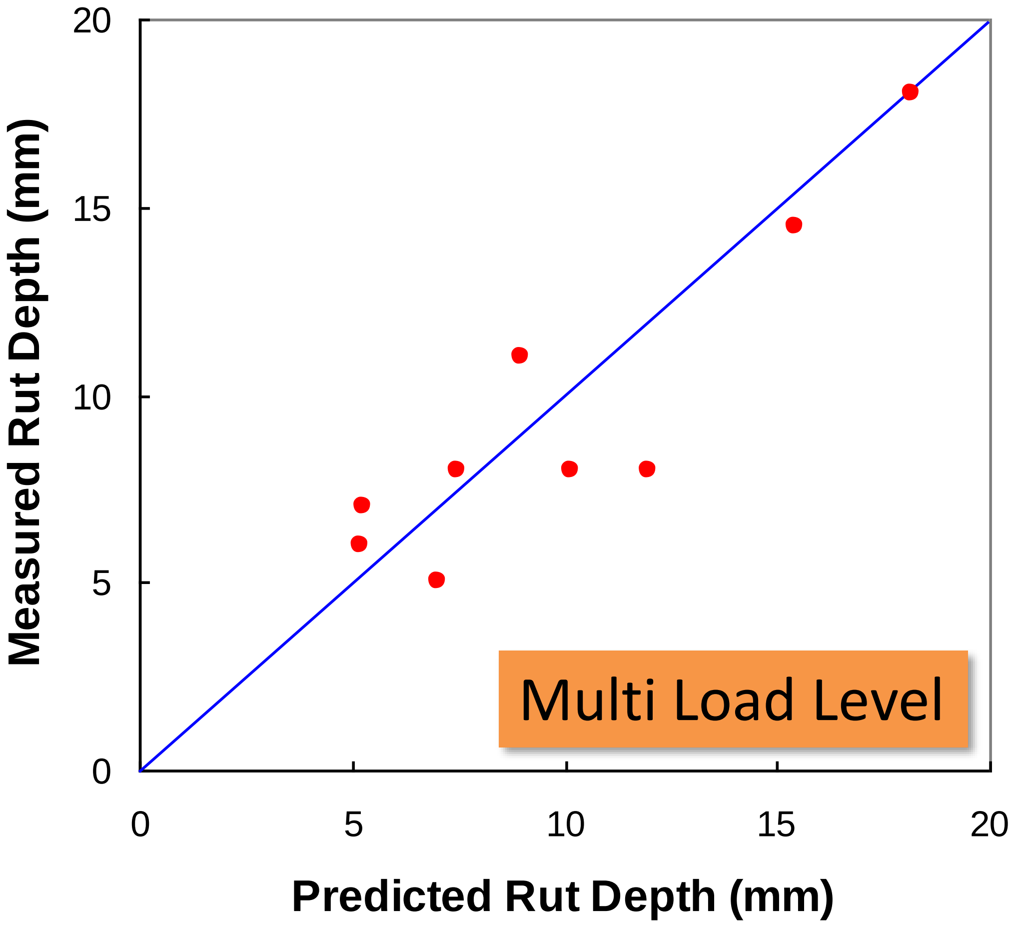
VESYS Rutting Parameters

Park 2000, Kenis 1997

Layer	Rutting Parameter	Temperature (°C)			
		15.5	25.6	30.0	35.0
Asphalt Concrete	α	0.75	0.74	0.73	0.72
	μ	0.30	0.31	0.32	0.34
Base	α	0.75	0.75	0.75	0.75
	μ	0.28	0.28	0.28	0.28
Subgrade	α	0.75	0.75	0.75	0.75
	μ	0.02	0.02	0.02	0.02

Predicted and Measured Rut Depths





Conclusions

- The study indicated that the deflection ratio obtained from multi-load level deflections could be used to predict the stress state dependency of the base/subgrade materials. The AC layer modulus and the tensile strain at the bottom of the AC layer were found to be good indicators for the condition of AC layer.
- The procedures for remaining life prediction using FWD multiload level deflections and cumulative damage concept are developed for flexible pavements.
- The performance of fatigue cracking can be predicted using the proposed procedure except for pavements with high and rapidly increasing cracking in wet freeze regions. Such trends may be due to the environment-induced distresses such as low temperature cracking or permanent deformation of unbound layers during the spring.
- Predicted rut depths using single load and multiload level deflections show reasonable agreement with measured rut depths over a wide range of rutting potential. The procedure using single load level deflections consistently underpredicts the rut depths.

NC STATE

Thank you