



ASTM Kummer Lecture 2007



Quantifying the Impact of JCP Curling and Warping on Pavement Roughness

Presented by
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Transtec Group



FHWA Curl/Warp Study

- Impact of Curling and Warping on JCP Performance

Major Findings

- New, robust profile synchronization and joint identification techniques
- Invention of 2GCI to better characterize slab curvature
- New, effective slab curvature analysis framework
- RoCK System to assess curvature's impact on roughness


Major Findings (cont'd)

- New technique to evaluate joint hinge functionality
- New system to classify joint edge geometry
- Robust procedure to estimate joint faulting

Today, We'll Cover....

- Curl/Warp Measurement
- Profile Synchronization and Joint ID
- 2GCI Curvature Index
- RoCK System for curvature-impact on roughness

About Curl/Warp 101



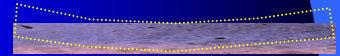
Technical Synthesis

Outlines

- **Curl/Warp Measurement**
- Profile Synchronization and Joint ID
- 2GCI Curvature Index
- RoCK System for Curvature-Impact-Roughness Analysis

Curl/Warp Measurement

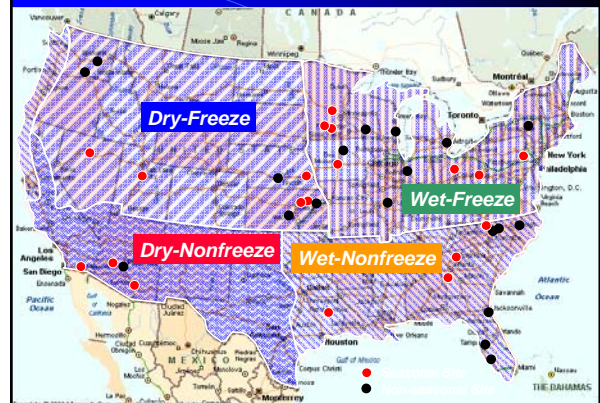
- What to be measured?
 - Site Selection
 - Data Collection
- How to measure?
 - Profiling
 - Temperature
 - Others



Site Categories

- FHWA LTPP: 11 Sites
- FHWA RIPPER: 1 Site
- FHWA HIPERPAV: 4 Sites
- FHWA Curling/Warping Study: 3 Sites
- Ohio Test Road (also Curling/Warping Study and LTPP site)
- Mn/ROAD (also Curling/Warping Study site)
- Kansas DOT/Kansas State University: 1 Site

Selected Sites

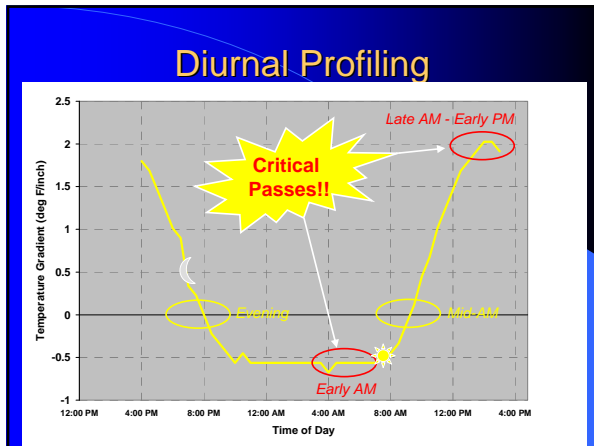


Data Collection

- Inertial profile and image log data
- Slab temperature data
- Visual distress survey
- FWD deflection
- Construction records
- Weather data

Diurnal Profiling

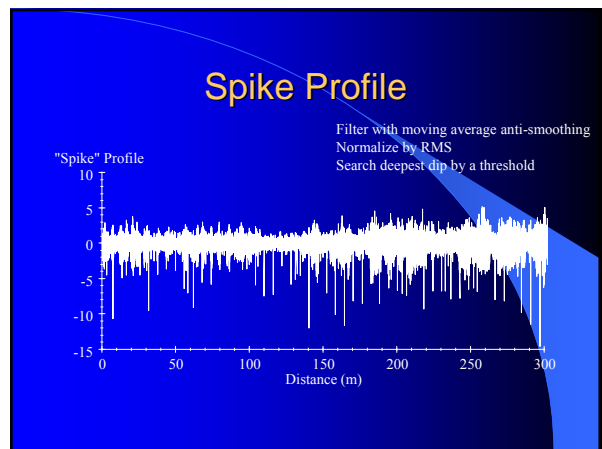
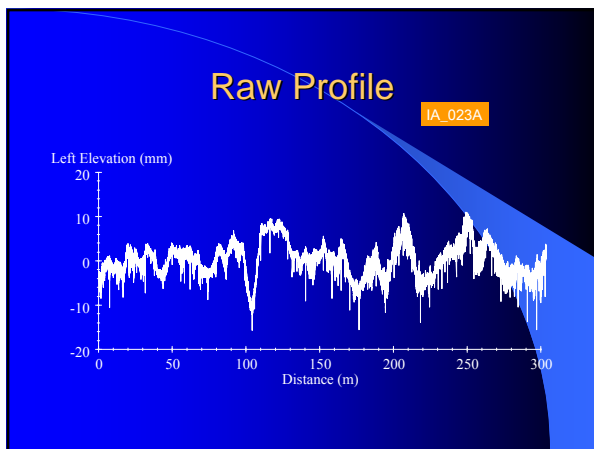
- Early Morning → Max (-) Temp. Gradient
- Mid-morning → ~ Zero Temp. Gradient
- Noon → Max (+) Temp. Gradient
- Evening → ~ Zero Temp. Gradient



- ### Seasonal Profiling
- “Seasons”
 - Spring: March-June
 - Summer: June-September
 - Fall: September-December
 - Winter: December-March
 - Minimum 15~20°F difference in average ambient temperature between seasonal visits
 - Minimum 2 months between seasonal visits

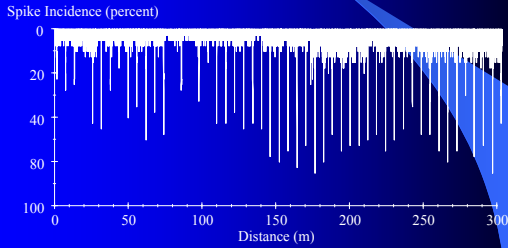
- ### Data Collected
- 95 site visits over 38 test sites
 - 96,000 miles traveled
 - 19 different States
 - 125 gigabytes electronic raw data
 - 6,000 profile runs
 - 400,000 slabs (within sections of detailed analyses) analyzed

- ### Outlines
- Curl/Warp Measurement
 - **Profile Synchronization and Joint ID**
 - 2GCI Curvature Index
 - RoCK System for Curvature-Impact-Roughness Analysis



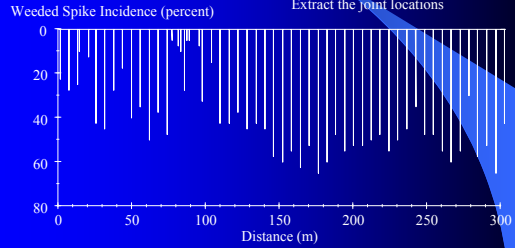
Spike Incidence

Assemble the dip count across the data set



Weeded Spike Incidence

Weed/Clear false hits
Extract the joint locations

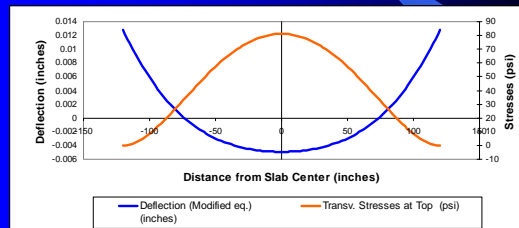


Outlines

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Westergaard Curling Formula

$$z = -z_w \frac{2 \cos \lambda \cosh \lambda}{\sin 2\lambda - \sinh 2\lambda} \left[(-\tan \lambda + \tanh \lambda) \cos \frac{x}{l\sqrt{2}} \cosh \frac{x}{l\sqrt{2}} + (\tan \lambda + \tanh \lambda) \sin \frac{x}{l\sqrt{2}} \sinh \frac{x}{l\sqrt{2}} \right]$$



Westergaard Curling Parameters

- **Radius of relative stiffness**
A fixed (theoretically known) quantity, and is a function of the slab thickness, modulus of elasticity, Poisson's ratio, and the modulus of reaction for the slab support.
- **Strain gradient**
A linear approximation of the combined thermal- and moisture-induced strains in the concrete slab per unit thickness. If slab geometry, materials, and support parameters are all known, this parameter alone could serve as a suitable curvature index.



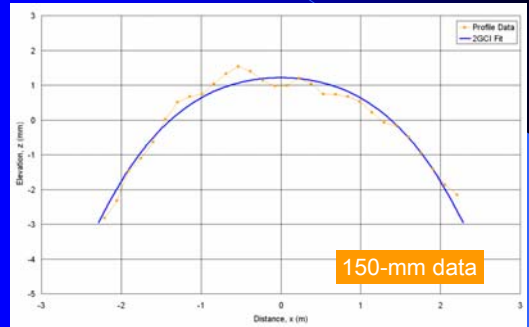
Adjusted Westergaard Curling Parameters

- Adjusted to overcome Westergaard assumptions
- Fit to actual slab deformation
- More fundamental than an arbitrary geometric function
- Fitted parameters:
 - **Pseudo-radius of relative stiffness**
 - **Pseudo-strain gradient**

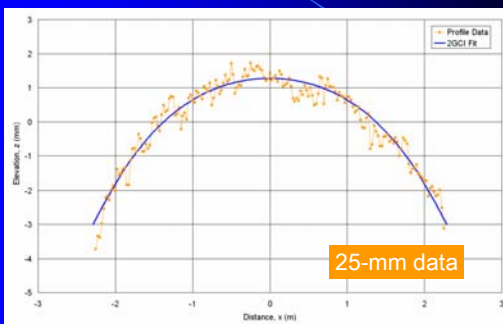
2GCI Computation Steps

- Isolate the individual slab segments
- Pre-process isolated segments
- Mask joints (optional)
- Define model parameters
- Perform nonlinear curve fitting based on Westergaard curling formula
- Parse and report the curvature indices

2GCI Fit – Curled Down Slab



2GCI Fit – Curled Down Slab



2GCI Fit – Curled Down Slab

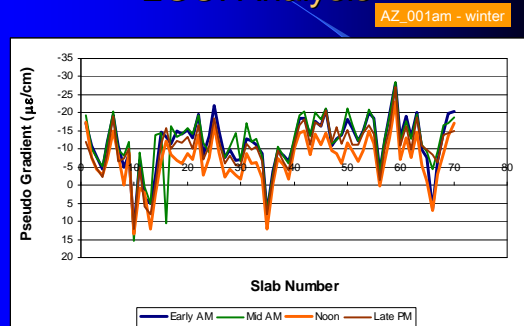
Profile Data Interval mm	2GCI Type	Pseudo-Radius (m)	Pseudo-Gradient ($\mu\text{e}/\text{cm}$)
150	2-parameter	0.947	28.2
150	1-parameter	0.965 (fixed)	27.0
25	2-parameter	0.988	26.2
25	1-parameter	0.965 (fixed)	27.8

Positive values

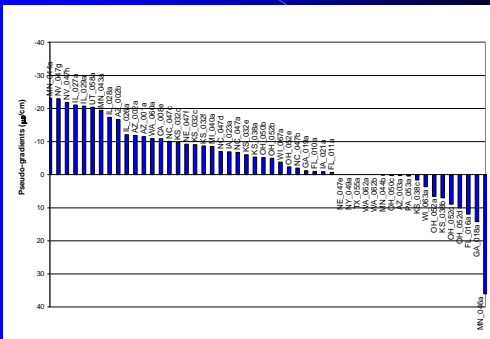
2GCI Computation

- Isolate the individual slab segments
- De-trend and de-mean the profile segment
- Mask joints
- Define model parameters
- Perform nonlinear curve fitting

2GCI Analysis



Mean Curvatures

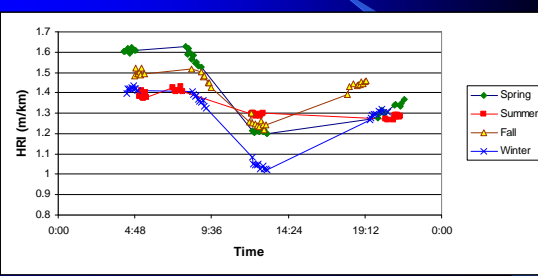


Outlines

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- Profile Synchronization and Joint ID
- 2GCI Curvature Index
- **RoCK System for Curvature-Impact-Roughness Analysis**

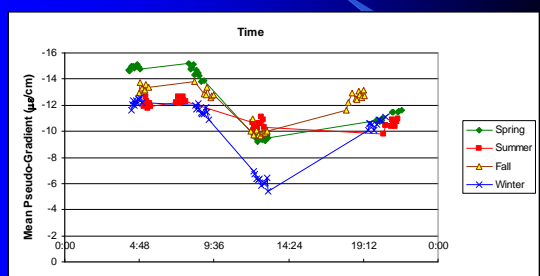
2GCI vs Roughness

AZ_001m



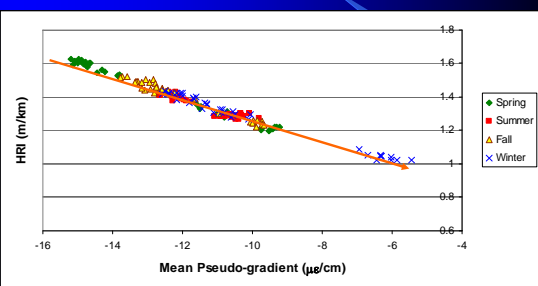
2GCI vs Roughness

AZ_001m



2GCI vs Roughness

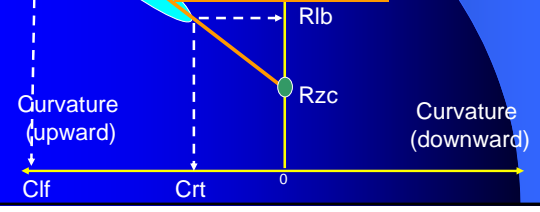
AZ_001m

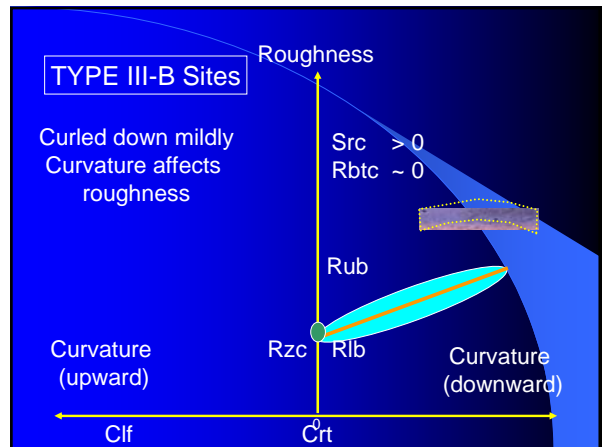
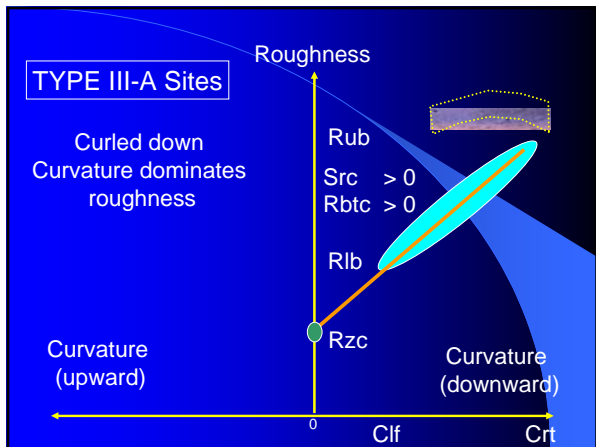
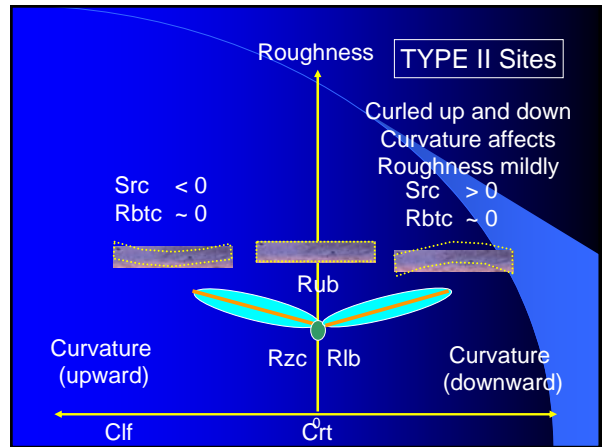
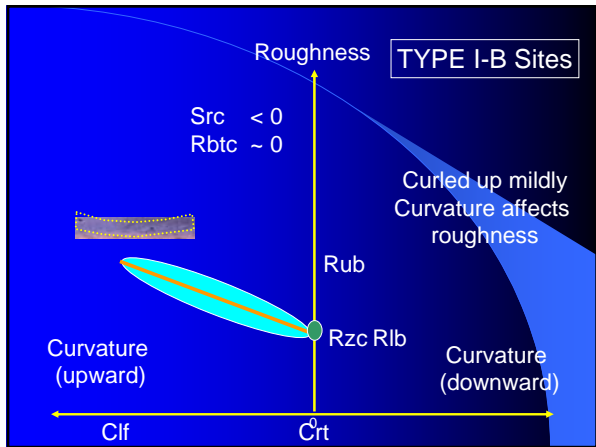
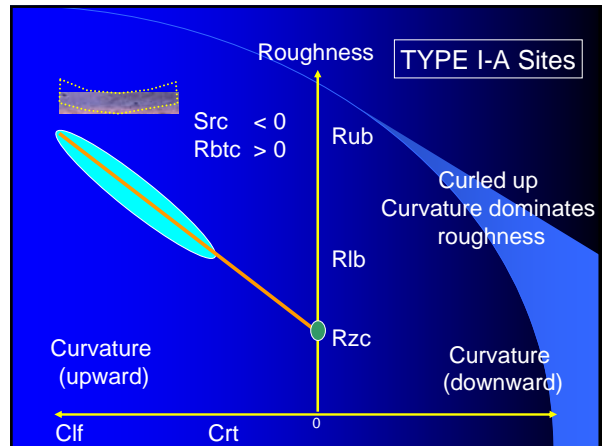
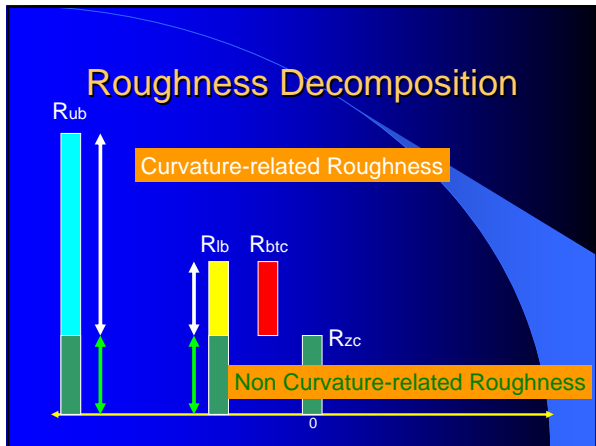


Roughness

- Rub: Upper Bound Roughness
- Rlb: Lower Bound Roughness
- Crt: Right bound Curvature
- Clf: Left bound Curvature
- Sr: Roughness Curvature Slope
- Rzc: Zero-Curvature Roughness
- Rtc: Built-in Curvature Roughness

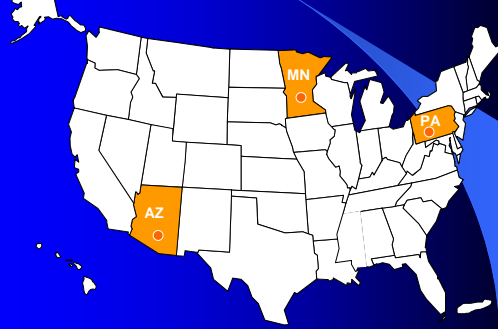
The RoCK Chart





Here are some applications

A Tale of 3 Test Sites



A Tale of 3 Test Sites

- AZ_001a
 - HIPERPAV AZ site, frontage road of I-10, Tucson AZ
- MN_046a
 - LTPP GPS 27-3003, TH 15, Lafayette, MN
- PA_053a
 - LTPP GPS 42-3044, I-78, Lenhartsville, PA

AZ_001a Site



MN 046a Site



PA 053a Site

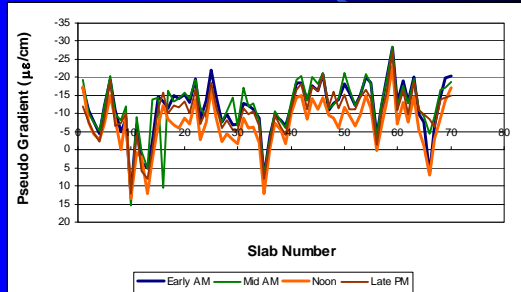


A Tale of 3 Test Sites

Site	Slab Thick mm(inch)	Base Type	Base Thick mm(inch)	Slab Width m(ft)	Joint Space mm(ft)	Dowel
AZ 001a	254 (10)	1	102 (4)	3.7 (12)	4.6 (15)	N
MN 046a	191 (7.5)	8	127 (5)	4.3 (14)	4.6 (15)	N
PA 053a	330 (13)	8	203 (8)	3.7 (12)	6.1 (20)	Y

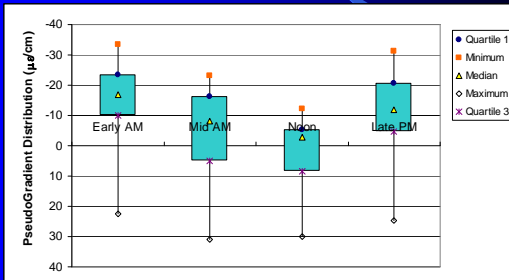
2GCI Analysis

AZ_001am - winter

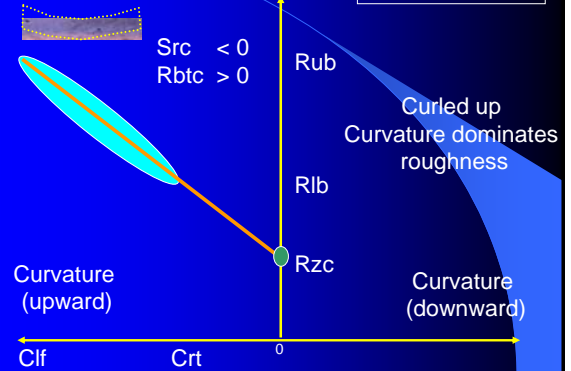


2GCI Analysis

AZ_001am - winter

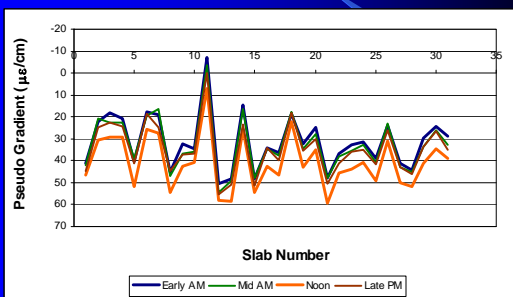


Roughness TYPE I-A Sites



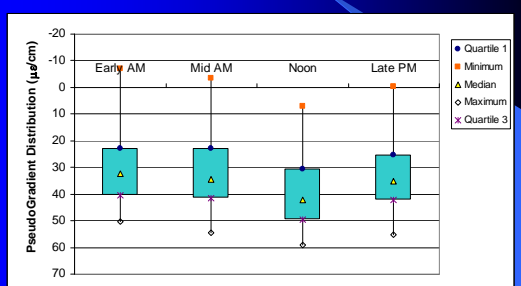
2GCI Analysis

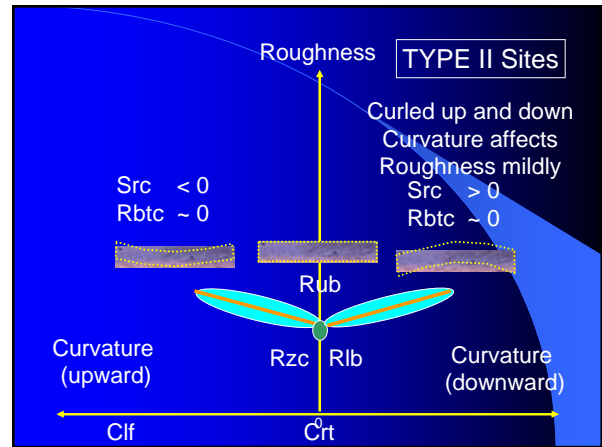
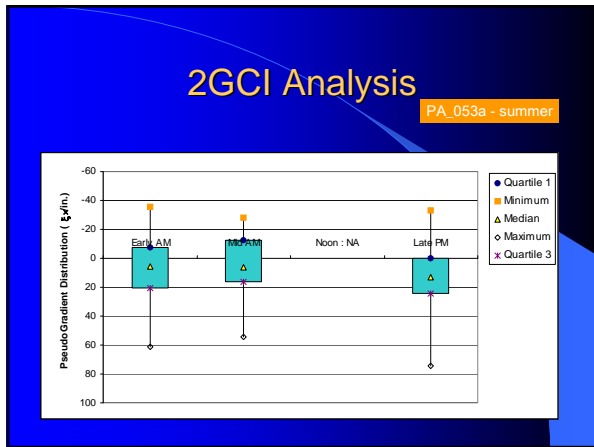
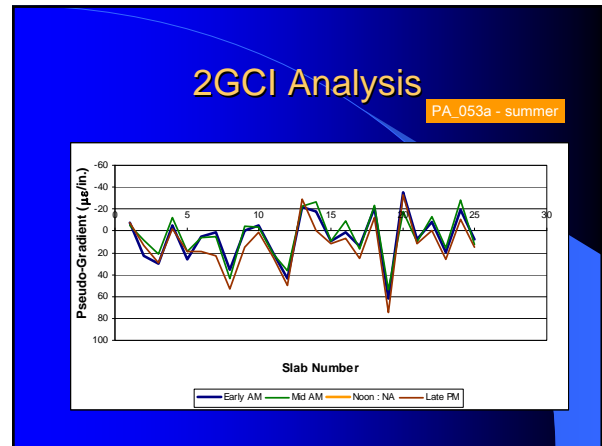
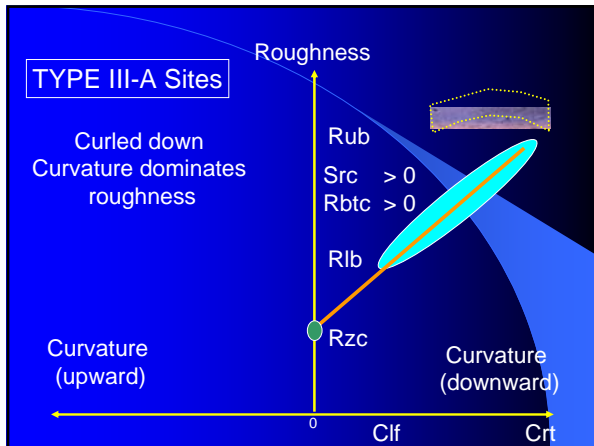
MN_046a - summer



2GCI Analysis

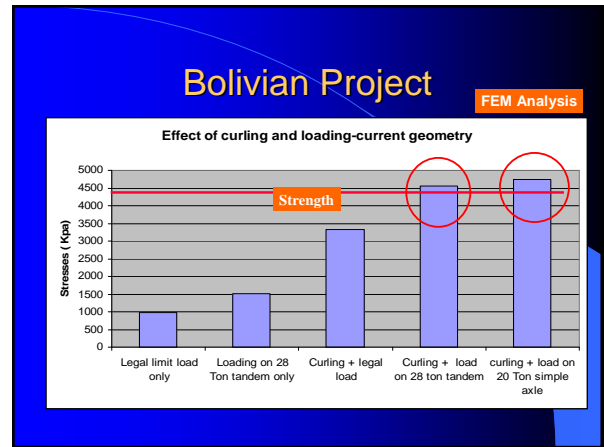
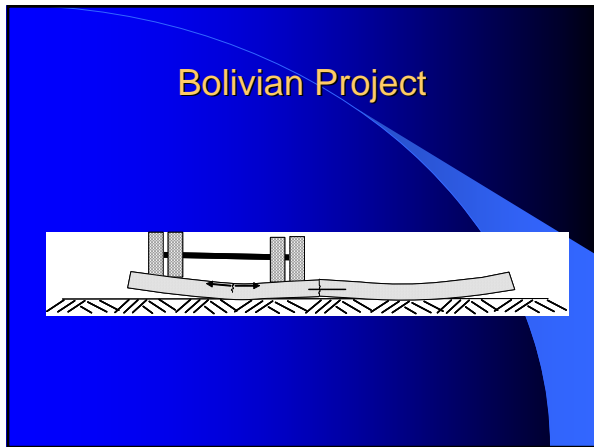
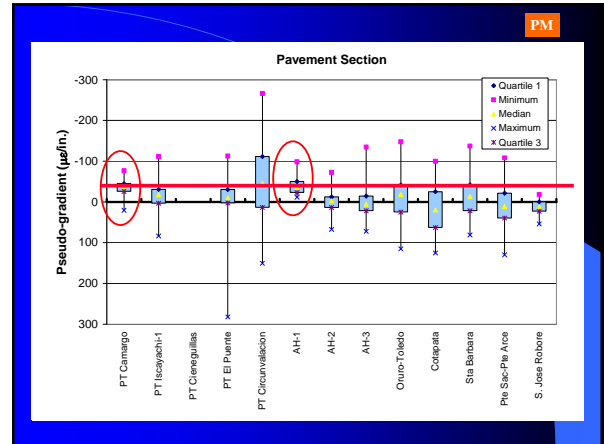
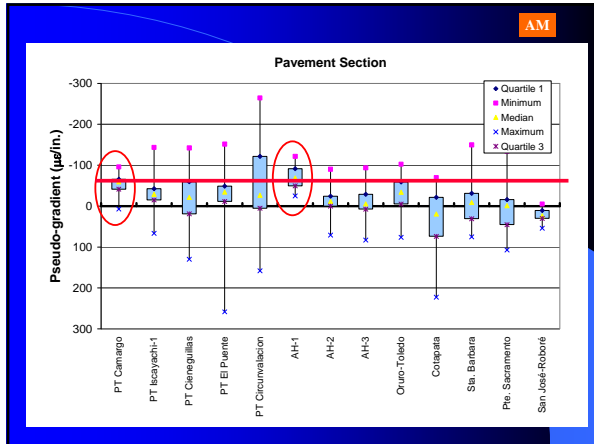
MN_046a - summer





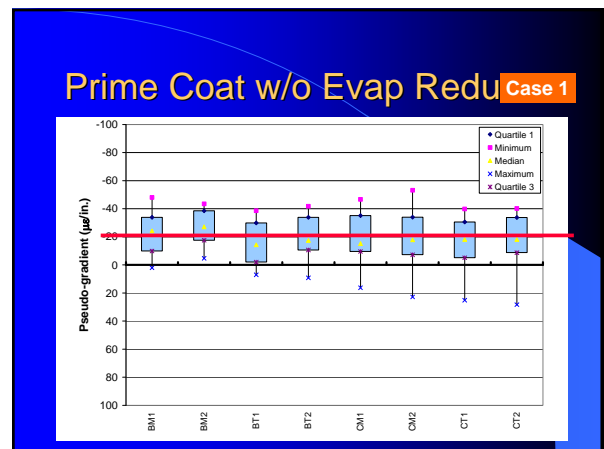
- ### Bolivian Project
- Two-lane undivided JCP
 - Mountainous terrain with moderate fills and cuts
 - 24-ft wide, 12-ft joint spacing
 - 8-inch slab on 6-inch granular base
 - Local climate is arid with rains from December to March
 - Drastic overnight temperature drops

- ### Bolivian Project
- Low relative humidity and extreme temperatures
 - Mix with a relatively high water cement ratio, high CTE aggregate, and inadequate curing techniques.
 - Longitudinal cracks at the center of the slab in both travel directions after the first winter

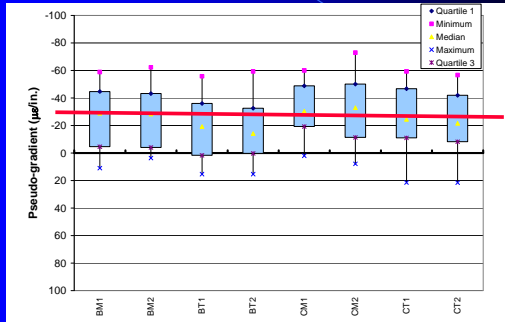


Base & Curing Study

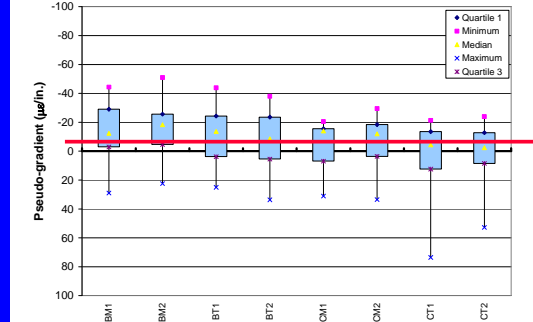
Cases	Prime Coat	Evap reducer
1	✓	
2	✓	✓
3		✓



Prime Coat w/ Evap Reduc Case 2



No Prime Coat w/ Evap Reduc Case 3



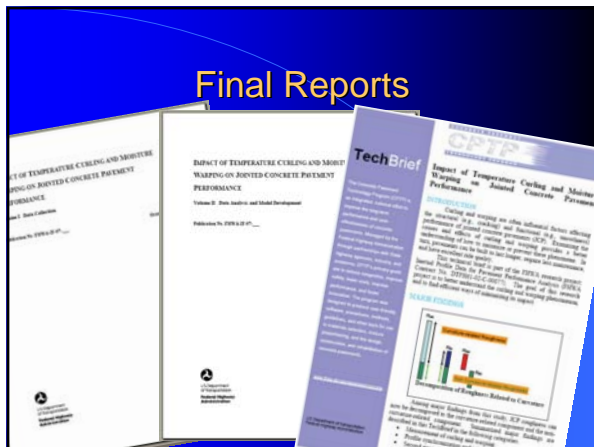
The Implications...

- What's timing to measure roughness for a pavement acceptance testing?
- What's the best practice to avoid curl and warp?
- What's the best time to grind the pavements to improve smoothness?

Tools you can use...

- New, robust profile synchronization and joint identification techniques
- Invention of 2GCI to better characterize slab curvature
- New, effective slab curvature analysis framework
- RoCK System to assess curvature's impact on roughness

Final Reports



Acknowledgement

AZ: Cliff Riley, Andy Conez, Craig Cornwell
 CA: John Poppe, Raymond Morin, Mark Ross
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 FL: John Barker, Jim Ward
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 IA: Kevin Jones, Kelly Morris, George Feazell
 IL: LaDonna Rowden, Mark Gard
 IA: Lee Gallivan, Tommy Nantung, Kenny Robertson
 KS: John Wojajowski, William Parcels, Kenneth DeLong
 MI: Mark Grazioli
 MN: Curt Turgeon, Robert "Woody" Woodruff, Ben Worel
 NC: Judith Corley-Lay, Mustan Kadibhai, Mark Crook
 NC: Carl McCanne, Mustan Kadibhai, Bobby Lewis
 NE: George Woolstrum, Eldon Schoen, Richard Crow
 NV: Dean Wetzel, Patty Polish, Lonnie See
 NY: Brad Allan, Mike Knapp, Todd Moore
 OH: Brian Schleppe, Roger Green, Brad Young
 PA: Frank Baron, Bill Wollyung
 TX: Dennis Cooley, Cheryl Flood, Robert Evers



Thank You !