A Future History of Concrete Pavement Design and Construction in the U.S.

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National Concrete Pavement Technology Center

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In The Beginning…

- 1879 - First concrete pavement in the world in Inverness, Scotland
- 1893 - First U.S. concrete pavement constructed (Court Street, Bellefontaine, OH)
  - Two-course construction
    - Hard aggregate on top to resist horseshoe wear
    - Grooved in 4-in squares: surface friction for horses!
  - George Bartholomew (builder) posted $5000 bond for 5-year guarantee
  - Paved other 3 sides of square in 1893

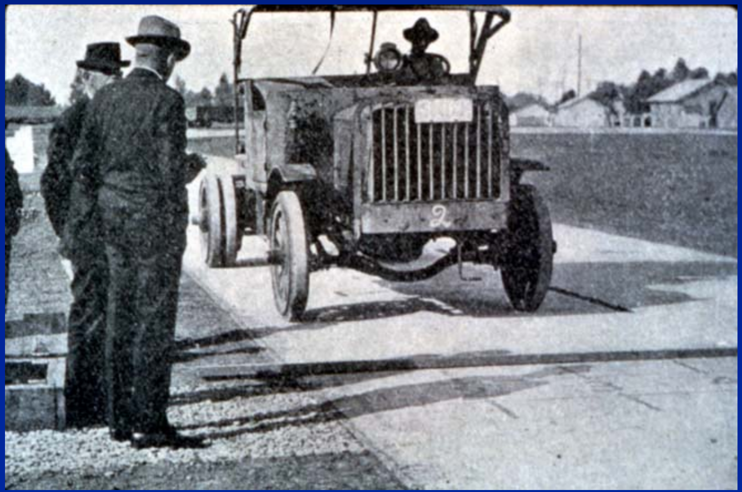
US Concrete Industry – 1910s - Early Activities

"Seedling" Roads

- By 1916, there were 10,000 autos in the U.S., operating mostly on unpaved roads
- The industry built single-lane, 9-ft wide concrete pavements, hoping that motorists would like them and would lobby for more miles of concrete roads

1910s to 1950s: Beginning to Understand Concrete Pavement Behavior

- Advances in pavement analysis
- Early road tests
  - Pittsburg, CA – 1921-22
    - Benefits of slab reinforcing
  - Bates (IL) Road Test – 1922-23
    - Performance of concrete vs. asphalt, brick, etc.
    - Benefits of longitudinal joints and thickened edges
- Use of joints, load transfer, improved foundations



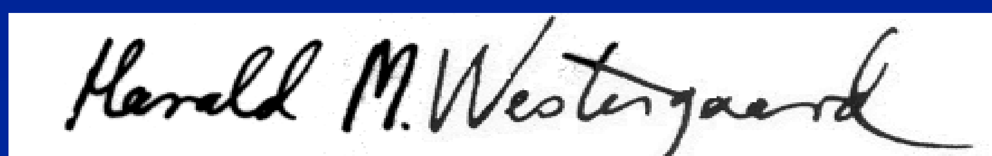
Pavement Engineering

"….the art of molding materials we do not wholly understand into shapes we cannot precisely analyze, so as to withstand forces we cannot assess, in such a way that the community at large has no reason to suspect our ignorance."

Credits: ERES Consultants, Inc./ ARA, Inc.

Harald Malcolm Westergaard (1888-1950)

H. Malcolm Westergaard and his daughter Mary, with the family's 1928 Hupmobile



Credits: U of Illinois, Tasos Ioannides

The 'Father' of Modern Pavement Mechanics

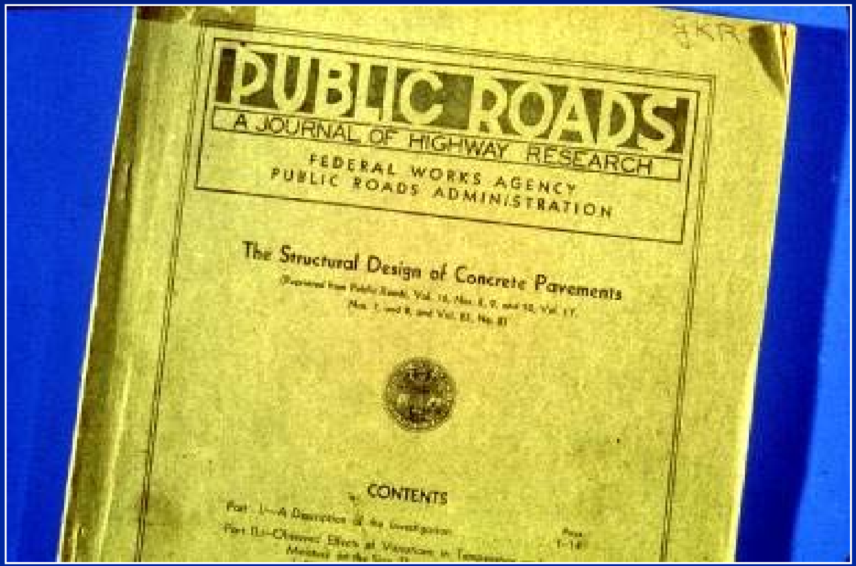
First Design Equations (1920s, 1930s)

- In 1926, Prof. Westergaard, University of Illinois, published equations for stresses and deflections of concrete pavement

$$d = \sqrt{\frac{cp}{s}}$$

d = thickness
c = stress coefficient
p = wheel load
s = allowable tensile stress

- To test Westergaard's equation, the Bureau of Public Roads (forerunner of FHWA) conducted four years of testing and published a very complete report on the "Structural Design of Concrete Pavements".



Westergaard (1948)

H. Malcolm Westergaard, 1928

AMERICAN SOCIETY OF CIVIL ENGINEERS

Founded November 5, 1852

TRANSACTIONS Vol. 113 (1948)

Paper No. 2340

NEW FORMULAS FOR STRESSES IN CONCRETE PAVEMENTS OF AIRFIELDS

BY H. M. WESTERGAARD,[1] M. ASCE

WITH DISCUSSION BY MESSRS. ROBERT HORONJEFF, EVAN P. BONE, AND H. M. WESTERGAARD.

SYNOPSIS

The stresses investigated here are caused by loads. The load is a pressure transmitted through the oblong "footprint" of a tire of a landing gear. Three positions of this load are considered: The first is at a considerable distance from any edge or joint, in the interior of the area of a panel of the pavement; the

$$\sigma_i = \frac{0.3162(W)}{h^2}\left[4\log_{10}\left(\frac{l}{b}\right) + 1.069\right]$$

$$\sigma_e = \frac{0.572(W)}{h^2}\left[4\log_{10}\left(\frac{l}{b}\right) + 0.359\right]$$

$$\sigma_c = \frac{3(W)}{h^2}\left[1 - \left(\frac{a\sqrt{2}}{l}\right)^{0.6}\right]$$

Sources: U of Illinois
Tasos Ioannides

Westergaard's Assumptions

H. Malcolm Westergaard and his son Peter, 1934

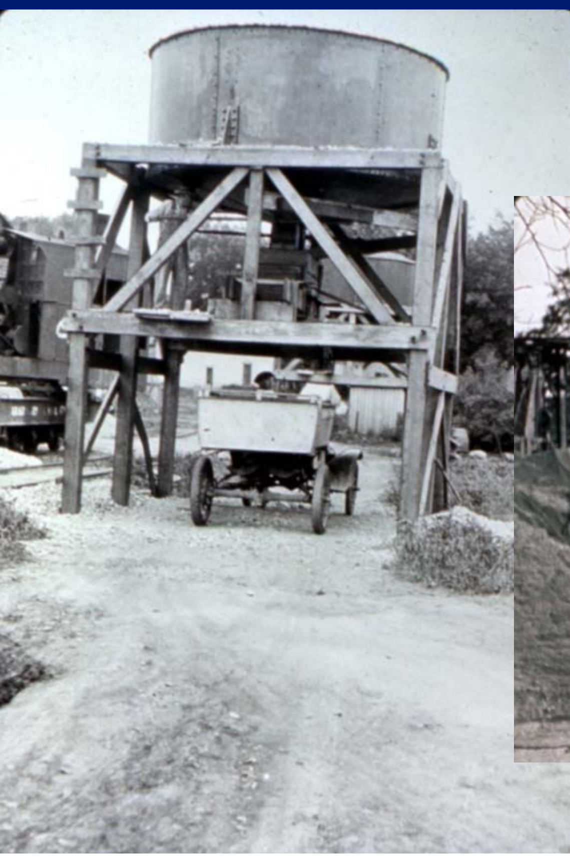
1. **Uniform Support – No curling**
2. **One slab - No load transfer**
3. **Single Wheel Load - No mulitple wheel loads**
4. **Single Placed Layer - No base**
5. **Infinite Slab**
6. **Semi Infinite Foundation - No rigid bottom**

Credits: Tasos Ioannides

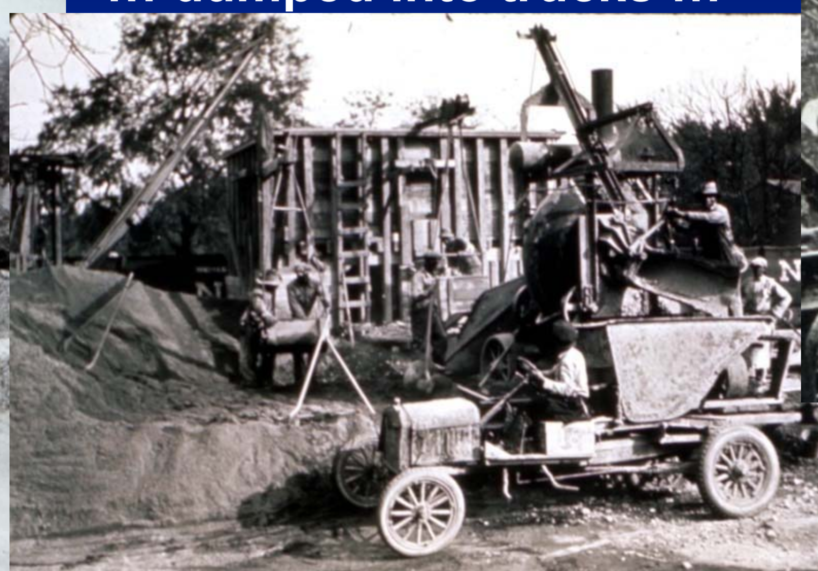
Early Concrete Pavement Construction

At first, concrete road construction was a bit crude …

Concrete mixes were dry-batched …



… dumped into trucks …



… and mixed on grade in fixed forms.

Construction Improvements

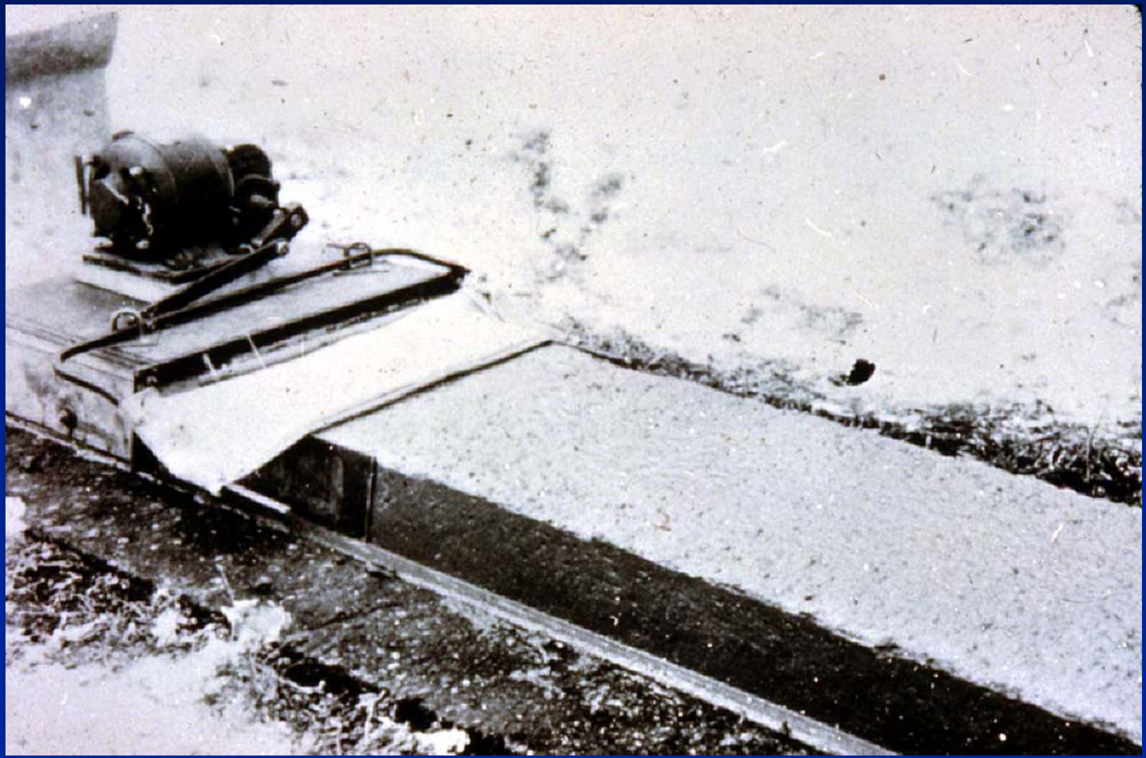
- Traveling mixers were developed to provide more uniform dry-batched concrete mixes.

The 27E travelling mixer

- 1920s until about 1960: almost all PCC pavements built with side forms

Construction Improvements: Slip-form Paving

- In 1947, an Iowa DOT engineer built the first prototype slip-form paver
  - Laboratory demonstration
  - Paved 14 inches wide and 5 inches thick.



First Slipform Paving—1949
(Primghar, IA)

- ½-mile county highway
  - 6-in JPCP, 20 ft wide
  - Paved in two passes
  - Cost: $1.47 / yd^2 (vs. $2.21 / yd^2 [estimated] for side-form paving)
- 1955: Development of self-propelled, track-mounted 24-ft wide pavers

Construction Improvements: Central Plant Mixer

- Capacities of 8 to 12 cubic yards
- 10 times faster than 27E traveling mixer (dry-batch method).
- Made it possible to pave one two-lane mile per day.

Brief History of U.S. Dowel Design

(through 1990)

- **First U.S. use of dowels:**

  1917-1918 Newport News, VA Army Camps
  - **Two ¾-in dowels across each 10-ft lane joint**
- **Rapid (but non-uniform) adoption through ‘20s and ‘30s**
  - **1926 practices: two ½-in x 4 ft, four 5/8-in x 4 ft, eight ¾-in x 2 ft**
- **Numerous studies in ‘20s, ’30s, ‘40s and ‘50s (Westergaard, Bradbury, Teller and Sutherland, Teller and Cashell, and others) led to 1956 ACI recommendations that became *de facto* standards until the ‘90s:**
  - **Diameter – D/8, 12-in spacing**
  - **Embedment to achieve max LTE:**
    - **8*dia for 3/4-in or less, 6*dia for larger dowels.**
    - **18-in length chosen to account for joint/dowel placement variability.**

Construction Improvements: Joint Sawing

- Prior to 1940s, joints were hand grooved in plastic concrete
  - Created a bump at most joints.
- Use of diamond blade saws started in the 1940s.
  - Standard practice since the 1950s

Design Advancements

- In the 1950's, Dr. Gerald Pickett and Gordon Ray developed influence charts
  - o Calculated pavement stresses for any wheel configuration,
- PCA prepared design charts for individual aircraft.
  - o With the advent of multi-wheel gear, 747 has 16 wheels in it's main gear, the use of Influence Charts became quite tedious

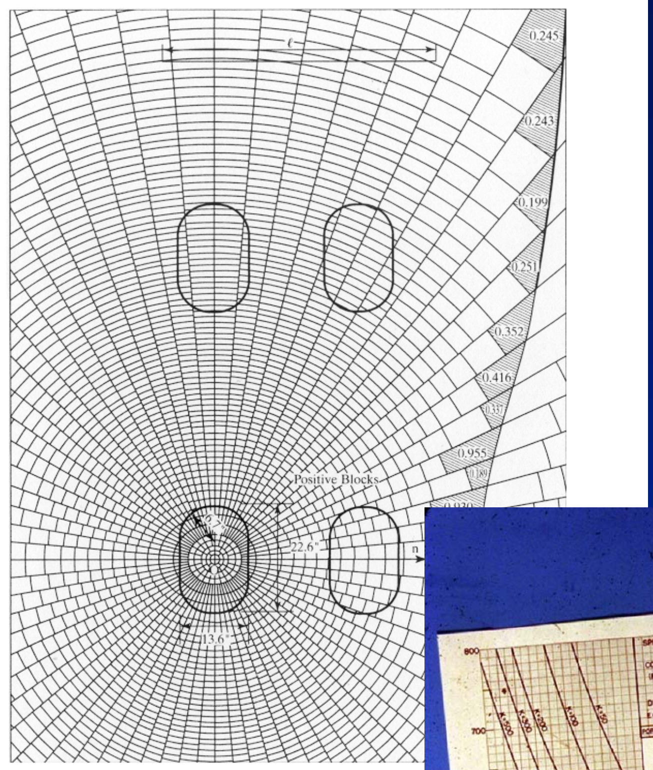
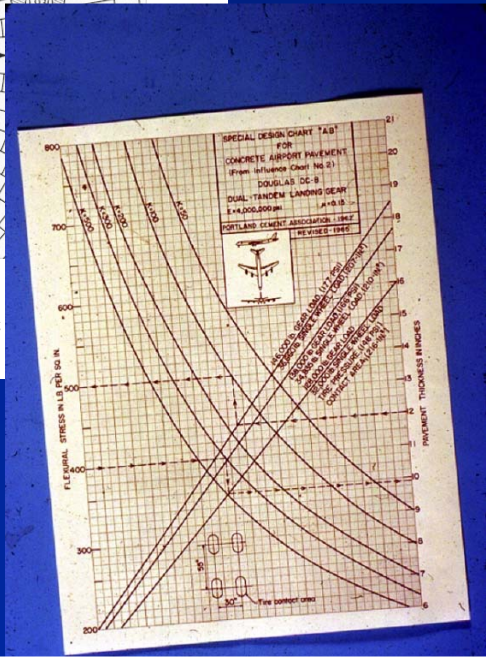


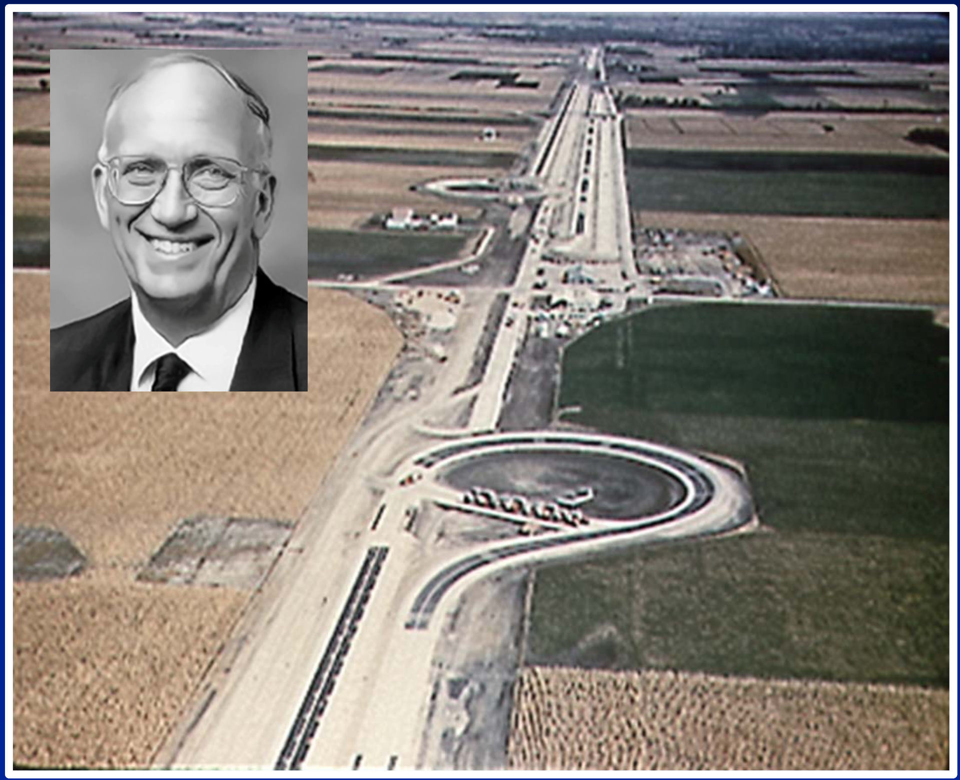
FIGURE 4.12

Application of influence chart for determining moment (After Pickett and Ray (1951).)

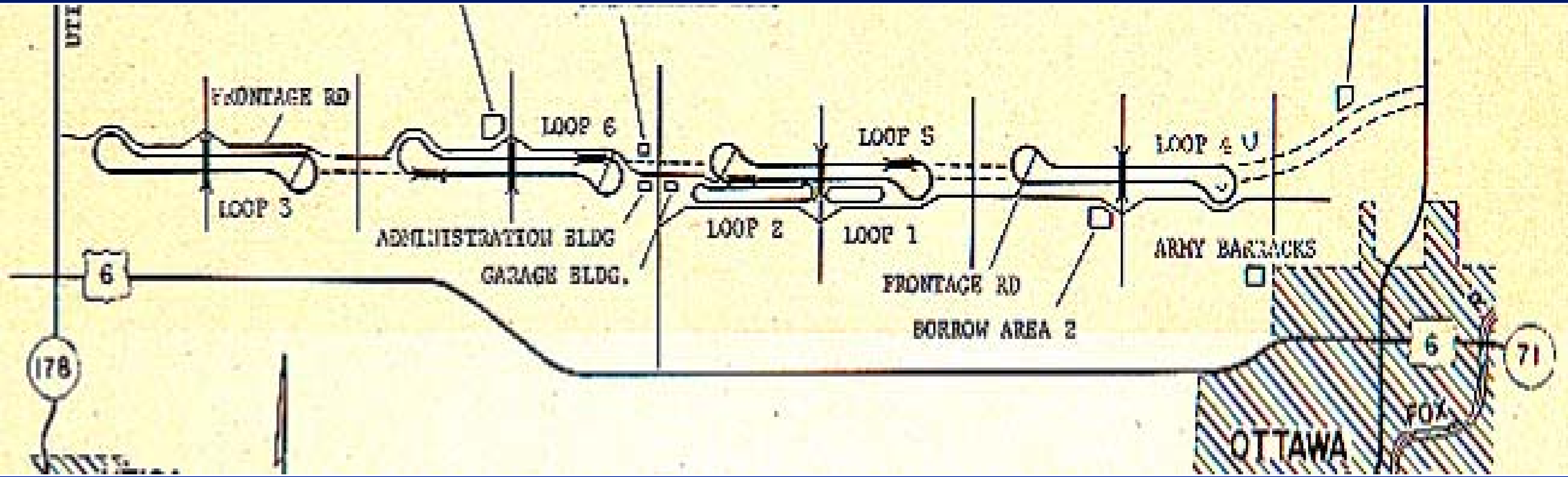


AASHO Road Test: 1958-1960

The AASHO Road Test was conceived and sponsored by the American Association of State Highway Officials to study the performance of pavement structures of known thickness under moving loads of known magnitude and frequency.



AASHO Test Loops Layout



AASHO Test Traffic

- Started Nov. 1958
- Loops 3-6:
  - 6 veh/lane
  - 10 veh/lane (Jan '60)
- Operation
  - 18 hr. 40 min. @ 35 mph.
  - 6 days/wk
- Total Loads
  - 1,114,000 Applications
  - Avg. ESAL - 6.2 million
  - Max ESAL - 10 million (Flex)

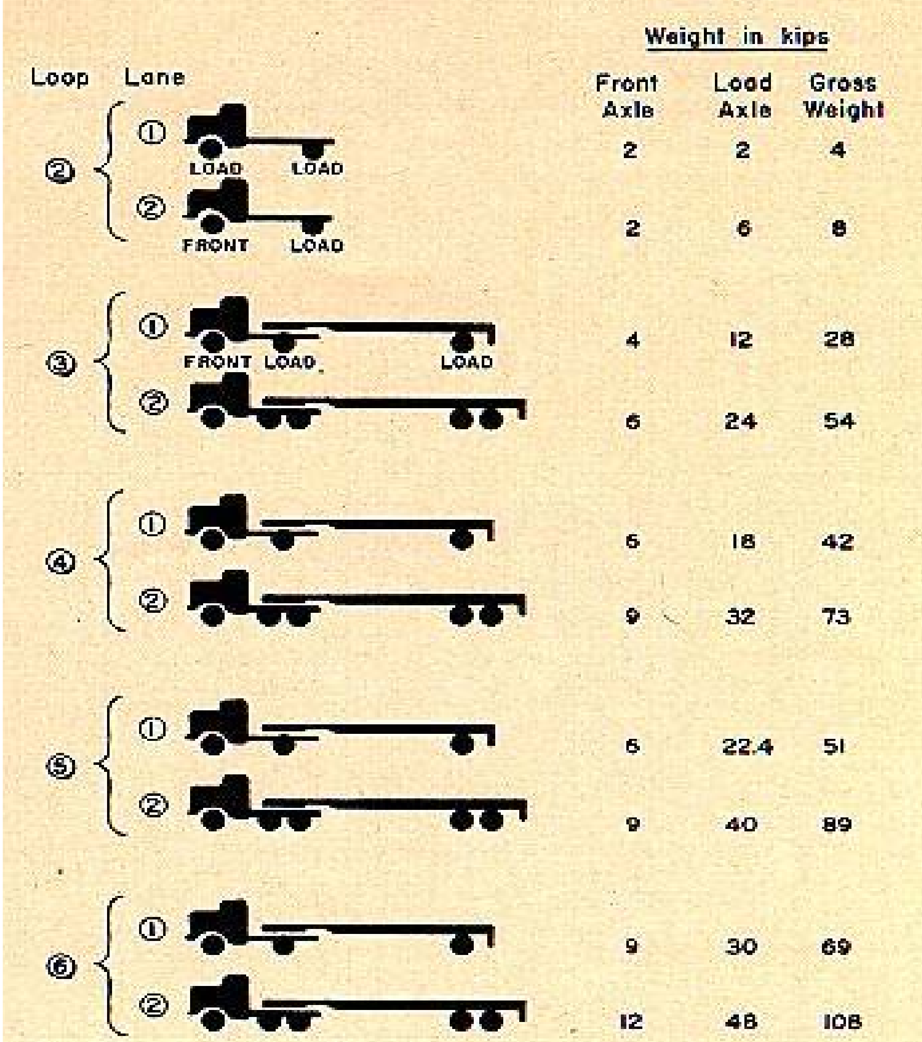


Figure 22. Typical test vehicle axle loadings.

AASHO Road Test

Empirical Loop Equation:

$$\text{Log}(W) = \text{Log } R + \frac{G}{F}$$

$$\text{Log } R = 5.85 + 7.35 * \log (D+1) - 4.62 * \log (L1+L2) + 3.82 * \log L2$$

$$F = 1.00 + \frac{3.63 * (L1+L2)^{5.2}}{(D-1)^{8.46} * L2^{3.52}}$$

$$G = \text{Log} \left[\frac{(P1-P2)}{(P1-1.5)} \right]$$

D = Concrete slab thickness, in
L1 = Load on single/tandem axle, kips
L2 = Axle code
P1 = Initial serviceability
P2 = Terminal serviceability

1960s to 1980s - Era of Advancements

(US Interstate Highway Construction)

- Improved analysis techniques
  - Finite Element Analysis
- Advanced design procedures
- Slip-form paving
- Concrete mixture improvements
- Improved design features

AASHO Road Test
Extended Design Equation

- Not everybody used the same concrete
- Some used reinforced or CRC designs
- Developed mechanistic-empirical relationship between Log W and stress ratio.

$$\text{Log}(W) = A + B \text{ Log } \frac{S'c}{\sigma}$$

W = Number of axle loads to terminal serviceability
(from main loop equation)
A = Regression constant
B = Slope of Log W vs. Log $S'c/\sigma$ curve
S'c = 28-day flexural strength, 3rd point loading
σ = Spangler's corner stress

1962 Rigid Pavement Design Equation

$$\text{Log}(ESAL) = 7.35 * \text{Log}(D + 1) - 0.06 + \left[\frac{\text{Log}\left[\frac{4.5 - 1.5}{4.5 - 1.5}\right]}{1 + \frac{1.624 * 10^{7}}{(D + 1)^{8.46}}} \right]$$

$$+ (4.22 - 0.32p_t) * \text{Log}\left[\frac{S'_c}{(215.63 * J)} \frac{\left[D^{0.75} - 1.132\right]}{\left[D^{0.75} - \frac{18.42}{(E_c / k)^{0.25}}\right]} \right]$$

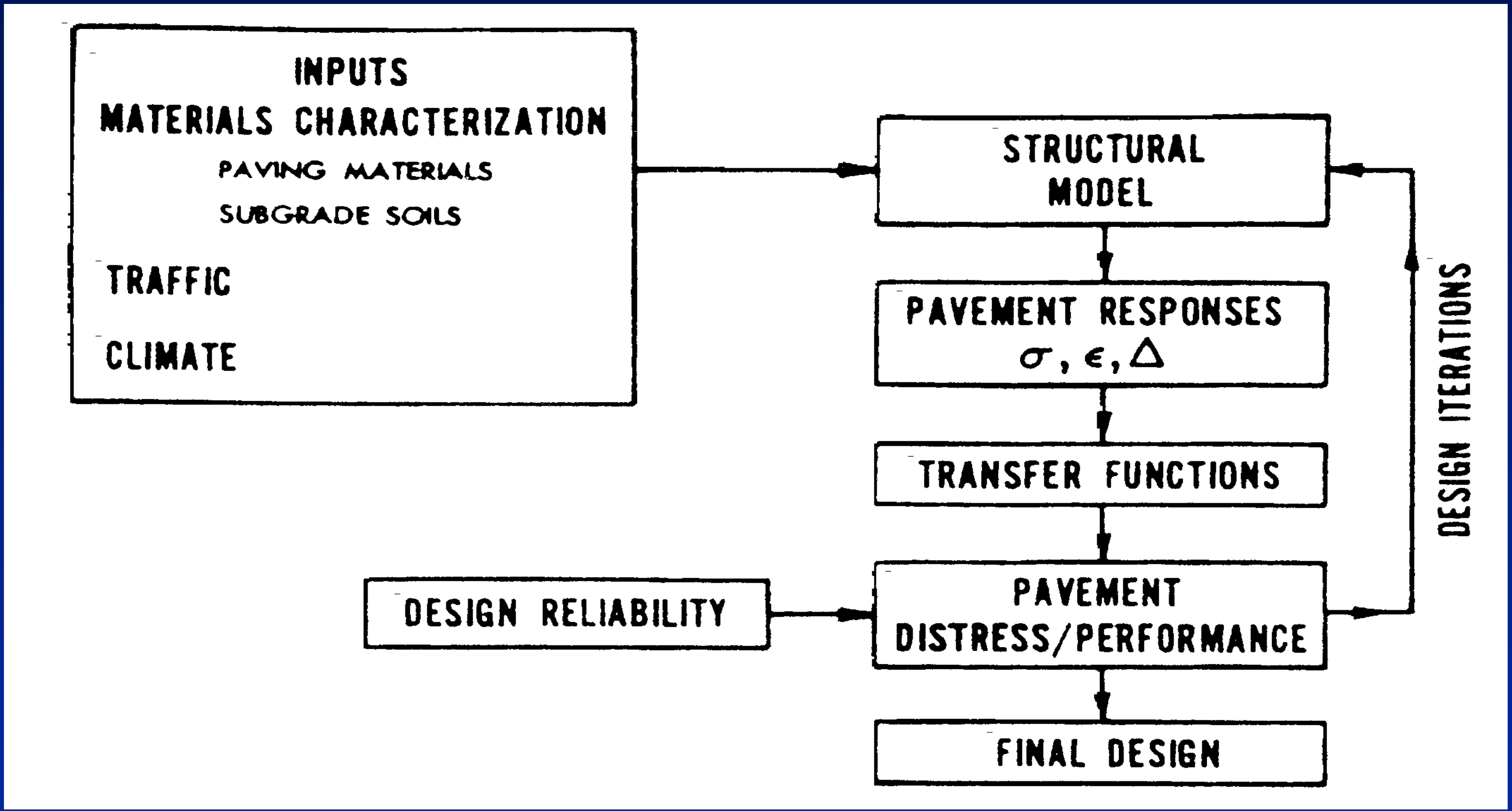
1986/1993 Rigid Pavement Design Equation

$$\log(ESALs) = Z_R * s_o + 7.35 * \log(D + 1) - 0.06 + \frac{\log\left[\frac{\Delta PSI}{4.5 - 1.5}\right]}{1 + \frac{1.624 * 10^7}{(D + 1)^{8.46}}}$$

$$+ (4.22 - 0.32p_t) * \log\left[\frac{S'_c * C_d * \left[D^{0.75} - 1.132\right]}{215.63 * J * \left[D^{0.75} - \frac{18.42}{(E_c / k)^{0.25}}\right]}\right]$$

- Standard Normal Deviate
- Overall Standard Deviation
- Change in Serviceability
- Modulus of Rupture
- Drainage Coefficient
- Terminal Serviceability
- Load Transfer
- Modulus of Elasticity
- Modulus of Subgrade Reaction

Mechanistic-Empirical Design Procedures



After Thompson (2002)

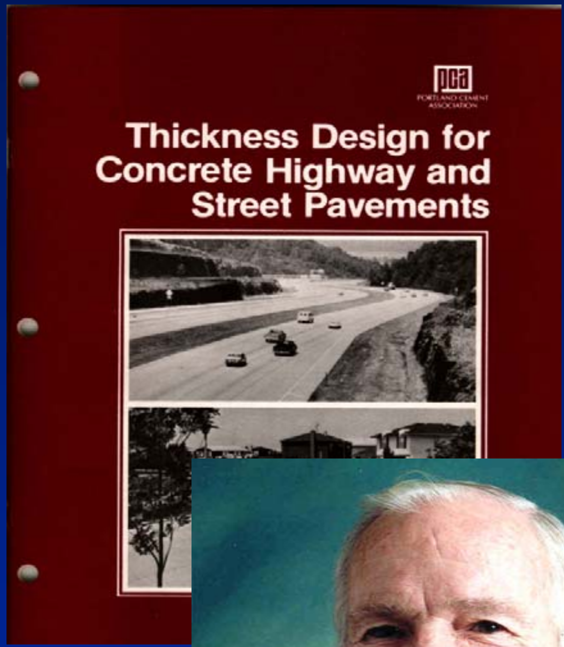
Benefits of M-E Design

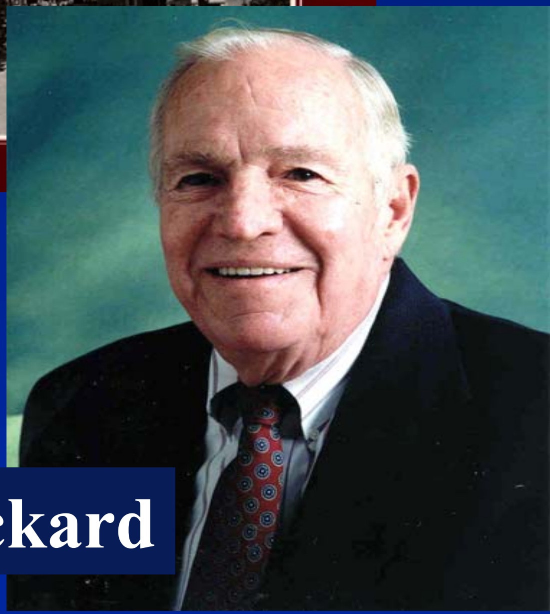
- Ability to predict specific distress types and then improve design as needed
- Ability to extrapolate much better from limited field and laboratory results
- Evaluate new loading impacts
- Make better use of available materials
- Characterize materials changes with time
- Characterize seasonal effects
- Improved reliability of design

M-E Design

PCA Thickness Design Procedure

- In 1966, PCA's design was revised (Fordyce and Packard) based on AASHO Road Test, but with stresses computed mechanistically with edge load influence charts.
- Failure modes examined:
  - Fatigue
  - Erosion (potential for pumping, faulting)
- Refined in 1984 (Packard & Tayabji) based on finite element-based (JSLAB) mechanistic stress & deflection analysis





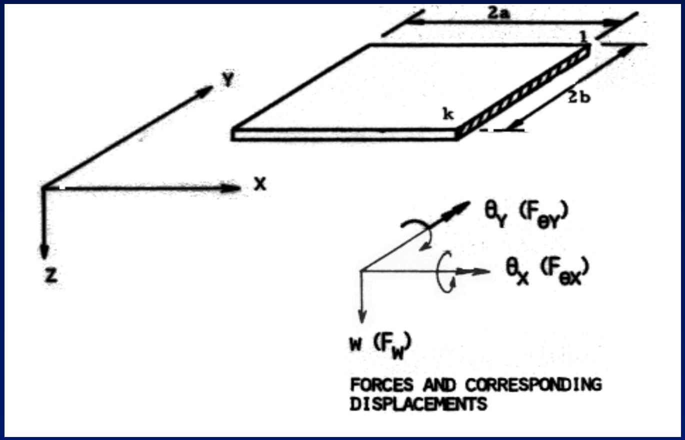
Bob Packard

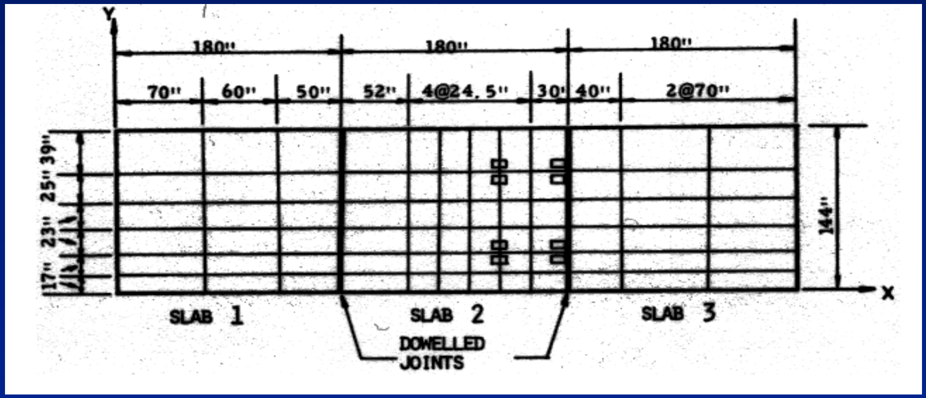
Other M-E Design Procedures of the Era

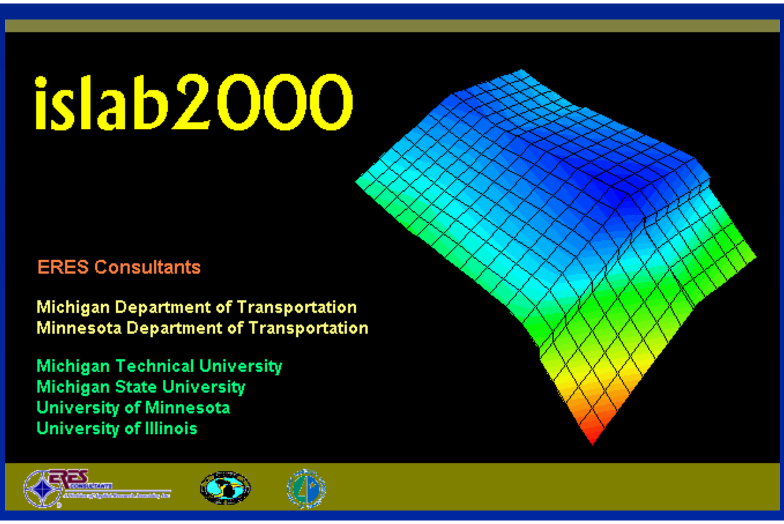
- **Darter and Barenberg "Zero-Maintenance Design" (1977 FHWA)**
  - **Westergaard-based analysis for plain, jointed pavements, single and tandem axle loads**
  - **Fatigue cracking**
  - **Consideration of curling stresses**
  - **Cumulative damage**
  - **Consideration of dowels**
- **NCHRP 1-26 (Barenberg and Thompson, 1988)**

“2-D” FE Analysis (1970s)

- KENSLAB
  - Huang - U-Kentucky
- ILLI-SLAB
  - Barenberg and Tabatabaie – U-Illinois
- JSLAB (1984)
  - Tayabji and Colley



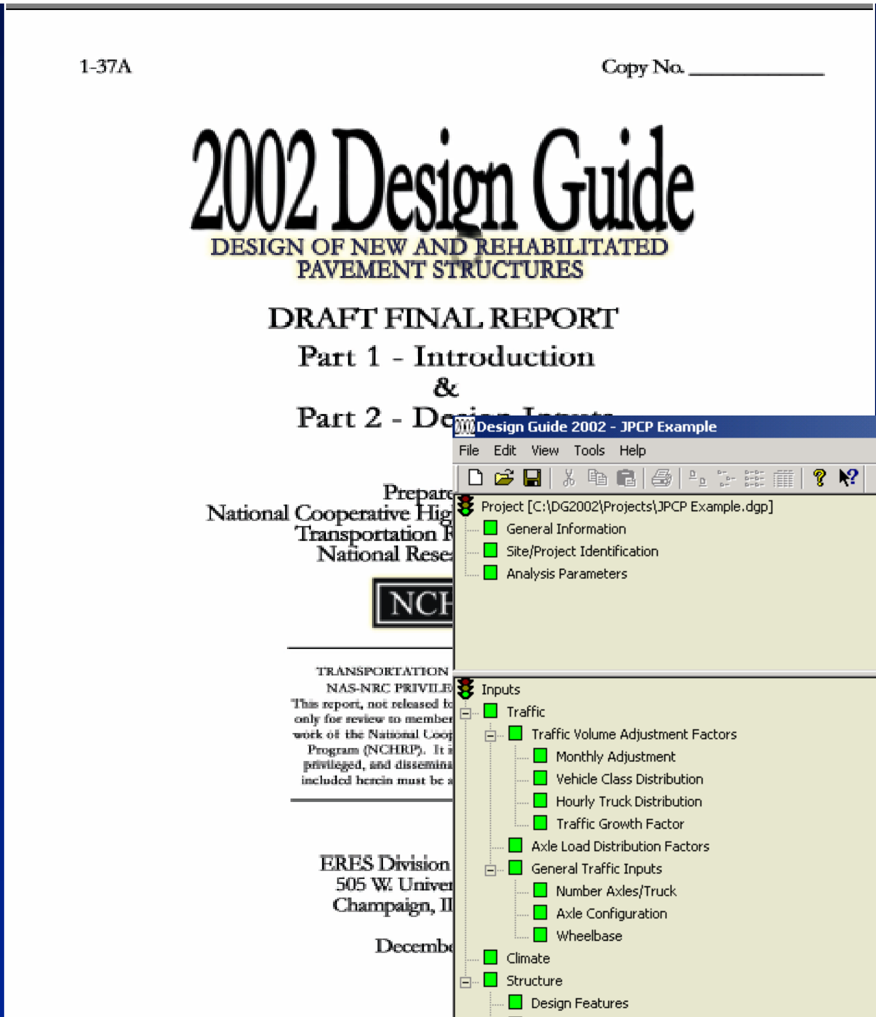


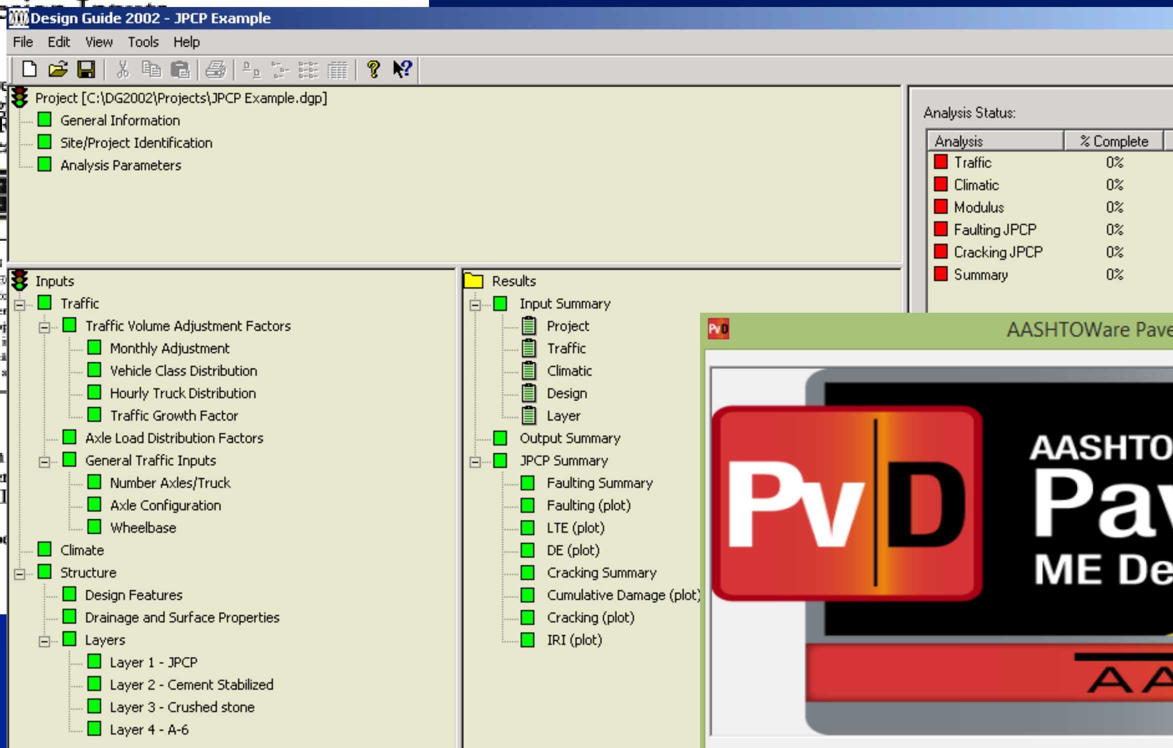


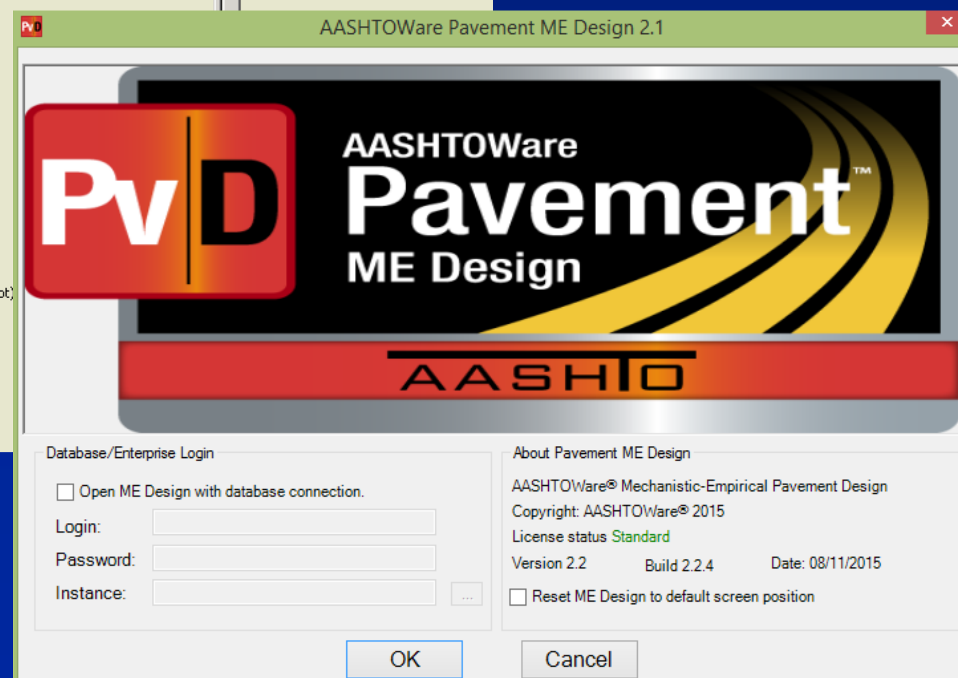
1990s to present: Modern Concrete Pavement Technology

- Advanced M-E Design
- MnROAD
- Concrete Overlays
- Improvements in Construction Technology
- Concrete mixture improvements
- Precast Concrete Pavements

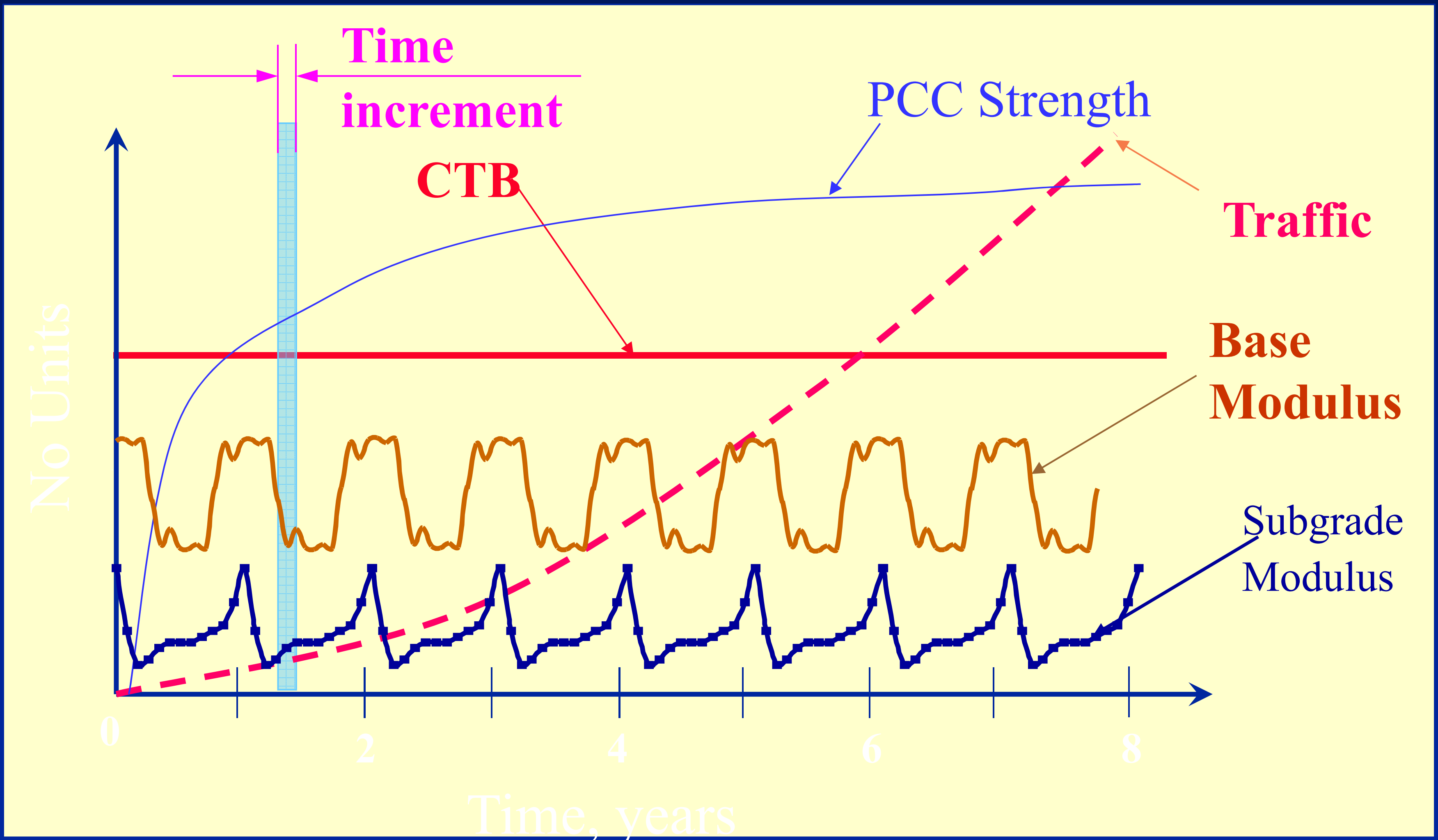
AASHTO 2002/MEPDG and PavementME Design







Models Consider Changing Conditions



MEPDG Incremental Damage Approach (fatigue cracking example)

$$Fatigue\ \ Damage = \sum_{i}\sum_{j}\sum_{k}\sum_{l}\sum_{m}\sum_{n}\frac{n_{ijklmn}}{N_{ijklmn}}$$

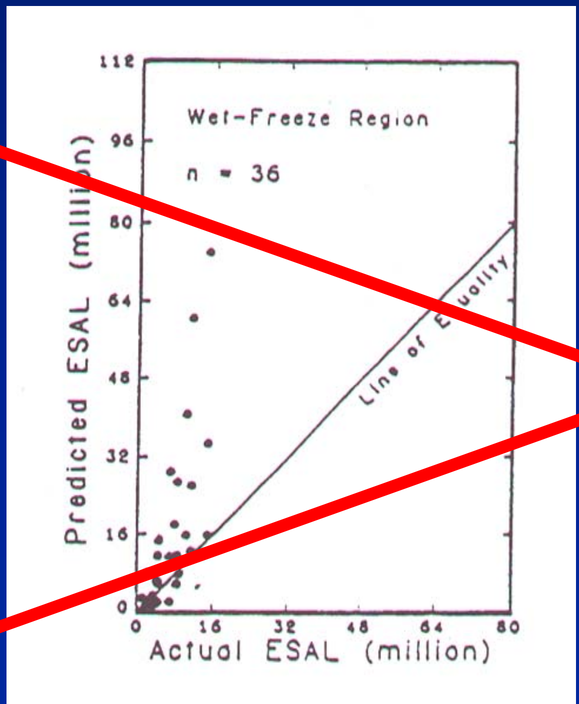
$$Log(N) = 2.0 * \left(\frac{M_r}{\sigma_{total}}\right)^{1.22}$$

n_{ijklmn} = Applied number of load applications at condition i,j,k,…
N_{ijklmn} = Allowable number of load applications at condition i,j,k,…

i = Age ; j = Season; k = Axle combination
l = Load level; m = Temperature gradient; n = Traffic path

Local Calibration

For the first time, design procedures can be calibrated for local conditions (i.e., materials, environment, performance observations, etc.)



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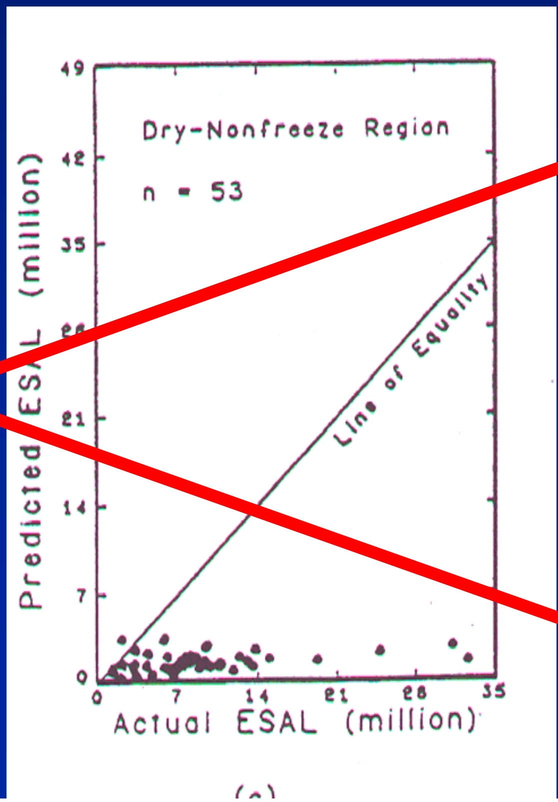


New Developments in Construction Tech

- Stringless grading and slip-form paving
  - Laser/GPS Elevation Control
  - No stringlines or forms required

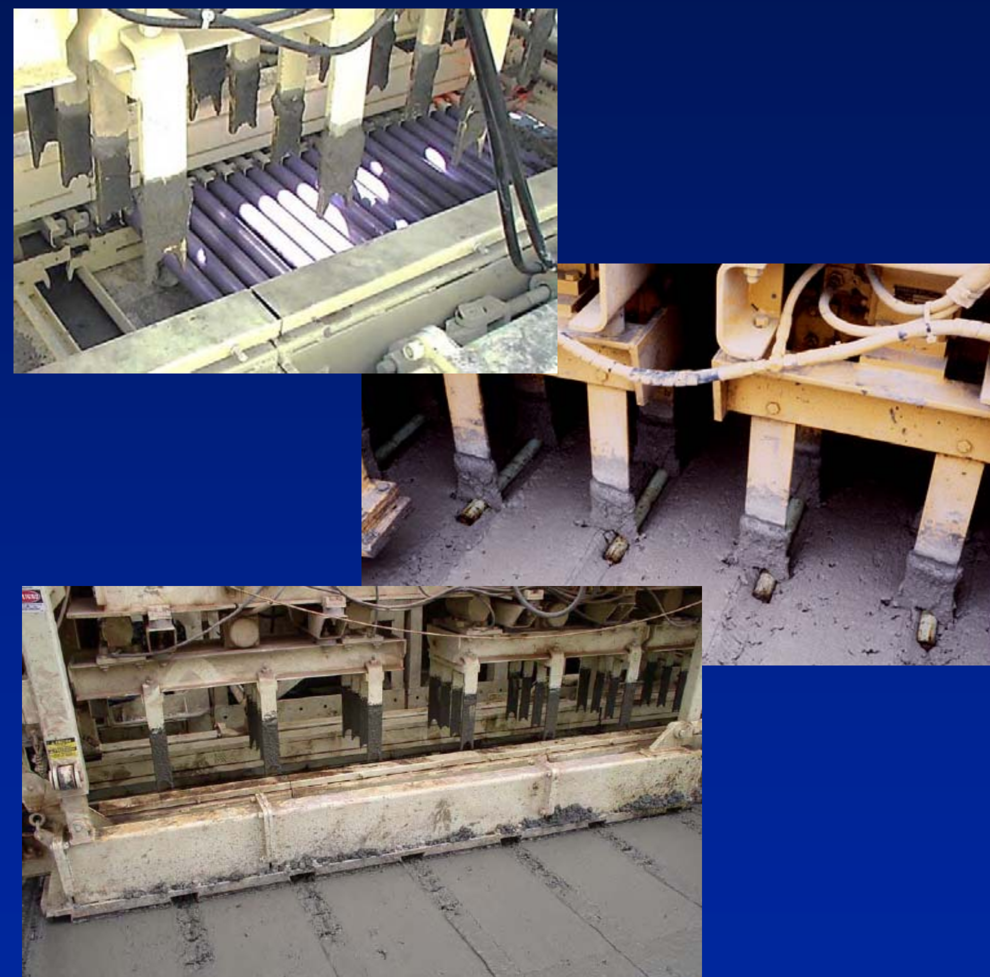
Quality and Process Control Benefits with Stringless Paving

- More precise machine control (digital) to much smaller increments.
- Better and more consistent ride quality.
- Control over material quantities and costs.
- Lower yield loss.

Control of horizontal and vertical curves is significantly more accurate to the plan – arcs are paved rather than a series of chords!

Evolution of Dowel Bar Inserters

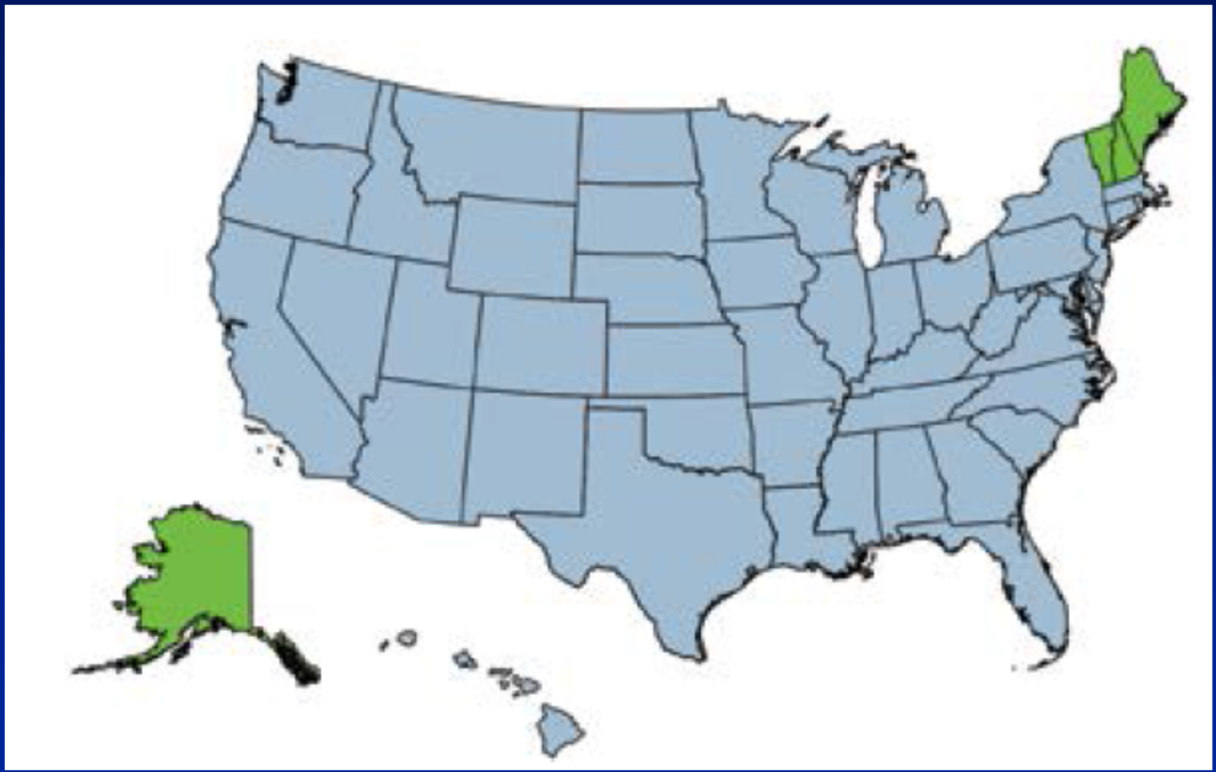
Baskets



Dowel Bar Insertion

Concrete Overlays

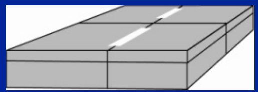
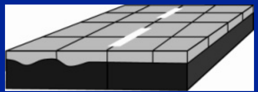
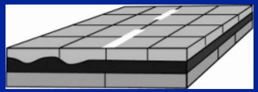
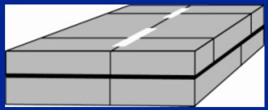
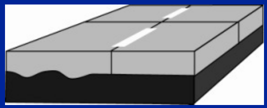
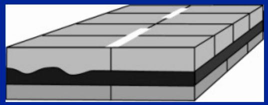
- More than 1,200 concrete overlays in the U.S., dating from **1901** through present (the database is continuing to grow)
- Concrete overlays have been successfully constructed in 45 different states



Concrete Overlays Systens

Concrete Overlays

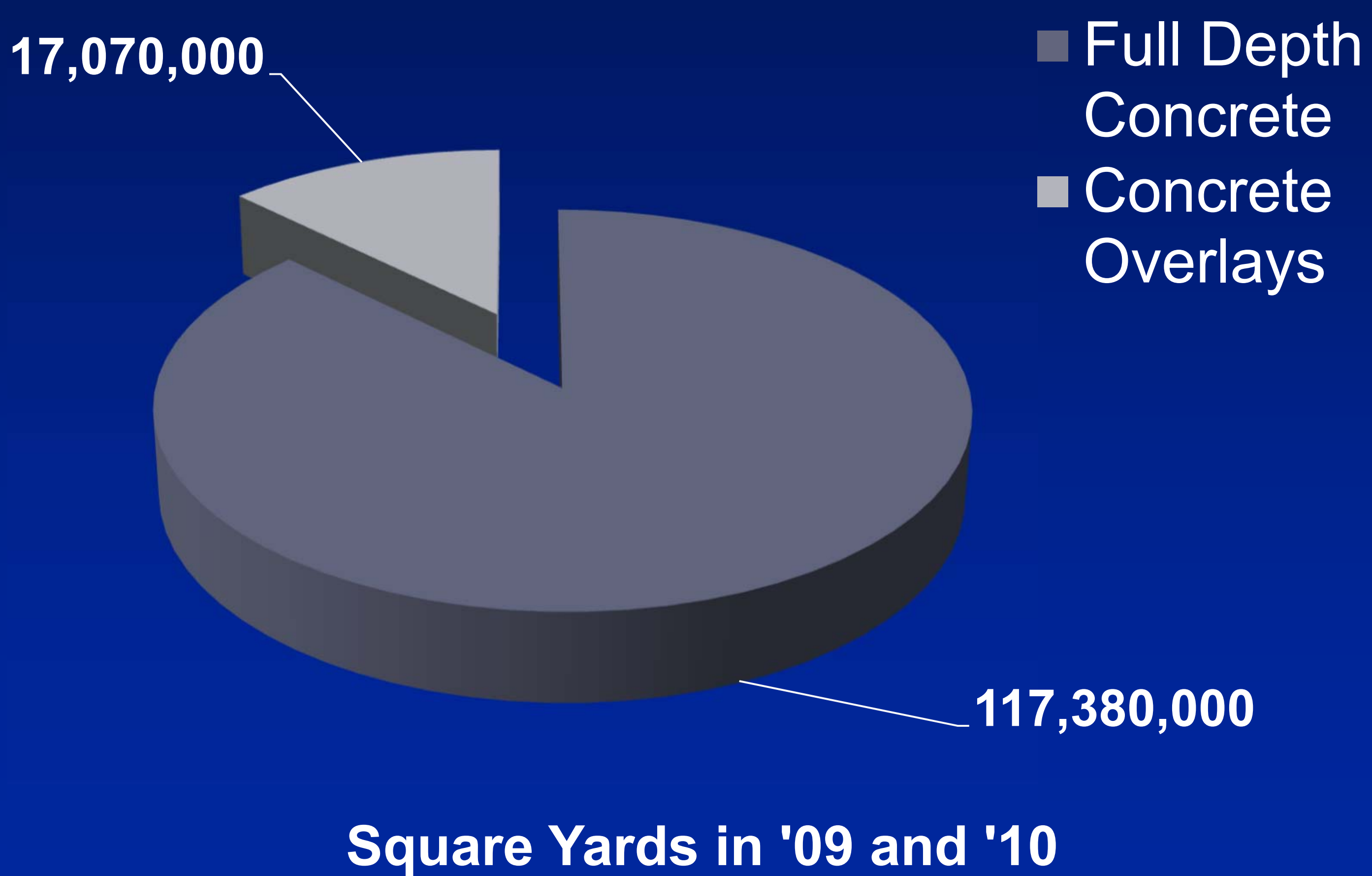
- **Bonded Overlay System**
  - Concrete Pavements
  - Asphalt Pavements
  - Composite Pavements
- **Unbonded Overlay System**
  - Concrete Pavements
  - Asphalt Pavements
  - Composite Pavements

Bond is integral to design

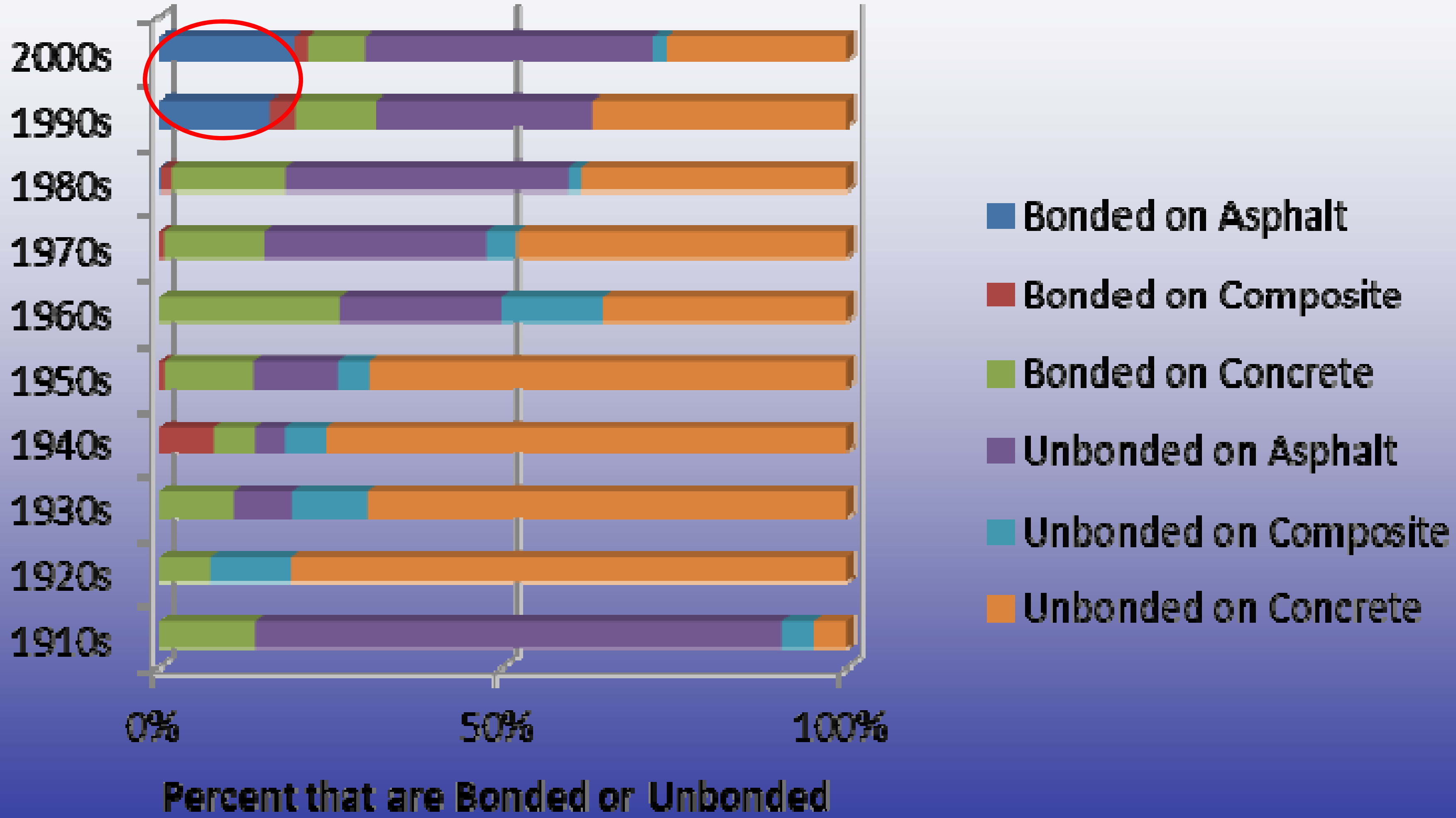
Old pavement is subbase

Overlays Now Comprise ~14% of Concrete Surfacing Construction, Annually



[Source: Oman and ACPA]

Proportion of Overlays of Asphalt Pavement Increasing Rapidly



MnROAD (1992 – present): Most Significant Road Test Since AASHO

Lessons:

- Pavement Design and Performance and Studies
  - Data for MEPDG calibration
  - Curl/Warp Studies
- Effect of Drainage on Concrete Pavement Performance
- Effect of Subbase Thickness on Concrete Pavement Performance
- Design, Construction and Rehabilitation of Whitetopping
- Thin Concrete Pavement Studies
- Whitetopping Design and Rehab Studies
- Innovative Surface Textures
- Much more …

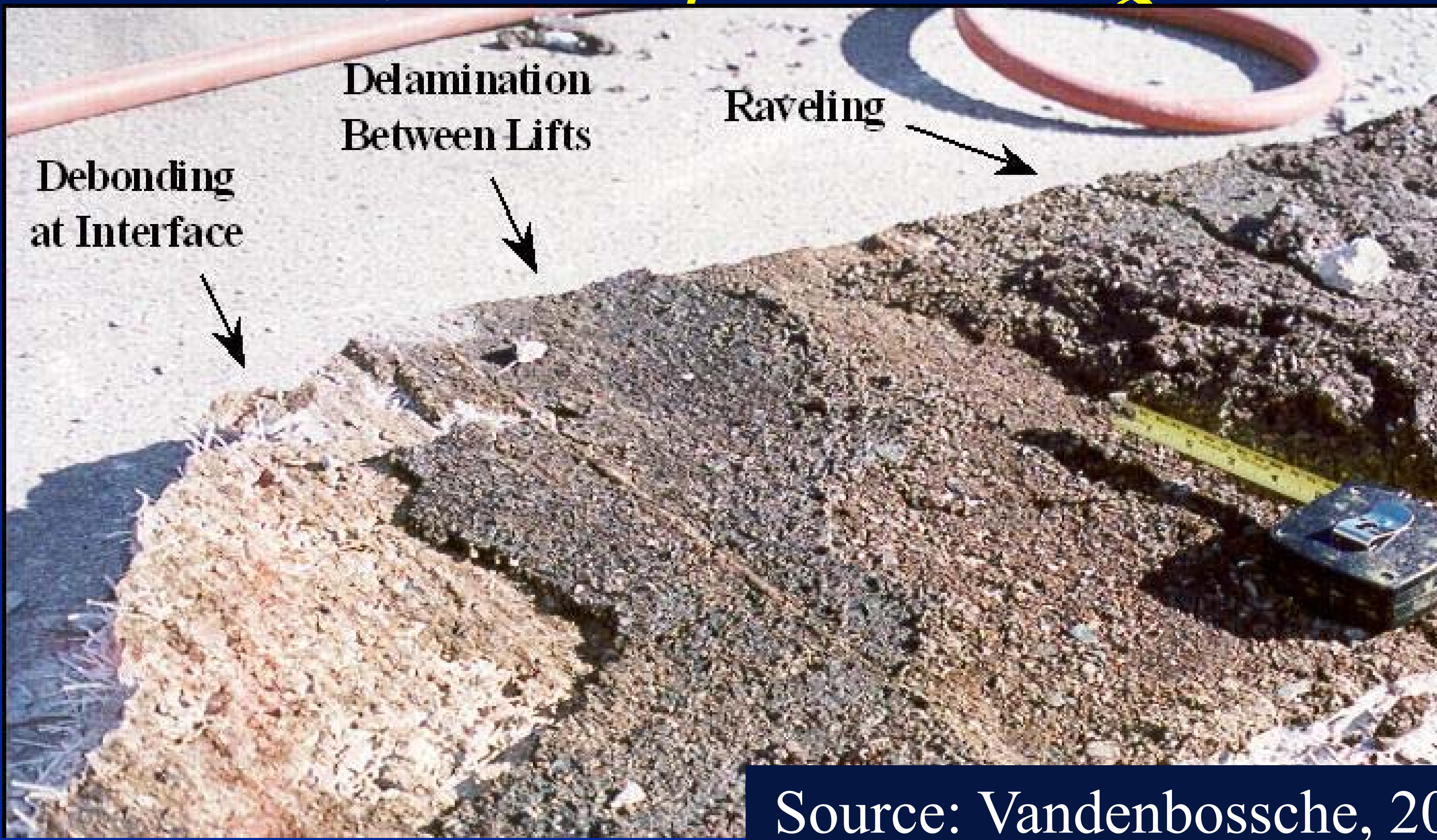
5 inches of concrete road …

… carries the load!

Cell 94, November 2003

Source: Burnham, 2005

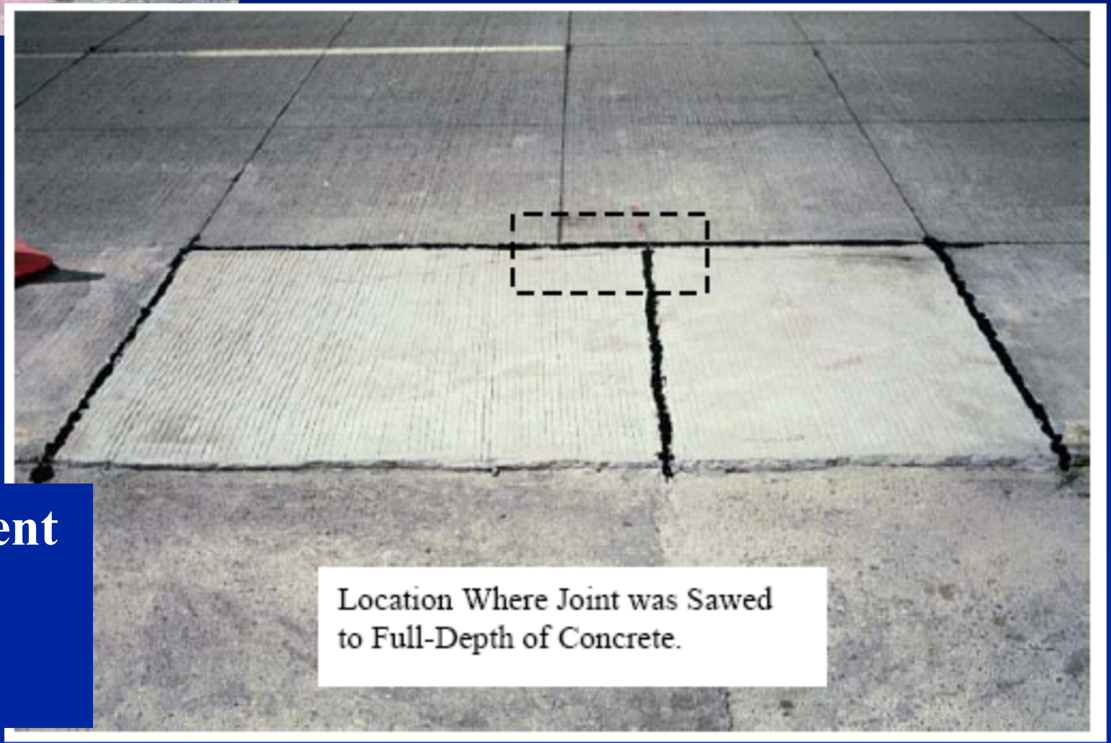
Interlayer Bonding Studies: 3 Modes of Debonding



Source: Vandenbossche, 2005

Each mode reduces slab support and increases PCC stresses.

Use of fabric or "tar paper" to prevent reflection cracking



Saw cut of longitudinal joint to prevent bond and corner cracking due to mismatched transverse joints.

New Product Testing (Plate Dowels)

Evolution of Concrete Pavement Surface Texture

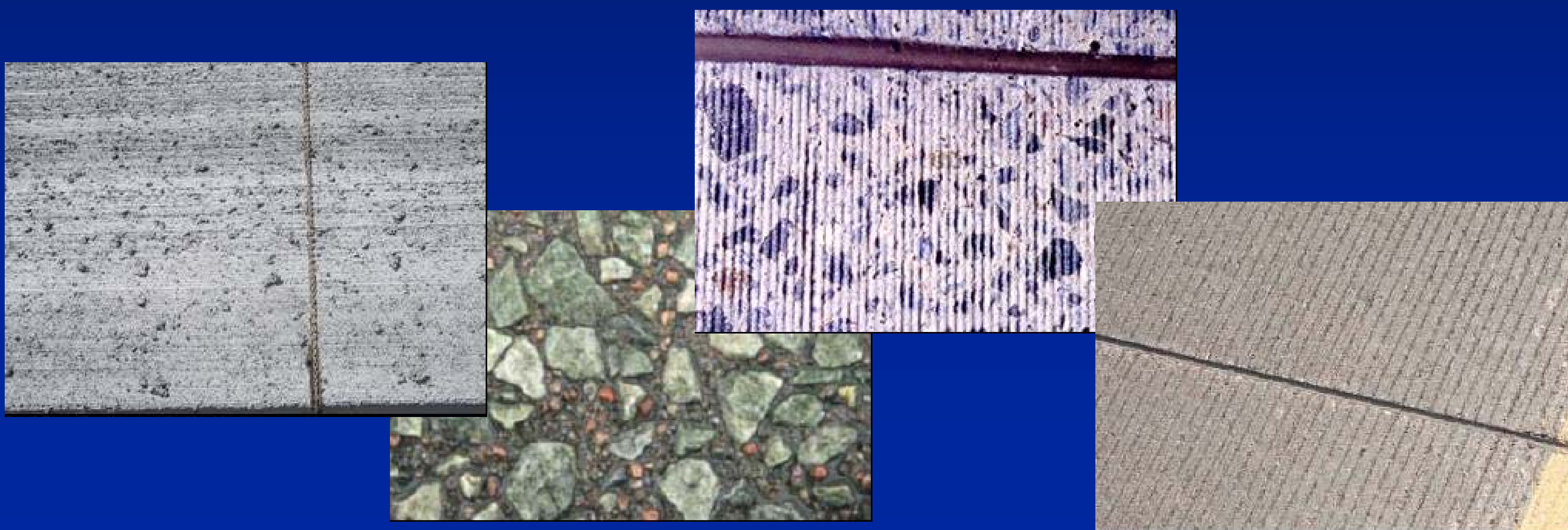
Balancing Safety and Noise

- Early pavements: no texture, burlap drag, brush texture
- 1970s – 2000s: transverse tining (noisy!)

Evolution of Concrete Pavement Surface Texture

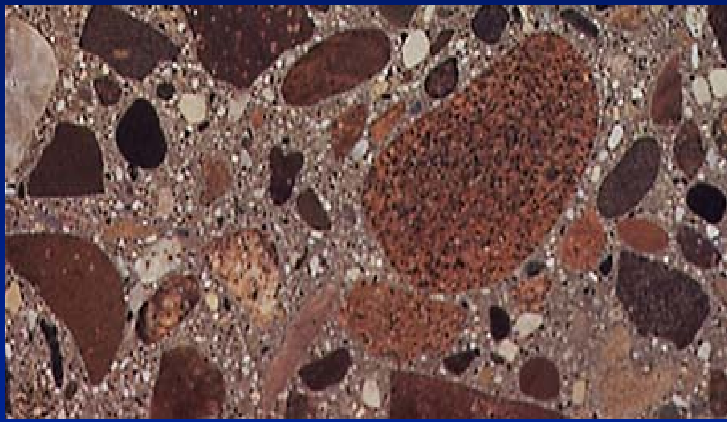
Balancing Safety and Noise

- Now : moving towards "Astroturf drag", longitudinal tining, grinding, NGCS, exposed aggregate surface (European-style), more …



Concrete Mixture Design: Focus on Durability, Workability

- Design philosophy – concrete pavement failure should be due to traffic loading and not due to concrete material failure



- Concrete mixture technology has improved significantly
  - Avoid early materials-related failures
  - Higher concrete strengths can be attained, as needed

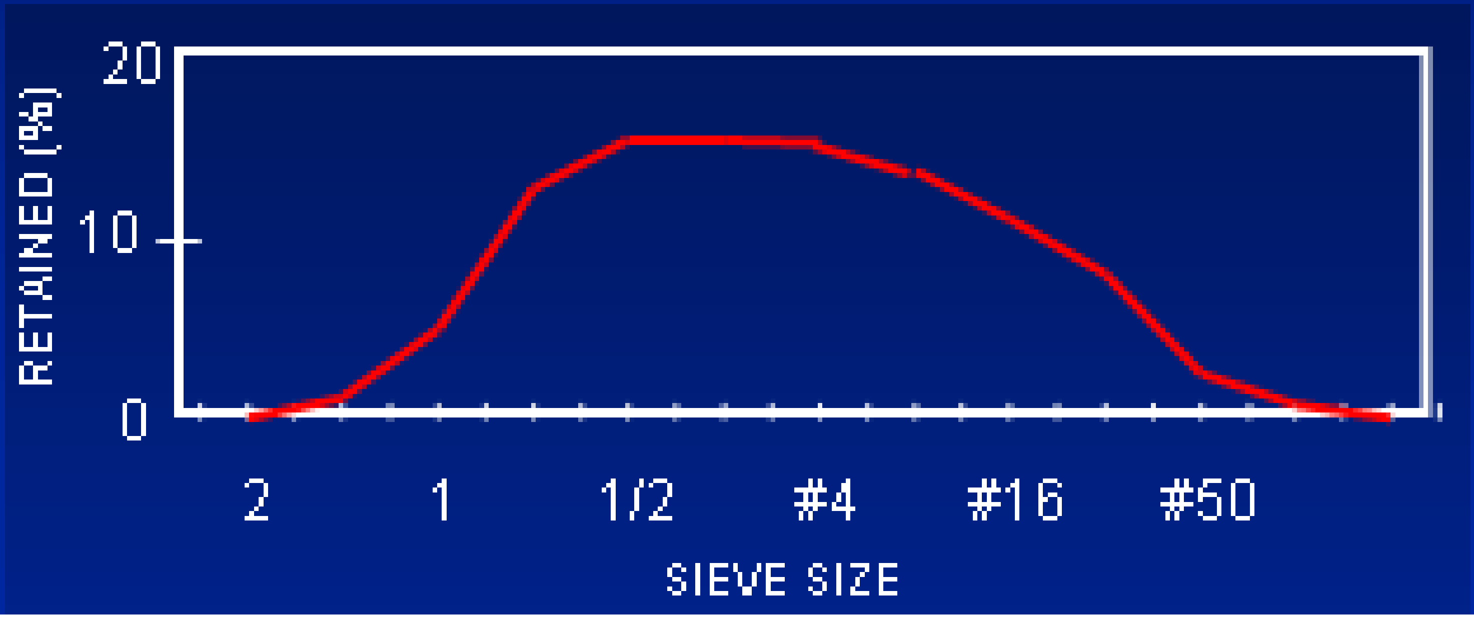
POZZOLANS AND SLAG USE

- Class F (siliceous) fly ash: 15% - 25%
- Class C (cementitious) fly ash: 15% - 35%
  (used with caution)
- Gran. Blast Furnace Slag: 25% - 50%
- Silica fume: 6% - 10%
  (not common in US for paving applications)
- Ternary Blends = Class F + GBFS

Also, blended cement use is allowed and is common

Aggregate Gradation
(From Gap-Graded to Shilstone to "Tarantula" Curve)

- Combined gradation
  - Better for slip-form paving
  - Dense mixture
  - Less sensitive to consolidation effort
  - Less cement; more economical
- Gap graded
  - Possibly poorer concrete performance
  - Segregation is a big concern



Corrosion-Resistant/Proof Dowel Bar Materials

Many materials products are available

Precast Concrete Pavement

(For Accelerated Repair & Construction)

- Individual panel repairs – plain concrete panels
  - o Full-depth full panel replacement
- Reconstruction or repair of larger areas
  - o Conventional panels
  - o Prestressed panels – fewer active joints

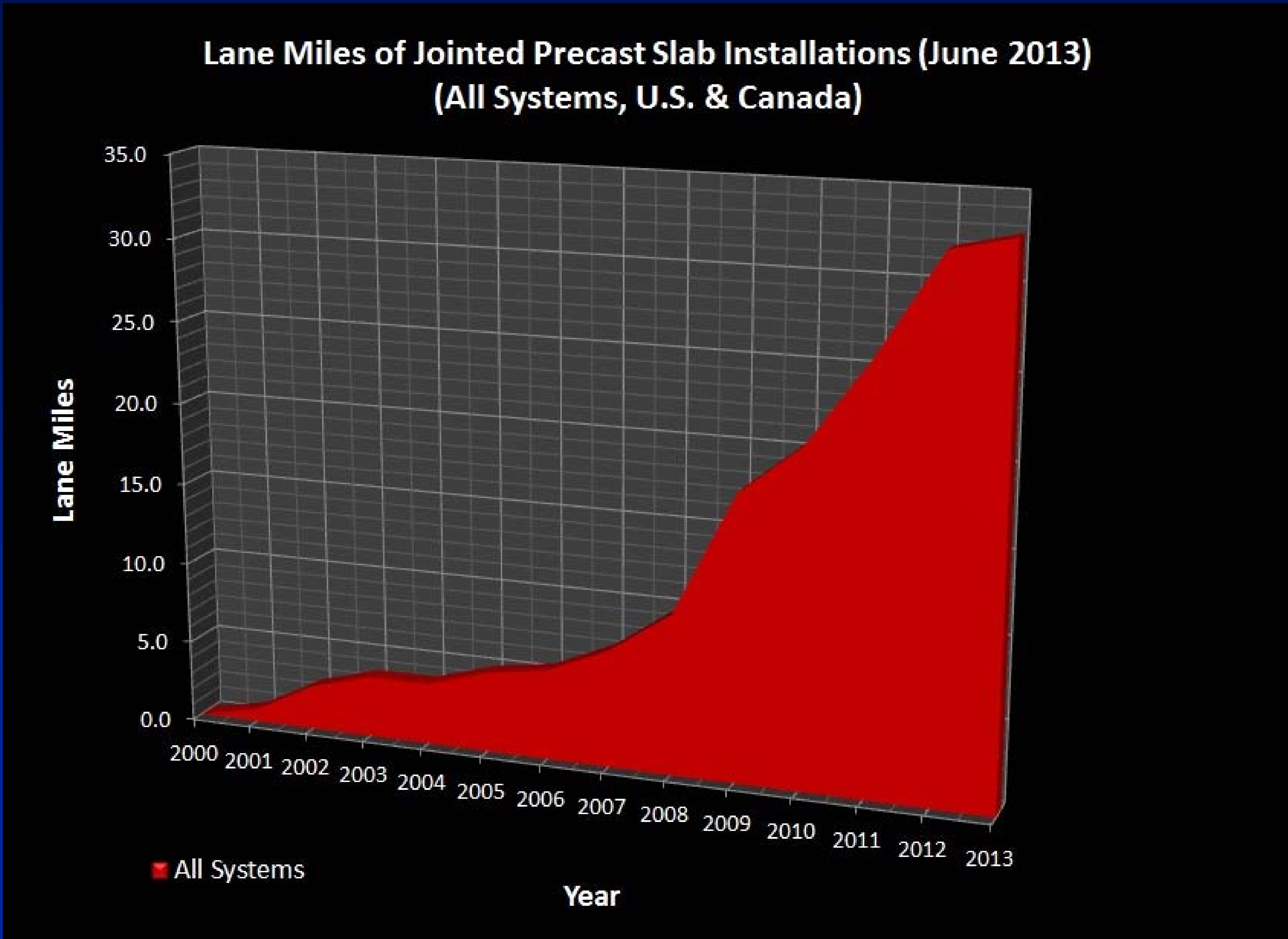
Many Uses


Tappan Zee Bridge Toll Plaza

Santa Monica, California Bus Pad


New York City Intersection


LaGuardia Airport (New York)


Lane Miles of Jointed Precast Slab Installations (June 2013)
(All Systems, U.S. & Canada)
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Lane Miles
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
All Systems
Year

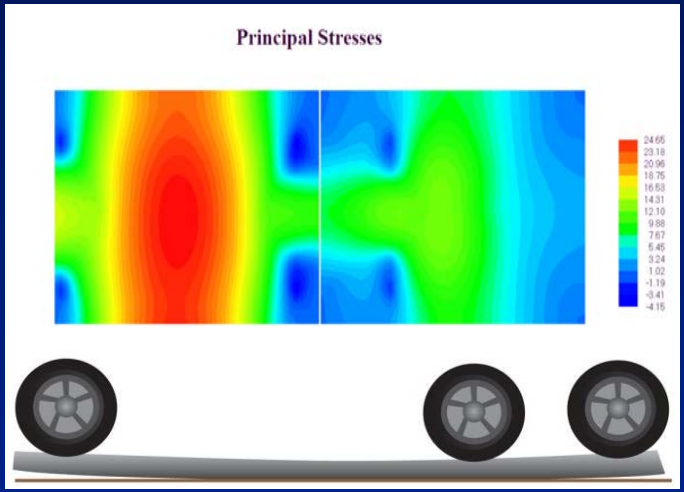
2016 – 2036: The Future …

U.S. Future Directions - General

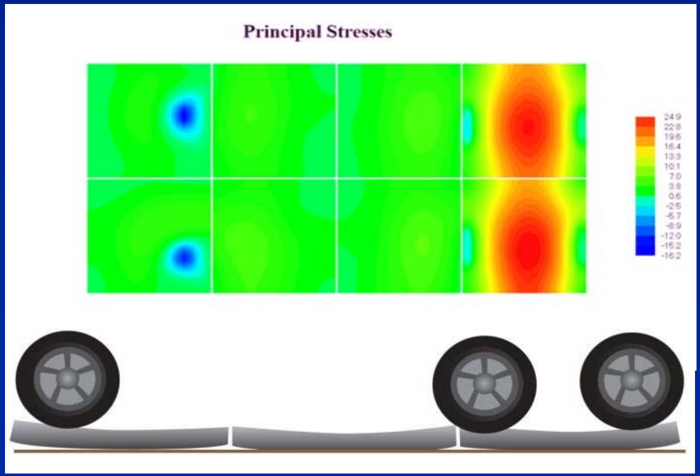
- Many incremental improvements in design, materials & construction processes
- More emphasis on construction quality & durability
- M-E procedures will allow optimum designs
  - Design lives of 40, 50 or 100+ years will be more common and reliable
  - Use of design catalogs will become more common

TCPavements®

Slab sizes and thicknesses for same top stress (2.5MPa)



Thickness: 10 inches
Concrete
Slabs 14.8 ft x 11.8

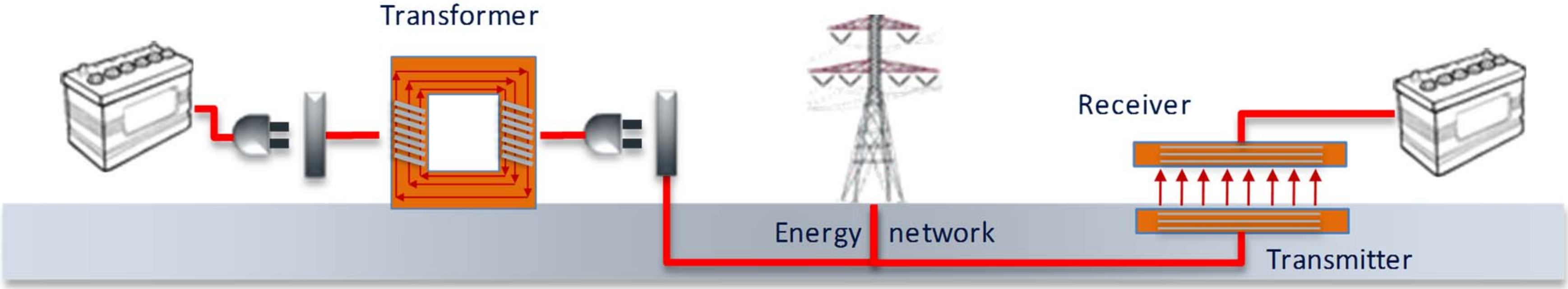


Thickness: 6.3 inches
Concrete
Slabs 5.9 ft x 5.9 ft

Inductive charging of electric vehicles

Principle: Wireless energy transfer through electromagnetic field

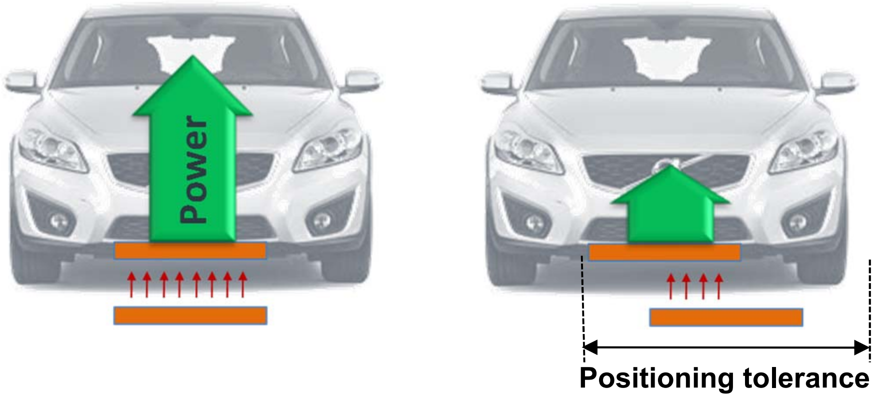
Charging with cable | **Inductive charging**



Static inductive charging of cars

Research

- Inductive systems 3.6 kW (7h charging) and 22kW (1h charging)
- Electric Volvo C30 (add-on approach)



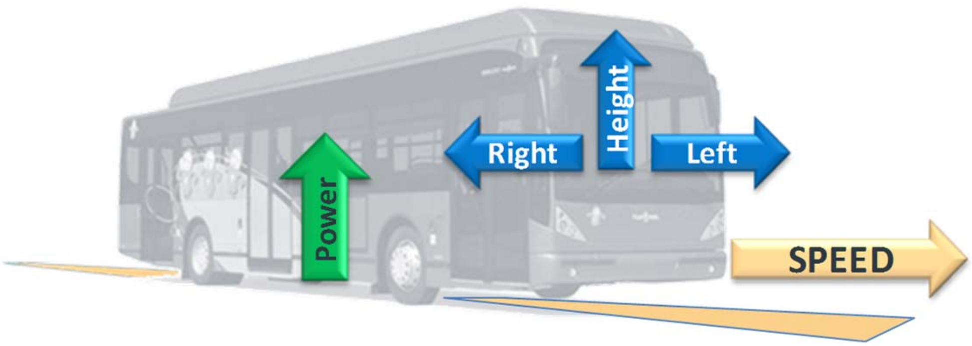
Results

- Energy efficiency: 90%   (94% for charging with charging cable)
  - 30 cm “positioning tolerance“
  - Distance transmitter – receiver 10 cm
- Inductive systems for cars are possible from 3.6 kW to 22kW

Inductive charging of buses - 1

Research

- Inductive system 80 kW,
  while standing still (bus stop) and when moving (up to 70km/h)

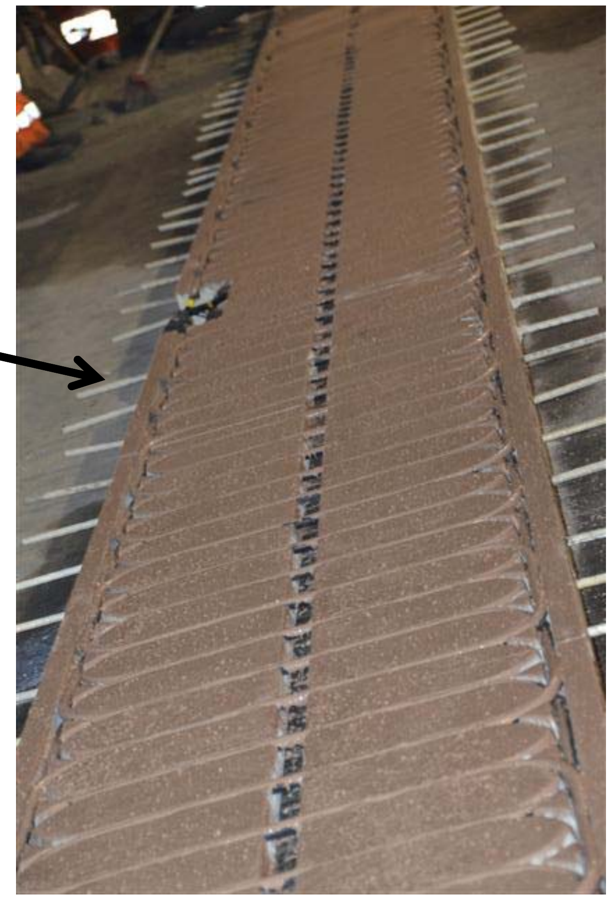


Results

- Energy efficiency: 88 - 90%
- Integration in road surface:
  - concrete and asphalt are possible
  - prefabricated modules are recommended
- Static and dynamic charging are technically feasible

Challenges for the incorporation

Incorporation of windings => prefabricated modules



Anchorage of the modules in the concrete pavement with polymer rebars

Extra adherence between module and top layer of 50 mm

The Evolution of PCCP …

More than a **CENTURY** of improvements in design, construction & material technologies

… and the Journey Continues!

Acknowledgments

- American Concrete Pavement Association
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- Tasos Ioannides, University of Cincinnati
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- … and many more