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

Mark B. Snyder, Ph.D., P.E.
Representing the 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
“...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.”
Harald Malcolm Westergaard
(1888-1950)

The ‘Father’ of Modern Pavement Mechanics

Credits: U of Illinois, Tasos Ioannides
First Design Equations (1920s, 1930s)

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

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”.

\[ d = \sqrt{\frac{cp}{s}} \]

- \( d \) = thickness
- \( c \) = stress coefficient
- \( p \) = wheel load
- \( s \) = allowable tensile stress
Westergaard (1948)

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

1. Uniform Support – No curling
2. One slab - No load transfer
3. Single Wheel Load - No multiple 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.

- 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
   o 6-in JPCP, 20 ft wide
   o Paved in two passes
   o Cost: $1.47 / yd² (vs. $2.21 / yd² [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
  - Calculated pavement stresses for any wheel configuration,
- PCA prepared design charts for individual aircraft.
  - With the advent of multi-wheel gear, 747 has 16 wheels in its main gear, the use of Influence Charts became quite tedious
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)
AASHO Road Test

Empirical Loop Equation:

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

$$\log R = 5.85 + 7.35 \times \log (D+1) - 4.62 \times \log (L_1+L_2) + 3.82 \times \log L_2$$

$$F = 1.00 + \frac{3.63 \times (L_1+L_2)^{5.2}}{(D-1)^{8.46} \times L_2^{3.52}}$$

$$G = \log \left[ \frac{(P_1-P_2)}{(P_1-1.5)} \right]$$

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.

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

$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  
$\sigma = $ Spangler’s corner stress
1962 Rigid Pavement Design Equation

\[
\log(\text{ESAL}) = 7.35 \times \log(D + 1) - 0.06 + \frac{\log \left(\frac{4.5 - 1.5}{4.5 - 1.5} + \frac{1.624 \times 10^7}{(D + 1)^{8.46}}\right)}{\log(1)} \\
+ (4.22 - 0.32p_t) \times \log \left(\frac{S'_c}{(215.63 \times J)}\right) \\
- \left[\frac{D^{0.75} - 1.132}{D^{0.75} - \frac{18.42}{(E_c / k)^{0.25}}}\right]
\]
1986/1993 Rigid Pavement Design Equation

Log(ESALs) = \( Z_R \times s_o - 7.35 \times \log(D + 1) - 0.06 \) + \( \log(4.5 - 1.5 \times 1.624 \times 10^7) \) + \( 4.22 - 0.32p_t \) * \( \log(S' C_d) \times \left[D^{0.75} - 1.132\right] \times \left[215.63 \times J \times \frac{D^{0.75}}{18.42 - \left(E_c / k\right)^{0.25}}\right]\)
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
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
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
Models Consider Changing Conditions

![Graph showing changes in Time, Traffic, PCC Strength, CTB, Base Modulus, and Subgrade Modulus over time.](image)
MEPDG Incremental Damage Approach (fatigue cracking example)

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

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

- \(n_{ijklmn}\) = Applied number of load applications at condition \(i,j,k,\ldots\)
- \(N_{ijklmn}\) = Allowable number of load applications at condition \(i,j,k,\ldots\)

- \(i\) = 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.)
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 Systems

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

Square Yards in '09 and '10

117,380,000

17,070,000

Full Depth Concrete
Concrete Overlays

[Source: Oman and ACPA]
Proportion of Overlays of Asphalt Pavement Increasing Rapidly

Percent that are Bonded or Unbonded

- Bonded on Asphalt
- Bonded on Composite
- Bonded on Concrete
- Unbonded on Asphalt
- Unbonded on Composite
- Unbonded on Concrete
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!
Interlayer Bonding Studies: 3 Modes of Debonding

Debonding at Interface
Delamination Between Lifts
Raveling

Each mode reduces slab support and increases PCC stresses.

Source: Vandenbossche, 2005
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.

Location Where Joint was Sawed to Full-Depth of Concrete.
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

![Aggregate Gradation Graph](image-url)
Corrosion-Resistant/Proof Dowel Bar Materials

Many materials products are available
Precast Concrete Pavement
(For Accelerated Repair & Construction)

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

Tappan Zee Bridge Toll Plaza

New York City Intersection

Santa Monica, California Bus Pad

LaGuardia Airport (New York)
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
Slab sizes and thicknesses for same top stress (2.5MPa)

Thickness: 10 inches
Concrete
Slabs 14.8 ft x 11.8 ft

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

Transformer

Energy network

Inductive charging

Receiver

Transmitter

Images of electric vehicle components and charging equipment.
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

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!
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