Performance Engineered Mixtures (PEM) Two Years Later: An Update

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Unless otherwise noted, FHWA is the source of all images in this presentation.
Performance Engineered Mixture Concept

- Understand what makes concrete last and what failure mechanisms we see.
- Specify for durability and move away from acceptance based on slump, strength, and air content.
- Starting point for a performance-driven QA specification and acceptance program for owner agencies.
PEM Components

- AASHTO PP-84
- Development and integration of enhanced/robust Quality Control practices and oversight
- Specification changes—moving from prescriptive to performance
  - Slump
  - Minimum cement content
  - Single aggregate gradation requirements
Why is PEM Important

- Increased evidence of premature deterioration/failure
- Cultural and programmatic move to a performance-driven highway program
- Specifications have not kept up with:
  - Materials
  - Testing technologies
  - QC practices
  - Agency and industry personnel levels and operations
- Innovation
Concrete Acceptance Nationally

- How do we accept concrete?
  - Slump
  - Temperature
  - Air
  - Strength
  - Thickness
  - Ride

- How do we adjust price?
  - Strength
Current Specifications

- **Slump**
  - No correlation with durability
  - Doesn’t assess quality

- **Air Content**
  - Poor correlation with durability
  - Does not measure the air system

- **Strength**
  - No correlation with durability

*Courtesy Dr. Peter Taylor*
Concrete Acceptance

We are getting what we are willing to accept.

• We’re getting strong concrete.
• We’re not getting durable concrete.
MCTC Strength Data from Field Projects

- 7 Day
- 28 Day
- 56 Day

28 Day Typical Design Requirement

Compressive Strength, PSI

Tennessee (TN), North Dakota (ND), Virginia (VA), Virginia-2 (VA-2), Illinois (IL), Illinois-2 (IL-2), Michigan (MI), Pennsylvania (PA), Iowa (IA), Florida (FL), Kansas (KS), Kansas-2 (KS-2), Arizona (AZ), Nevada (NV), Alabama (AL)
AASHTO PP 84: A Better Specification

Specifying for Durability

- Strength
- Shrinkage
- Freeze-thaw resistance
- Transport properties (Permeability)
- Aggregate stability
- Workability*
Jerry Voigt, ACPA

“It’s the agency’s responsibility to allow for innovation. It’s the contractor’s responsibility to deliver.”
### Prescriptive vs. Performance Specifications

<table>
<thead>
<tr>
<th>Prescriptive</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Agency dictates how the material or product is formulated and constructed</td>
<td>- Agency identifies desired characteristics of the material or product</td>
</tr>
<tr>
<td>- Based on past experience</td>
<td>- Contractor controls how to provide those characteristics</td>
</tr>
<tr>
<td>- Minimal/uncertain ability to innovate</td>
<td>- Maximum ability to innovate</td>
</tr>
<tr>
<td>- Requires agency to have proper manpower and skill set to provide oversight</td>
<td>- Reduced oversight burden on the agency</td>
</tr>
</tbody>
</table>
Quality Assurance Defined: 23 CFR 637

- Agency Acceptance
- **Contractor Quality Control**
  - Qualified (certified) Personnel
  - Qualified Laboratories
  - Independent Assurance
  - Dispute Resolution for Test Results

}> State processes, independent of material
Quality Control

- PP 84 acknowledges the key role of QC in a performance specification
- Requires an approved QC Plan
  - Testing targets, frequency, and action limits
  - Equipment and construction inspection
  - Mirror design-build experience
- Requires QC testing and control charts
  - Unit weight
  - Air content/SAM
  - Water content
  - Formation Factor (via Surface Resistivity)
  - Strength
Mirror Design-Build (DB) Experience

- DB shifts control from agency to contractor
  - Risk shifts with control
- Agency retains responsibility and accountability to the taxpayers
- Contractor submits proposal including how it will develop and deliver the project
- Post-award, contractor submits a detailed QC Plan
- Performance specifications have a similar shift of risk and control
- QC Plans are analogous
National Implementation Effort

FHWA Cooperative Agreement with Iowa State University

- Deploy innovative technologies to improve pavement performance
- Develop and transfer new technologies
- Deliver tools and guidance documents to States to support the increased knowledge of concrete materials, concrete pavement design, construction, and maintenance
FHWA Cooperative Agreement with Iowa State University

- Performance Engineered Mixtures/AASHTO PP84
  - Model QC Plan template for highway projects (with guidance)
  - QC control chart tools
  - Model performance specification

- Precision and Bias Statements
PEM Pooled Fund Partners

- FHWA
- State Departments of Transportation (DOTs)
- Industry (American Concrete Pavement Association, Portland Cement Association, National Ready Mixed Concrete Association, others)
Pooled Fund Participants

19 States + FHWA + Industry (January 2020)
<table>
<thead>
<tr>
<th>States with PEM Shadow Projects, 2018/2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Pennsylvania</td>
</tr>
<tr>
<td>• North Carolina</td>
</tr>
<tr>
<td>• South Dakota</td>
</tr>
<tr>
<td>• Kansas</td>
</tr>
<tr>
<td>• Idaho</td>
</tr>
<tr>
<td>• Iowa</td>
</tr>
<tr>
<td>• Illinois</td>
</tr>
<tr>
<td>• New York</td>
</tr>
<tr>
<td>• Minnesota</td>
</tr>
<tr>
<td>• Wisconsin</td>
</tr>
</tbody>
</table>
FHWA - PEM Implementation Incentive Funding

A, B, C, D
A, B, D
A, B
Considering/Preparing
Image provided by CP Tech Center under FHWA contract.
Praul, Michael (FHWA), 2/1/2018
**Category A: Incorporating two or more AASHTO PP 84-17 tests in the mix design/approval process (shadow testing acceptable)**

<table>
<thead>
<tr>
<th>State</th>
<th>SAM</th>
<th>Box test</th>
<th>V-Kelly</th>
<th>Unit Weight</th>
<th>CaOXY test</th>
<th>Surface resistivity</th>
<th>Additional tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illinois</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ASTM C157</td>
</tr>
<tr>
<td>Iowa</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Minnesota</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Maturity for flexural strength</td>
</tr>
<tr>
<td>New York</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>Compressive strength</td>
</tr>
<tr>
<td>North Carolina</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✔ - formation factor from resistivity ASTM C157, rate of flexural strength development, w/c ≤ 0.45, vol of paste</td>
</tr>
<tr>
<td>South Dakota</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wisconsin</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Flexural strength, optimized aggregate gradation, concrete mix design</td>
</tr>
</tbody>
</table>
**Category B: One or more new tests in the acceptance process**  
*(shadow testing acceptable)*

<table>
<thead>
<tr>
<th>State</th>
<th>SAM</th>
<th>Box Test</th>
<th>V-Kelly</th>
<th>Unit Weight</th>
<th>CaOXY Test</th>
<th>Surface Resistivity</th>
<th>Additional tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illinois</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td>Require slump, air, temperature, comp strength and w/c on tickets</td>
</tr>
<tr>
<td>Iowa</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓ formation factor</td>
<td>Plastic air, temperature</td>
</tr>
<tr>
<td>Minnesota</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>w/c with Phoenix, acceptance - optimized gradation and w/c ratio</td>
</tr>
<tr>
<td>New York</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>Exploring Payment factor for SAM, surface resistivity, f factor &amp; strength</td>
</tr>
<tr>
<td>North Carolina</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>Comparing to limits proposed in PP-84 and UNC Charlotte Research</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td>Require slump, air, temperature, comp strength and w/c on tickets</td>
</tr>
<tr>
<td>South Dakota</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fresh air content by SAM</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Flexural strength (typically use compressive strength) and optimized gradation</td>
</tr>
</tbody>
</table>
**Category C:** Requiring a comprehensive QC Plan from the contractor that will be approved and monitored by the state

<table>
<thead>
<tr>
<th>State</th>
<th>QC plan</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iowa</td>
<td>required</td>
<td>QC will be modified to include SAM, formation factor, PWL for plastic air content and related corrective action.</td>
</tr>
<tr>
<td>Minnesota</td>
<td>required</td>
<td>QC will be modified to reflect PP 84, including unit weight, air content, water content, formation factor, flexural strength, moisture and gradation testing.</td>
</tr>
<tr>
<td>New York</td>
<td>developed</td>
<td>Currently, DOT has been performing the QC through their acceptance program.</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>required</td>
<td>Additional tests will add unit weight, SAM, water content, resistivity (f) and box test.</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>will be developed</td>
<td>WI requires a QMP plan currently. SPV will be developed requiring contractor to submit QC plan.</td>
</tr>
</tbody>
</table>
### Category D: Requiring the use of control charts as called for in AASHTO PP 84-17

<table>
<thead>
<tr>
<th>State</th>
<th>Intend to use</th>
<th>Currently required for</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iowa</td>
<td>• SAM test&lt;br&gt;• Box test&lt;br&gt;• Formation factor&lt;br&gt;• PWL for plastic air specification compliance</td>
<td>• Combined aggregate gradation&lt;br&gt;• Air content before and after paver&lt;br&gt;• Unit weight&lt;br&gt;• Moistures&lt;br&gt;• w/c ratio</td>
</tr>
<tr>
<td>Minnesota</td>
<td>• Unit weight&lt;br&gt;• SAM number&lt;br&gt;• Formation factor&lt;br&gt;• Flexural strength</td>
<td>• Air content before and after paver&lt;br&gt;• Composite gradations&lt;br&gt;• Moisture content (%)&lt;br&gt;• w/c ratio</td>
</tr>
<tr>
<td>New York</td>
<td>• w/c ratio&lt;br&gt;• Unit weight&lt;br&gt;• Air content</td>
<td>Plan includes producer and contactor to use control charts to monitor and track performance.</td>
</tr>
<tr>
<td>North Carolina</td>
<td>• Box test&lt;br&gt;• SAM test&lt;br&gt;• Resistivity test</td>
<td>• Air content&lt;br&gt;• Slump&lt;br&gt;• Unit weight&lt;br&gt;• Concrete temperature</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>• SAM test&lt;br&gt;• Air content&lt;br&gt;• Unit weight&lt;br&gt;• Water content&lt;br&gt;• Strength&lt;br&gt;• Formation factor from resistivity</td>
<td>Control chart is optional for concrete paving.</td>
</tr>
</tbody>
</table>
Super Air Meter status

- Iowa (considering for mix approval)
- Illinois (data gathering)
- Wisconsin (mix approval now, acceptance in 2021)
- Michigan (considering for mix approval)
- Kansas (mix approval and acceptance testing in 2021)
- Minnesota (considering)
- South Dakota (considering)
Establishing PWL Spec Limits In Wisconsin

### State U SAM

<table>
<thead>
<tr>
<th>n</th>
<th>190</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pop. Range</td>
<td>0.01 to 0.45</td>
</tr>
<tr>
<td>Pop. Median</td>
<td>0.16500</td>
</tr>
<tr>
<td>Population Mean μ</td>
<td>0.15921</td>
</tr>
<tr>
<td>Population Variance σ²</td>
<td>4.0569E-03</td>
</tr>
<tr>
<td>Pop. Stand. Deviation σ</td>
<td>0.063693539</td>
</tr>
</tbody>
</table>

If 90 PWL = Upper Spec Limit
90 PWL: 1 Limit z = 1.28

\[ Z = \frac{(\text{Mean} - \text{Spec. Limit})}{\text{Std. Dev.}} \]

Spec. Limit = Mean ± (Z * Std. Dev.)

Upper Spec Limit

Calculated 0.24

Calculated 90 PWL

Freq

SAM Number

WCPA 2020 Annual Concrete Pavement Conference
## SAM Data

<table>
<thead>
<tr>
<th>State</th>
<th>n</th>
<th>Mean</th>
<th>Std Deviation</th>
<th>Calc Upper Spec Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>124</td>
<td>0.21</td>
<td>0.0908</td>
<td>0.33</td>
</tr>
<tr>
<td>S</td>
<td>86</td>
<td>0.19</td>
<td>0.0896</td>
<td>0.30</td>
</tr>
<tr>
<td>T</td>
<td>21</td>
<td>0.17</td>
<td>0.0484</td>
<td>0.23</td>
</tr>
<tr>
<td>U</td>
<td>190</td>
<td>0.16</td>
<td>0.0637</td>
<td>0.24</td>
</tr>
<tr>
<td>V</td>
<td>173</td>
<td>0.20</td>
<td>0.124</td>
<td>0.36</td>
</tr>
</tbody>
</table>
Iowa Early Success Story

- FHWA PEM Implementation Incentive Funds
- “New” QC Plan?
- Box test experience
- Contractor moving forward

Images: Pixabay
Wisconsin On The Right Track

- Agency and industry involvement/leadership in ongoing PEM work
- Optimized gradation is a priority
- National leader in SAM implementation (approach)
- Every contractor is gaining experience with the SAM
Wisconsin Leadership

“Provide control charts conforming to Section 8 of AASHTO PP84-17 with control limits prior to incorporating material into the project for all QC testing. Plot all QC, QV, and process control test results on the control charts. Provide daily updated control charts results, hard copy or electronically, to the engineer and the Bureau of Technical Services, Chad Hayes at chad.hayes@dot.wi.gov.”
Next Steps/Challenges

- Maintain strong state/industry working relationship
- With AASHTO PP-84 as a guide, develop mix design approval process incorporating new tests as desired
- Begin to incorporate state construction staff (develop QC strategy)
- With the national concrete performance specification as a model, develop state-level specification (including QC requirements and oversight)
- Training, training, training!
PEM One Day Workshop

Purpose: Develop a state-specific plan to implement PEM principles

Target Audience: Specifiers and those involved with quality aspects of concrete pavement construction

Topics:
- Road to PEM – Why change things?
- Group discussion – What makes a good specification?
- AASHTO PP-84, philosophy and goals
- Group discussion – Barriers to performance evaluation
- Science and tests for PEM (Property-Test-Remedy)
- Group Discussion – What next?
- PEM in practice, Quality, Implementation, Training
## Technology Sharing—Concrete Clips

<table>
<thead>
<tr>
<th>Currently Available</th>
<th>Under Development</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Internal Curing</td>
<td>• Admixtures</td>
</tr>
<tr>
<td>• Blended Cements</td>
<td>• Ensuring Durable Concrete Paving Mixtures</td>
</tr>
<tr>
<td>• Aggregates for Paving</td>
<td>• Concrete Durability Tests</td>
</tr>
<tr>
<td>• Cement Manufacturing</td>
<td>• Mechanistic-Empirical Pavement Design</td>
</tr>
<tr>
<td>• Supplementary Cementitious Materials</td>
<td>• Curing</td>
</tr>
<tr>
<td>• Real Time Smoothness (3)</td>
<td>• Engineering Concrete Mixtures for Performance</td>
</tr>
<tr>
<td>• Mobile Concrete Technology Center</td>
<td></td>
</tr>
<tr>
<td>• Workability</td>
<td></td>
</tr>
<tr>
<td>• Maturity</td>
<td></td>
</tr>
</tbody>
</table>
Technology Sharing—MCTC One Pagers

- Cement Content
- Optimized Mix Design
- Cores vs. Cylinders
- NDT Thickness Measurement
- Surface Resistivity
- Texture
- Maturity
- Curing
- Calorimetry
- Supplementary Cementitious Materials
Questions?

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207-512-4917