Performance Engineered Mixtures Program

Dr Peter Taylor, PE (IL)
PEM - What is it?

- A program to
  - Understand what makes concrete “good”
  - Specify the critical properties and test for them
  - Prepare the mixtures to meet those specifications
What is it?

- Performance – choosing what we need
- Engineered – delivering what is needed
- Mixtures – focus on the mixture, for now
**Track 1. Mix Design Analysis**

**Goal:** Mixtures that are sustainable (consistently long-lasting, constructible, cost-efficient, and environmentally sound)

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**Subtrack: Tests**

- Uniformity / QC
- Acceptance / QA

**Subtrack: Relationships, Models, and Computer Programs**

- Effects of Mix Proportioning & Environment
- Effects of Materials Interactions

- Parameters
- Effects

**Subtrack: Specifications**

- Guide Specifications (Guidelines on balancing priorities)
- Guide Sheets (Instructions for specific people)

**Subtrack: Communication**

- Field Trials
- Tech Transfer

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**PCC Mix Design Laboratory Testing & Equipment**

**PCC Mix Design Modeling**

**PCC Mix Design System Development & Integration**

**PCC Mix Design Evaluation & Implementation**

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*Extract from a slide used at NC2 in 2008*
The Team

- FHWA - Gina Ahlstrom, Mike Praul
- Consultants – Tom VanDam, Cecil Jones, Tom Cackler
- Researchers – Jason Weiss, Tyler Ley
Why bother?

• Current approaches
  ✓ May not measure critical parameters
  ✓ Are often built around previous failures – thereby introducing unintended consequences
  ✓ Limit innovation

• Need to deliver mixtures that meet needs, reliably
Why bother?

- Iowa Highway Research Board funded project
- Collecting data on overlay performance in the whole IA system
- This plot represents 12 foot slabs showing Pavement Condition Index (PCI) vs age
- Typical of all data collected
Why bother?

- Clear bifurcating data set
  - Orange = normal
  - Blue = premature distress
    - 30/257 data points
    - Joints
    - Foundation system
    - Design
Why bother?

- Modelling system performance insists we use all data = gray line
  - 27 years before 60% Pavement Condition Index
- If we could improve our practices to eliminate the premature failure
  - 45 years before 60% PCI
- Adds ~20 years
Step 1

• A better specification
  ✓ Require the things that matter
    ➢ Transport properties (everywhere)
    ➢ Aggregate stability (everywhere)
    ➢ Strength (everywhere)
    ➢ Cold weather resistance (cold locations)
    ➢ Shrinkage (dry locations)

  ➢ Workability (everywhere)
Step 1

• A better specification
  ✓ Measure them at the right time
    ➢ Prequalification
    ➢ Process control
    ➢ Acceptance
  ✓ A buffet of approaches
    ➢ Prescriptive: w/cm, paste volume
    ➢ Performance: Formation factor
Step 1

- A better specification
  ✓ AASHTO PP84 on track to publish in March
    - Guide Specification
    - “Deemed to satisfy”
    - Avoids PWL discussion – that is local
    - Provisional = meaning we can modify as we learn things
# Transport Properties/Permeability (6.6)

<table>
<thead>
<tr>
<th>Section</th>
<th>Property</th>
<th>Specified Test</th>
<th>Specified Value</th>
<th>Mixture Qualification</th>
<th>Acceptance</th>
<th>Selection Details</th>
<th>Special Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.6.1.1</td>
<td>Water to Cement Ratio</td>
<td>AASHTO T 318</td>
<td>0.45</td>
<td>~</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>6.6.1.2</td>
<td>RCPT Value</td>
<td>AASHTO T 277</td>
<td>2000</td>
<td>~</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>6.6.1.3</td>
<td>Formation Factor/Resistivity</td>
<td>AASHTO xx or AASHTO yy</td>
<td>500</td>
<td>~</td>
<td>Yes</td>
<td>through ρ</td>
<td>* Note this is currently based on saturated curing and an adjustment is needed to match with AASHTO Spec</td>
</tr>
<tr>
<td>6.6.2.1</td>
<td>Ionic Penetration, F Factor</td>
<td>AASHTO xx or AASHTO yy</td>
<td>25 mm at 30 year</td>
<td>Yes, F</td>
<td>through ρ</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

0.42
# Aggregate Stability (6.7)

<table>
<thead>
<tr>
<th>Section</th>
<th>Property</th>
<th>Specified Test</th>
<th>Specified Value</th>
<th>Mixture Qualification</th>
<th>Acceptance</th>
<th>Selection Details</th>
<th>Special Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.7</td>
<td>Aggregate Stability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.7.1</td>
<td>D Cracking</td>
<td>AASHTO T 161, ASTM C 1646/666</td>
<td>~</td>
<td>~</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>6.7.2</td>
<td>Alkali Aggregate Reactivity</td>
<td>AASHTO PP 65</td>
<td>~</td>
<td>~</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>

ASTM C 1260/1561 <0.15%
## Concrete Strength (6.3)

<table>
<thead>
<tr>
<th>Section</th>
<th>Property</th>
<th>Specified Test</th>
<th>Specified Value</th>
<th>Mixture Qualification</th>
<th>Acceptance</th>
<th>Selection Details</th>
<th>Special Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.3 Concrete Strength</td>
<td>6.3.1 Flexural Strength</td>
<td>AASHTO T97</td>
<td>4.1 MPa</td>
<td>600 psi</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.3.2 Compressive Strength</td>
<td>AASHTO T22</td>
<td>24 MPa</td>
<td>3500 psi</td>
<td>Yes</td>
<td>Yes</td>
<td>Choose either or both</td>
<td>&gt;3700 psi</td>
</tr>
</tbody>
</table>
### Hardened Cement Paste Freeze-Thaw Durability (6.5)

<table>
<thead>
<tr>
<th>Section</th>
<th>Property</th>
<th>Specified Test</th>
<th>Specified Value</th>
<th>Mixture Qualification</th>
<th>Acceptance</th>
<th>Selection Details</th>
<th>Special Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5.1.1</td>
<td>Water to Cement Ratio</td>
<td>AASHTO T 318</td>
<td>0.45</td>
<td>~</td>
<td>Yes</td>
<td>Yes</td>
<td>Choose Either 6.5.1.1 or 6.5.2.1</td>
</tr>
<tr>
<td>6.5.1.2</td>
<td>Fresh Air Content</td>
<td>AASHTO T 152, T196, TP 118</td>
<td>5 to 8 %</td>
<td>Yes</td>
<td>Yes</td>
<td>Choose only one</td>
<td>7 ± 1.5</td>
</tr>
<tr>
<td>6.5.1.3</td>
<td>Fresh Air Content/SAM</td>
<td>AASHTO T 152, T196, TP 118</td>
<td>≥ 4% Air; SAM &lt; 0.2</td>
<td>%, psi</td>
<td>Yes</td>
<td>Yes</td>
<td>Variation controlled with mixture proportion observation or F Factor and Porosity Measures</td>
</tr>
<tr>
<td>6.5.2.1</td>
<td>Time of Critical Saturation</td>
<td>&quot;Bucket Test&quot; Specification</td>
<td>30 Years</td>
<td>Yes</td>
<td>No</td>
<td>Note 1</td>
<td>Note 2</td>
</tr>
<tr>
<td>6.5.3.1</td>
<td>Deicing Salt Damage</td>
<td>~</td>
<td>35% SCM</td>
<td>Yes</td>
<td>Yes</td>
<td>30% max</td>
<td>Are calcium or magnesium chloride used</td>
</tr>
<tr>
<td>6.5.3.2</td>
<td>Deicing Salt Damage</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>Yes</td>
<td>Yes</td>
<td>Are calcium or magnesium chloride used, needs a use of specified sealers</td>
</tr>
<tr>
<td>6.5.4.1</td>
<td>Calcium Oxychloride Limit</td>
<td>Test sent to AASHTO</td>
<td>&lt; 0.15g CaOXY/g paste</td>
<td>Yes</td>
<td>No</td>
<td>Are calcium or magnesium chloride used</td>
<td></td>
</tr>
</tbody>
</table>

**Note 1:** Choose Either 6.5.1.1 or 6.5.2.1

**Note 2:** Choose either 6.5.1.2, 6.5.1.3, or 6.5.2.1

**2017 WCPA Annual Concrete Pavement Workshop**
Reducing Unwanted Cracking Due to Shrinkage (6.4)

<table>
<thead>
<tr>
<th>Section</th>
<th>Property</th>
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<th>Special Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.4.1.1</td>
<td>Volume of Paste</td>
<td></td>
<td>25%</td>
<td>Yes</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.4.1.2</td>
<td>Unrestrained Volume Change</td>
<td>ASTM C157</td>
<td>420 με</td>
<td>at 28 days</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>6.4.2.1</td>
<td>Unrestrained Volume Change</td>
<td>ASTM C157</td>
<td>360, 420, 480 με</td>
<td>at 91 days</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>6.4.2.2</td>
<td>Restrained Shrinkage</td>
<td>AASHTO T334</td>
<td>crack free</td>
<td>at 180 days</td>
<td>Yes</td>
<td>No</td>
<td>Choose only one</td>
</tr>
<tr>
<td>6.4.2.3</td>
<td>Restrained Shrinkage</td>
<td>AASHTO T???</td>
<td>$\sigma &lt; 60% f'$</td>
<td>at 7 days</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>6.4.2.4</td>
<td>Probability of Cracking</td>
<td>~</td>
<td>5, 20, 50%</td>
<td>as specified</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>
# Workability (6.8)

<table>
<thead>
<tr>
<th>Section</th>
<th>Property</th>
<th>Specified Test</th>
<th>Specified Value</th>
<th>Mixture Qualification</th>
<th>Acceptance</th>
<th>Selection Details</th>
<th>Special Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.8 Workability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.8.1</td>
<td>Box Test</td>
<td>~</td>
<td>&lt;6.25 mm, &lt; 30% Surf. Void</td>
<td>Yes</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.8.2</td>
<td>Modified V-Kelly Test</td>
<td>~</td>
<td>15-30 mm per root seconds</td>
<td>Yes</td>
<td>No</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Step 2

• Better test methods (for those critical properties)
  ➢ VKelly
  ➢ Box
  ➢ Resistivity / Formation factor
  ➢ Bucket / Sorptivity
  ➢ Dual ring
  ➢ SAM
Kelly ball test
- Developed in the 1950s in US
- Standardized in California DOT test
- Comparable to slump test
VKelly

- Measure initial slump (initial penetration)
- Start vibrator for 36 seconds at 8000 vpm
- Record depth every 6 seconds
- Repeat
- Plot on root time
- Calculate slope = VKelly Index
Box Test

- A test that examines:
  - ✓ Response to vibration
  - ✓ Filling ability of the grout (avoid internal voids)
  - ✓ Ability of the concrete to hold an edge
Box Test

- Add 9.5” of unconsolidated concrete to the box
- Insert 1” diameter stinger vibrator (8000 vpm) into the center of the box over a three count and then remove over a three count
Box Test

- The edges of the box are then removed and inspected for honey combing and edge slump.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Less than 10% overall surface voids.</td>
<td>10-30% overall surface voids.</td>
<td>30-50% overall surface voids.</td>
<td>Over 50% overall surface voids.</td>
</tr>
</tbody>
</table>
Super Air Meter

- Reports air content and SAM number
- SAM number correlates well with freeze thaw testing
Formation Factor

- The resistivity test gives you a single number that is an indication of a lot of different things -
  - Ionic concentration of the pore solution
  - Formation Factor
  - Moisture
  - Temperature
  - Geometry
  - Curing conditions
The Bucket Test

• Cast concrete and keep sealed for 14 days
• Measure the cylinder mass after demolding
• Place three concrete cylinders in lime water
• Measure their mass at 5 days
• Measure their mass again every 10 days until they are 60 days old
• Oven dry cylinder and take mass
• Vacuum saturate cylinder and take mass
• Calculate the time to critical degree of saturation.
Dual Ring Test

This ring can measure both expansion and contraction.

As the concrete shrinks the ring can measure the strains that occur.

We force a temperature gradient in the concrete and make it crack and compare that to 60% of the split tension capacity after 7 days.
Step 2

- QC should include
  - Unit weight
  - Calorimetry
  - Maturity
  - Strength development
  - Air void stability
Step 3

• Better mixtures
  ✓ Understand effects of materials
    ➢ Aggregate gradation
    ➢ SCMs
    ➢ Admixtures
  ✓ Proportioning tools
    ➢ Void ratio approach
  ✓ Sustainability
  ✓ Give contractor control
    of things they need
Proposed Mixture Proportioning Procedure

Aggregate system

Paste Quantity

Paste Quality

Koehler
Doing the Sums

The wonders of a spreadsheet and a solver function…

Measure $V_a$
# Doing the Sums

The wonders of a spreadsheet...

<table>
<thead>
<tr>
<th>Paste Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project</strong></td>
</tr>
</tbody>
</table>

**Materials**

<table>
<thead>
<tr>
<th></th>
<th><strong>Targets</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>Type 1</td>
</tr>
<tr>
<td>SCM 1</td>
<td>C Ash</td>
</tr>
<tr>
<td>SCM 2</td>
<td>Slag</td>
</tr>
<tr>
<td>Course Agg</td>
<td>1&quot;</td>
</tr>
<tr>
<td>Fine Agg</td>
<td>Sand</td>
</tr>
<tr>
<td>Intermediate</td>
<td>3/8&quot;</td>
</tr>
<tr>
<td>Water</td>
<td></td>
</tr>
</tbody>
</table>

Cementitious 472 per

- w/cm 0.42
- Air % 5.0%
- % SCM 1 20%
- % SCM 2 0%

Voids in aggregate 28.1%

- Required Vp/Vv 125%

Strength

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RCP</td>
<td>psi</td>
<td>7 days</td>
</tr>
<tr>
<td>Weneer</td>
<td>kD-cm</td>
<td>28 days</td>
</tr>
</tbody>
</table>

Blue = Input Data

Red = Calculation

Yellow = Output

Black = Working
## Doing the Sums

The wonders of a spreadsheet...

<table>
<thead>
<tr>
<th>Mixture Proportions</th>
<th>Project</th>
<th>Effect of gradation</th>
<th>9/29/2016</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cement</strong></td>
<td>Type 1</td>
<td>378</td>
<td>3.15</td>
</tr>
<tr>
<td><strong>SCM 1</strong></td>
<td>C Ash</td>
<td>94</td>
<td>2.65</td>
</tr>
<tr>
<td><strong>SCM 2</strong></td>
<td>Slag</td>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td><strong>Coarse Agg</strong></td>
<td>1&quot;</td>
<td>1495</td>
<td>2.68</td>
</tr>
<tr>
<td><strong>Fine Agg</strong></td>
<td>Sand</td>
<td>1522</td>
<td>2.66</td>
</tr>
<tr>
<td><strong>Intermediate</strong></td>
<td>3/8&quot;</td>
<td>314</td>
<td>2.68</td>
</tr>
<tr>
<td><strong>Water</strong></td>
<td></td>
<td>198</td>
<td>1.00</td>
</tr>
<tr>
<td><strong>Air %</strong></td>
<td></td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>4000</td>
<td>27.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Concrete Pavement</strong></th>
<th><strong>Technology Center</strong></th>
<th><strong>National</strong></th>
<th><strong>Institute for Transportation</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Blue = Input Data</strong></td>
<td><strong>Red = Calculation</strong></td>
<td><strong>Don’t touch</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Yellow = Output</strong></td>
<td><strong>Don’t touch</strong></td>
<td><strong>Black = Working</strong></td>
<td></td>
</tr>
</tbody>
</table>

- Cementitious: 472 472 pcy
- Volume of paste: 26.0 %
- Volume of aggregate: 74.0 %
- Volume of voids: 20.8
- vp/νν: 125 125.0 5.2
- w/cm: 0.42 0.42
- % SCM 1: 20 20 %
- % SCM 2: 0 0 %
- Mass agg: 3330 3330 pcy
Step 3

- Better mixtures
Step 3

- WI project – as built

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**Tarantula**

Greater than 10% on the sum of #10 and #50;
74-83% of total sand (#30-200).

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**Individual and Combined Gradations**

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**Power 45**

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**Shistone Chart**

IV
Sandy

III
Small Agg

III
Coarse

I

\( \Phi \mu \)

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**Workability Factor**

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**Coarseness Factor**
Does it Work?

- West Des Moines spec
  - 5% minimum air behind the paver
  - 0.42 w/cm target
  - 35% fly ash
- Cracking risk
  - MN recommended 400 pcy cement
  - Blankets
What next?

- Understanding and education
- Validate tests in the field
- Parallel testing

- New tests
- Pooled fund to pay for it
What do we get?

- Concrete that delivers what is needed
  - Efficiently w.r.t.
    - Cost
    - Environmental impact
  - Reliably
    - "Quality"
Your turn…