New Advancements in Mixes, Strength, and Durability

Dr. Peter Taylor, PE (IL)
What Do We Do?

- Publications
- Training
- Research / demonstration projects
- Professional presence

Uniting agencies, industry, and universities to advance concrete pavements through research and technology
Staff

• Peter Taylor
• Bob Steffes
• Xuhao Wang
• Sharon Prochnow
• Denise Wagner

• 2 Vacancies

• Consultants
Who is the Boss

Cement
Use more cement

University
Deliver scholarship

Build Better Pavements

Owners
Make them cheaper and more reliable

Industry
Build more concrete pavements
Funding

• Income
  • Sponsorship
  • FHWA Cooperative Agreement
  • Competitive Contracts

• Expenditures
  • In house
  • Indirect
  • Subs
Performance Engineered Mixtures

Engineering – making hard choices between conflicting demands with limited resources to assure the buyer that the Mixture will achieve desired Performance
Design is more than copy/paste

- What do we need?
- The test
- The spec
- How do we get it
Who Does it Anyway?

- Readymix operator
  ✓ Some regularly, others never
- Consultant
  ✓ May review before “approving”
- Owner
  ✓ Mmm
- Contractor
  ✓ Only for bidding
- Researchers
  ✓ Of course!
Common Misconceptions

• More cement means stronger concrete
• Supplementary cementitious materials are dilutants
• Stronger concrete is more brittle & that is bad
• Strength and workability are correlated
• Strength and durability are correlated
But I have been doing it this way for 30 years…
What Do We Want?

• The Contractor wants:
  ✓ The right workability for his machine (water content, agg gradation)
  ✓ Control of the setting time (SCM type)
  ✓ Cost effective
What Do We Want?

- The Owner wants:
  - ✔ Strong enough
  - ✔ Crack free
  - ✔ Ability to resist the environment
  - ✔ Safety
  - ✔ Cost effective
How Does Concrete Fail

- *Freeze Thaw Cycling*
- *Salt Crystallization*
- *Chemical Attack*
Chemical Attack

- Salts react with paste
  - Calcium oxychloride
  - Friedel’s Salt – Calcium-chloro-aluminate
  - Ettringite
Putting It All Together

• w/cm
  ✓ ~0.38-0.42

• Air Void System
  ✓ Spacing factor <0.008 inch
  ✓ Air content >5% behind the paver
  ✓ 0.2 SAM number

• SCMds
  ✓ Enough, but not too much
  ✓ Ternary systems
What do we want to measure?

- Critical Properties at design / proportioning stage
- Uniformity at delivery
  - Testing
  - 3’rd party records
Test Methods

• Tests
  • Do we know what’s in there?
What do we need to measure?

- What is the potential distress?
  - Tougher environments
  - New materials
  - New practices
Test Methods

- Restrained shrinkage ASTM C 1581
Test Methods

- Electrical resistivity
  - AASHTO TP 95
    - 27 kΩ-cm at 28 days
- Formation factor
  - Under development
  - Allows for normalization of various test methods
Test Methods

• Tests
  • VKelly – workability response to vibration
Test Methods

• Tests
  • The Box – workability response to vibration
    • Edge slump vs honeycomb
Test Methods

• Tests
  • Calorimetry tells us about the chemistry of the system (Uniformity)
Test Methods

• Tests
  • Unit weight – something is wrong
Test Methods

- Tests
  - Super Air Meter (SAM)
  - Air void system in fresh concrete
Test Methods

• Tests
  • Ultrasonic Pulse Velocity (UPV)
  • Setting and therefore sawing time
Test Methods

• Tests
  • Ultrasonic Pulse Velocity (UPV)
  • Setting and therefore sawing time

![Graph showing the relationship between UPV Initial Set and Saw Time. The graph includes lines of best fit with equations and R² values: y = 0.9891x + 219.01 (R² = 0.8997) and y = 1.0227x + 299.05 (R² = 0.8114).]
Test Methods

- Tests
  - Maturity – strength development up to 24 hours
Guide Specification

- Add new thinking
- Take out some stuff
<table>
<thead>
<tr>
<th>Property</th>
<th>Prescriptive approach</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength</td>
<td>SCM type and content, w/cm</td>
<td>Flexural, compressive</td>
</tr>
<tr>
<td>Crack free</td>
<td>Shrinkage, paste content</td>
<td>Ring, bar</td>
</tr>
<tr>
<td>Durable (Cold weather)</td>
<td>Air void system, w/cm, SAM</td>
<td>C666, C672, Knick point</td>
</tr>
<tr>
<td>Durable (Salt resistant)</td>
<td>SCM type and content, w/cm</td>
<td>LT DSC</td>
</tr>
<tr>
<td>Durable (Impermeable)</td>
<td>SCM type and content, w/cm</td>
<td>Formation factor</td>
</tr>
<tr>
<td>Durable (Aggregate stability)</td>
<td>Pre-qualify</td>
<td>PP65, IA Pore index, C33</td>
</tr>
<tr>
<td>Workable</td>
<td>QC only</td>
<td>Box, VKelly, (slump)</td>
</tr>
</tbody>
</table>
Report

✓ Rate of strength development
✓ Rate of development of resistivity
✓ Workability
✓ Coefficient of thermal expansion and modulus of elasticity
Proportioning Approaches
Past

- Structural concrete 1:2:4
- Other concrete 1:3:6
- Waterproof concrete Add salt

- No chemicals
- No SCMs
- Precision was ugly
- Bulking made it worse
Proportioning Approaches Present

- Developed
  - Before water reducers
  - Before supplementary cementitious materials
- Primarily focused on structural concrete
  - 100 mm (4") slump
  - 30 MPa (~4000 psi)
- ACI 211 last revised in 1991
  - Linear
Proportioning Approaches
Future

Aggregate system

Paste quality

Paste quantity

Koehler
Proposed Mixture Proportioning Procedure

Choose the Aggregate System
- Combined gradation
- Determine void ratio
Aggregate System

• Tarantula Curve (Ley)
Aggregate System

- 50/50 – void ratio 27.1%
- Tarantula – void ratio 25.3%
Proposed Mixture Proportioning Procedure

Choose a Paste System for Performance

• Cementitious blend
• W/Cm
• Air content
Proposed Mixture Proportioning Procedure

Choose Paste Volume
- All voids must be filled with paste
- And a bit more to coat the particles for workability
Definitions...

- Blue = $V_{voids}$ (C29)
- Grey + Blue = $V_{paste}$
- Void ratio = $V_{paste}/V_{voids}$
Proposed Mixture Proportioning Procedure

Choose Paste Volume
• Need enough paste for base workability
Proposed Mixture Proportioning Procedure

Choose Paste Volume

- Need enough paste for mechanical properties ~125 - 175% of voids
Proposed Mixture Proportioning Procedure

Put it all together

• Measuring workability
### Proposed Mixture Proportioning Procedure

#### Put it all together

<table>
<thead>
<tr>
<th></th>
<th>Tarantula</th>
<th>50/50</th>
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</thead>
<tbody>
<tr>
<td>Void ratio</td>
<td>125</td>
<td>150</td>
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<tr>
<td>Cementitious</td>
<td>427</td>
<td>505</td>
</tr>
</tbody>
</table>

![Graph showing Kelly, In/s vs Vp/Vv, %](image_url)
Proposed Mixture Proportioning Procedure

Input aggregates

---

<table>
<thead>
<tr>
<th>Project</th>
<th>Gravel 1&quot;</th>
<th>12/11/2014</th>
</tr>
</thead>
</table>

### Materials

Cementitious: 428
Coarse Agg: Gravel
Fine Agg: River
Intermediate:

### Sieve Analysis Data

Max nominal aggregate size: 1.00 inch (0.75, 1.0 or 1.5)

<table>
<thead>
<tr>
<th>Percent mass</th>
<th>Coarse</th>
<th>Gravel</th>
<th>Fine</th>
<th>River</th>
<th>Intermediate</th>
<th>0</th>
<th>Combined</th>
<th>Fineness Modulus</th>
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</thead>
<tbody>
<tr>
<td>100.0</td>
<td>64.3</td>
<td></td>
<td>35.7</td>
<td></td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sieve:</th>
<th>% Pass</th>
<th>% Mix</th>
<th>% Pass</th>
<th>% Mix</th>
<th>% Pass</th>
<th>% Mix</th>
<th>%</th>
<th>%</th>
<th>%</th>
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</thead>
<tbody>
<tr>
<td>2&quot;</td>
<td>100.0</td>
<td>64.3</td>
<td>100.0</td>
<td>35.7</td>
<td>0.0</td>
<td>0.0</td>
<td>100.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1 1/2&quot;</td>
<td>100.0</td>
<td>64.3</td>
<td>100.0</td>
<td>35.7</td>
<td>0.0</td>
<td>0.0</td>
<td>100.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1&quot;</td>
<td>100.0</td>
<td>64.3</td>
<td>100.0</td>
<td>35.7</td>
<td>0.0</td>
<td>0.0</td>
<td>100.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>3/4&quot;</td>
<td>82.0</td>
<td>52.7</td>
<td>100.0</td>
<td>35.7</td>
<td>0.0</td>
<td>0.0</td>
<td>88.4</td>
<td>11.6</td>
<td>11.6</td>
</tr>
<tr>
<td>1/2&quot;</td>
<td>55.0</td>
<td>35.5</td>
<td>100.0</td>
<td>35.7</td>
<td>0.0</td>
<td>0.0</td>
<td>71.1</td>
<td>28.9</td>
<td>17.4</td>
</tr>
<tr>
<td>3/8&quot;</td>
<td>30.0</td>
<td>19.3</td>
<td>100.0</td>
<td>35.7</td>
<td>0.0</td>
<td>0.0</td>
<td>55.0</td>
<td>45.0</td>
<td>16.1</td>
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<tr>
<td># 4</td>
<td>5.0</td>
<td>3.2</td>
<td>98.9</td>
<td>35.3</td>
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<td>0.0</td>
<td>38.5</td>
<td>61.5</td>
<td>16.5</td>
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<tr>
<td># 8</td>
<td>0.2</td>
<td>0.1</td>
<td>92.4</td>
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<td>0.0</td>
<td>33.1</td>
<td>66.9</td>
<td>5.4</td>
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<tr>
<td># 16</td>
<td>0.2</td>
<td>0.1</td>
<td>77.5</td>
<td>27.7</td>
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<td>0.0</td>
<td>27.8</td>
<td>72.2</td>
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<td># 30</td>
<td>0.1</td>
<td>0.1</td>
<td>47.7</td>
<td>17.1</td>
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<td>0.0</td>
<td>17.1</td>
<td>82.9</td>
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<tr>
<td># 50</td>
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<td>0.1</td>
<td>11.0</td>
<td>3.9</td>
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<td>4.0</td>
<td>96.0</td>
<td>13.1</td>
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<tr>
<td># 100</td>
<td>0.1</td>
<td>0.1</td>
<td>0.8</td>
<td>0.3</td>
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<td>0.0</td>
<td>0.4</td>
<td>99.6</td>
<td>3.7</td>
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<tr>
<td># 200</td>
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<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>99.9</td>
<td>0.3</td>
</tr>
</tbody>
</table>

| Coarseness Factor | 67.29 |
| Workability Factor | 33.14 |
| Adjustments       | 0.00  |
| Adjusted Workability Factor | 33.14 |
Proposed Mixture Proportioning Procedure

Check aggregates
## Proposed Mixture Proportioning Procedure

### Input paste parameters

<table>
<thead>
<tr>
<th>Paste Quality</th>
<th>Project</th>
<th>Gravel 1&quot;</th>
<th>12/11/2014</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Materials</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cement</td>
<td>Type I</td>
<td></td>
<td>3.15</td>
</tr>
<tr>
<td>SCM 1</td>
<td>F Ash</td>
<td></td>
<td>2.65</td>
</tr>
<tr>
<td>SCM 2</td>
<td>Slag</td>
<td></td>
<td>1.00</td>
</tr>
<tr>
<td>Coarse Agg</td>
<td>Gravel</td>
<td></td>
<td>2.72</td>
</tr>
<tr>
<td>Fine Agg</td>
<td>River</td>
<td></td>
<td>2.66</td>
</tr>
<tr>
<td>Intermediate</td>
<td>0</td>
<td></td>
<td>1.00</td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td></td>
<td>1.00</td>
</tr>
<tr>
<td>Cementitious</td>
<td>428</td>
<td>pey</td>
<td></td>
</tr>
<tr>
<td>w/cm</td>
<td>0.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air %</td>
<td>5.0</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>% SCM 1</td>
<td>20</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>% SCM 2</td>
<td>0</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Voids in aggregate</td>
<td>25.3</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Required Vp/Vv</td>
<td>125</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Strength</td>
<td>4000 psi</td>
<td></td>
<td>7 days</td>
</tr>
<tr>
<td>RCP</td>
<td>1500 coulomb</td>
<td></td>
<td>56 days</td>
</tr>
<tr>
<td>Wenner</td>
<td>27 kΩ-cm</td>
<td></td>
<td>28 days</td>
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</tbody>
</table>
Proposed Mixture Proportioning Procedure

Calculate proportions

<table>
<thead>
<tr>
<th>Mixture Proportions</th>
<th>Targets</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pounds</td>
<td>R.D.</td>
</tr>
<tr>
<td>Cement Type I</td>
<td>531</td>
<td>3.15</td>
</tr>
<tr>
<td>SCM 1 C Ash</td>
<td>133</td>
<td>2.65</td>
</tr>
<tr>
<td>SCM 2 Slag</td>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>Coarse Gravel</td>
<td>1543</td>
<td>2.68</td>
</tr>
<tr>
<td>Fine River</td>
<td>1543</td>
<td>2.72</td>
</tr>
<tr>
<td>Intermediate</td>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>Water</td>
<td>239</td>
<td>1.00</td>
</tr>
<tr>
<td>Air %</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3989</td>
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</tr>
</tbody>
</table>

- **Blue** = Input Data
- **Red** = Calculation
- **Yellow** = Output
- **Black** = Working
Proposed Mixture Proportioning Procedure

Check proportions
  • Check workability
  • Check air

  • Adjust paste volume

  • Check hardened properties
# Quality Monitoring

<table>
<thead>
<tr>
<th>Property</th>
<th>AASHTO Test Method</th>
<th>When Test Must be Conducted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air void system</td>
<td>Foam Drainage</td>
<td>Mixture design</td>
</tr>
<tr>
<td>Slump</td>
<td>Within 1” of design mix</td>
<td>T 119M/T 119</td>
</tr>
<tr>
<td>Unit weight</td>
<td>Within 3 pcf of design mix</td>
<td>T 121</td>
</tr>
<tr>
<td>Calorimetry</td>
<td>Adiacacl</td>
<td>Construction</td>
</tr>
<tr>
<td>Maturity</td>
<td>ASTM C 1074</td>
<td>Construction</td>
</tr>
<tr>
<td>Strength development</td>
<td>T 22</td>
<td>Construction</td>
</tr>
<tr>
<td>Resistivity Development</td>
<td>TP 95</td>
<td>Construction</td>
</tr>
</tbody>
</table>
Quality

- Saves money and heartburn
- Defines risk and responsibility
- Needs “good” tests
Closing

• Did you get what you thought you paid for?

• Did you measure what you really want?

• Concrete can last a long time…
Discussion...