Performance Engineered Mixtures

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Performance Engineered Mixtures

Engeneering – 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

- The mix
- What do we need?
- The test
- The spec
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…
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
Absolute Volume Approach

• Paste volume based on coarse aggregate size
• Coarse aggregate volume based on subtracting the fineness modulus (FM) of sand from a fudge factor
• Fill the remaining volume with sand
• Linear process
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)
I-96 Project - East Batch Plant - Mix 436513-2

MI DOT
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 = $V_{\text{voids}}$ (C29)
- Grey + Blue = $V_{\text{paste}}$
- Void ratio = $V_{\text{paste}} / V_{\text{voids}}$
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>
</tr>
</thead>
<tbody>
<tr>
<td>Void ratio</td>
<td>125</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>175</td>
<td></td>
</tr>
<tr>
<td>Cementitious</td>
<td>427</td>
<td>505</td>
</tr>
<tr>
<td></td>
<td>424</td>
<td>500</td>
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<tr>
<td></td>
<td>543</td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing the relationship between Vp/Vv and VKelly, In/Vis for Tarantula and 50/50 mixtures.](image)
# Proposed Mixture Proportioning Procedure

## Input aggregates

| 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>
</tr>
</thead>
<tbody>
<tr>
<td>100.0</td>
<td>64.3</td>
<td>35.7</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2'</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>
</tr>
<tr>
<td>1 1/2'</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>
</tr>
<tr>
<td>3/4'</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>
</tr>
<tr>
<td>1/2'</td>
<td>55.0</td>
<td>35.3</td>
<td>100.0</td>
<td>35.7</td>
<td>0.0</td>
<td>0.0</td>
<td>71.1</td>
<td>17.4</td>
</tr>
<tr>
<td>3/8'</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>
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<tr>
<td># 4</td>
<td>5.0</td>
<td>3.2</td>
<td>98.9</td>
<td>35.3</td>
<td>0.0</td>
<td>0.0</td>
<td>38.5</td>
<td>61.5</td>
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<tr>
<td># 8</td>
<td>0.2</td>
<td>0.1</td>
<td>92.4</td>
<td>33.0</td>
<td>0.0</td>
<td>0.0</td>
<td>33.1</td>
<td>66.9</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>
<td>0.0</td>
<td>0.0</td>
<td>27.8</td>
<td>72.2</td>
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<tr>
<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>
<td>0.1</td>
<td>0.1</td>
<td>11.0</td>
<td>3.9</td>
<td>0.0</td>
<td>0.0</td>
<td>4.0</td>
<td>96.0</td>
</tr>
<tr>
<td># 100</td>
<td>0.1</td>
<td>0.1</td>
<td>0.8</td>
<td>0.3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.4</td>
<td>99.6</td>
</tr>
<tr>
<td># 200</td>
<td>0.1</td>
<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>
</tr>
</tbody>
</table>

### Coarseness Factor

| Power 45 least difference | 0.0 | Tarnansia error | 0.0 |

### Workability Factor

| Power 45 error | 34.2 |

### 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></th>
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</thead>
<tbody>
<tr>
<td>Project</td>
<td>Gravel 1&quot;</td>
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<tr>
<td>Materials</td>
<td>Targets</td>
</tr>
<tr>
<td>Cement</td>
<td>Type I</td>
</tr>
<tr>
<td>SCM 1</td>
<td>F Ash</td>
</tr>
<tr>
<td>SCM 2</td>
<td>Slag</td>
</tr>
<tr>
<td>Coarse Agg</td>
<td>Gravel</td>
</tr>
<tr>
<td>Fine Agg</td>
<td>River</td>
</tr>
<tr>
<td>Intermediate</td>
<td>0</td>
</tr>
<tr>
<td>Water</td>
<td></td>
</tr>
<tr>
<td>Cementitious</td>
<td>428</td>
</tr>
<tr>
<td>w/cm</td>
<td>0.42</td>
</tr>
<tr>
<td>Air %</td>
<td>5.0</td>
</tr>
<tr>
<td>% SCM 1</td>
<td>20</td>
</tr>
<tr>
<td>% SCM 2</td>
<td>0</td>
</tr>
<tr>
<td>Voids in aggregate</td>
<td>25.3</td>
</tr>
<tr>
<td>Required Vp/Vv</td>
<td>125</td>
</tr>
<tr>
<td>Strength</td>
<td>4000 psi</td>
</tr>
<tr>
<td>RCP</td>
<td>1500 coulomb</td>
</tr>
<tr>
<td>Wenner</td>
<td>27 kΩ-cm</td>
</tr>
</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>
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<tr>
<td>Cement</td>
<td>531</td>
<td>3.15</td>
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<tr>
<td>SCM 1</td>
<td>133</td>
<td>2.65</td>
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<tr>
<td>SCM 2</td>
<td>0</td>
<td>1.00</td>
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<tr>
<td>Coarse Agg</td>
<td>1543</td>
<td>2.68</td>
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<tr>
<td>Fine Agg</td>
<td>1543</td>
<td>2.72</td>
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<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>
<td></td>
</tr>
</tbody>
</table>

Cementitious: 663 663 pcy
Volume of paste: 32.1 %
Volume of aggs: 67.9 %
Volume of voids: 27.06 18.4
v/v: 175 175.0
w/cm: 0.36 0.36
% SCM 1: 20 20 %
% SCM 2: 0 0 %
Mass aggs: 3087 3087 pcy
Proposed Mixture Proportioning Procedure

Check proportions
• Check workability
• Check air

• Adjust paste volume

• Check hardened properties
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
Saturated Freeze Thaw

• Prevention
  ✓ Reduce permeability
  ✓ Air
  ✓ Reduce water access

Relative Dynamic Modulus (N=6)
Typical Symptoms

- Shadowing
- Thin flakes
Drainage

- Water has to have a way out
- Or not get in
Salts

• Increase saturation
Chemical Attack

- Salts react with paste
  ✅ Calcium oxychloride
    - Causes paste to expand / separate from aggregate
Chemical Attack

• Salts react with paste
  ✓ Friedel’s Salt – Calcium-chloro-aluminate

Field Studies

• A Tale of Two Cores
  – Same slab – same joint
• Also found:
  • Significant chemical attack from deicers
Chemical Attack

- Salts react with paste
  - Ettringite
    - Accelerates water penetrating air bubbles
    - Saturation
Chemical Attack

- Salts react with paste
  - Reduce permeability (w/cm)
  - Good air
  - Must use (enough) SCMs
Chemical Attack

• Salts react with paste
  ✓ Keep the solutions away…
  ✓ Reduce permeability
  ✓ Use salts wisely
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

• SCM's
  ✓ 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

• 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)

![Graph showing hydration profile for different samples](image)
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

\[
y = 0.9891x + 219.01 \\
R^2 = 0.8997
\]

\[
y = 1.0227x + 299.05 \\
R^2 = 0.8114
\]
Test Methods

- Tests
  - Maturity – strength development up to 24 hours
Test Methods

• Tests
  • Resistivity – Potential Durability
  • Trending – Formation Factor…
Test Methods

- Sensors
  - Movement
  - Temperature
  - Moisture
  - Chemicals

Slowik

Ceylan
Guide Specification

- Add new thinking
- Take out some stuff
Performance

• What do we know how to measure now?
  ✓ Compressive strength
  ✓ Electrical resistivity
  ✓ Freeze-thaw resistance
  ✓ Shrinkage

• When do we test?
  ✓ Some at design stage
  ✓ Others for acceptance
Prescriptive

- Cementitious materials content
- Supplementary cementitious materials type and dosage
- Water to cementitious materials ratio
- Aggregates
- Workability
- Air void system
# Which One?

<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
## Quality Monitoring

<table>
<thead>
<tr>
<th>Property</th>
<th>AASHTO Test Method</th>
<th>When Test Must be Conducted</th>
</tr>
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<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>Adiocal</td>
<td>Construction</td>
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<tr>
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<td>ASTM C 1074</td>
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<td>Strength development</td>
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<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...