Development of Ternary OPC/FA/SF Binder System for Bridge Decks Concrete

Prof. Jan Olek (Purdue University)
Dr. Mateusz Radlinski (Exponent)
• Nearly half of 500,000 bridges in the U.S. are over 40 years old and thus require serious maintenance (Huang et al. 2004)

• Estimated Cost: $70-90 billion (Liu and Weyers 1998; Kirkpatrick 2002)

• Major Durability Problems
  - Reinforcement corrosion
  - Freeze-thaw damage
  - Shrinkage cracking
  - Salt scaling
• SCMs (fly ash, silica fume, GGBFS) introduced in part to address durability problems

• When used individually in binary binder systems, SCMs have some disadvantages...

• Ternary OPC/FA/SF binder systems exhibit properties superior to binary systems

• Performance commonly attributed to synergistic effects between FA and SF

• FA compensates for deficiencies of SF, and vice versa...
Literature Research

- Identified total of 50 technical papers reporting use of OPC/FA/SF mixtures
- In 10 papers OPC/FA/SF mixtures specifically considered for bridge decks
Scope of Evaluation

1. Synergistic Effects
2. Transport-Related Properties
3. Compressive Strength Development
4. Salt Scaling Resistance
5. Shrinkage and Resistance to Shrinkage Cracking
6. Sensitivity to Curing Conditions
7. Freeze-Thaw Resistance
8. Air-Void System Requirements
9. Optimum Fly Ash and Silica Fume Contents
10. Field Performance
Synergistic Effects

• Definition of Synergy
  “Interaction of two or more agents or forces so that their combined effect is greater than the sum of their individual effects”

• Objective
  Verify whether synergy exists, and if so, whether due to:
  1) Physical source (higher solid concentration/packing density)
  2) Chemical source (higher amount of hydration products)
Synergistic Effects

- 4 Mixtures Tested
  - OPC
  - 20FA
  - 5SF
  - 20FA/5SF

- Theoretical Values of Property for Ternary Mixture

\[ P_{\text{Theor.20FA/5SF}} = \]
\[ = P_{\text{OPC}} + \Delta P_{20FA} + \Delta P_{5SF} = \]
\[ = P_{20FA} + P_{5SF} - P_{\text{OPC}} \]
Synergistic Effects – Physical Source

- Solid Concentration (at constant \( \text{w/cm}_{\text{mass}} = 0.41 \)):

\[
\phi = \frac{V_c}{V}
\]

<table>
<thead>
<tr>
<th></th>
<th>OPC</th>
<th>20FA</th>
<th>5SF</th>
<th>20FA/5SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi )</td>
<td>0.468</td>
<td>0.485</td>
<td>0.477</td>
<td>0.490</td>
</tr>
</tbody>
</table>

- Volumetric Difference (“Hidden Effect”):

<table>
<thead>
<tr>
<th>V\text{solids per 100 cm}^3 \text{ of paste (cm}^3\text{)}</th>
<th>OPC</th>
<th>20FA</th>
<th>5SF</th>
<th>20FA/5SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/cm by mass</td>
<td>0.41</td>
<td>0.41</td>
<td>0.41</td>
<td>0.41</td>
</tr>
<tr>
<td>w/cm by volume</td>
<td>1.29</td>
<td>1.23</td>
<td>1.26</td>
<td>1.21</td>
</tr>
</tbody>
</table>

- Solid Concentration (at const. \( \text{w/cm}_{\text{vol.}} = 1.29 \)):

<table>
<thead>
<tr>
<th></th>
<th>OPC</th>
<th>20FA</th>
<th>5SF</th>
<th>20FA/5SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi )</td>
<td>0.468</td>
<td>0.473</td>
<td>0.473</td>
<td>0.473</td>
</tr>
</tbody>
</table>

Voids ratio \( \varepsilon = 1 - \phi \)

Wong and Kwan, 2008
Synergistic Effects
– Chemical Source

- Isothermal Calorimetry

- Thermogravimetric Analysis
Mixture Composition

- 4 Ternary Mixtures with FA (20% or 30%) and SF (5% or 7%)

- Mix Design Parameters:
  - Cement Content = 231 kg/m³
  - W/CM = 0.41
  - Target Air Content: 6.5% (±0.5%)
  - Target Slump: 150 mm (± 50 mm)

<table>
<thead>
<tr>
<th>Mix designation</th>
<th>20FA/5SF</th>
<th>20FA/7SF</th>
<th>30FA/5SF</th>
<th>30FA/7SF</th>
<th>SPEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water-cementitious materials ratio</td>
<td>0.41</td>
<td>0.41</td>
<td>0.41</td>
<td>0.41</td>
<td>0.38-0.42</td>
</tr>
<tr>
<td>Total cementitious materials (kg/m³)</td>
<td>308</td>
<td>317</td>
<td>356</td>
<td>367</td>
<td>-</td>
</tr>
<tr>
<td>Water (kg/m³)</td>
<td>127</td>
<td>130</td>
<td>146</td>
<td>151</td>
<td>-</td>
</tr>
<tr>
<td>Paste (%)</td>
<td>23</td>
<td>24</td>
<td>27</td>
<td>28</td>
<td>Max. 28</td>
</tr>
<tr>
<td>Cement (kg/m³)</td>
<td>231</td>
<td>231</td>
<td>231</td>
<td>231</td>
<td>Min. 231</td>
</tr>
<tr>
<td>Fly ash (kg/m³)</td>
<td>62</td>
<td>63</td>
<td>107</td>
<td>110</td>
<td>-</td>
</tr>
<tr>
<td>Fly ash (% by mass of binder)</td>
<td>20</td>
<td>20</td>
<td>30</td>
<td>30</td>
<td>20-30</td>
</tr>
<tr>
<td>Silica fume (kg/m³)</td>
<td>15</td>
<td>22</td>
<td>18</td>
<td>26</td>
<td>-</td>
</tr>
<tr>
<td>Silica fume (% by mass of binder)</td>
<td>5</td>
<td>5</td>
<td>7</td>
<td>7</td>
<td>5-7</td>
</tr>
<tr>
<td>Fine aggregate (SSD) (kg/m³)</td>
<td>746</td>
<td>738</td>
<td>706</td>
<td>696</td>
<td>-</td>
</tr>
<tr>
<td>Coarse aggregate (SSD) (kg/m³)</td>
<td>1116</td>
<td>1104</td>
<td>1055</td>
<td>1040</td>
<td>-</td>
</tr>
</tbody>
</table>
Transport-Related Properties - Objectives

- Evaluate Transport Properties of Ternary Concretes Using
  - Non-Steady Diffusion Test: **Bulk Diffusion** (ASTM C1556)
  - Migration-Based Tests: **RCP** (ASTM C1202) and **RMP** (AASHTO TP64)
  - Absorption-Type Tests: **Sorptivity** (ASTM C1585) and **Absorptivity**
Transport-Related Properties – Test Results

- RCP vs. time
- RMP vs. time
- Da vs. time
- Initial absorptivity (mm/s^1/2)
- Initial sorptivity (mm/s^1/2)
Effects of Initial Curing

4 Initial Curing Regimes

1. Air Drying
2. 7-day Curing Compound Application
3. 3-day Wet Burlap Curing
4. 7-day Wet Burlap Curing
Transport-Related Properties – Effect of Curing
Compressive Strength Development

- **20FA/5SF**
- **20FA/7SF**
- **30FA/5SF**
- **30FA/7SF**

- Moistured cured
- Air dry
- 7 days curing comp.
- 3 days burlap
- 7 days burlap
Scaling Test Results – Early Age

- ASTM C672 Method Used
- Testing Started at 14, 17 or 21 days
- Visual Inspection and Mass Loss Determined
Scaling Test Results – Late Age

• ASTM C672 Method Used

• Testing Started at 90 days

• Visual Inspection and Mass Loss Determined
Unrestrained (Free) Shrinkage

- **INDOT Class C**
  - Air drying
  - 7 days burlap

- **20FA/5SF**
  - Air drying
  - 3 days burlap
  - 7 days curing compound

- **20FA/7SF**
  - Air drying
  - 3 days burlap
  - 7 days curing compound

- **30FA/5SF**
  - Air drying
  - 3 days burlap
  - 7 days curing compound

- **30FA/7SF**
  - Air drying
  - 3 days burlap
  - 7 days curing compound
Unrestrained (Free) Shrinkage

- Free shrinkage of standard-cured specimens normalized by aggregate content of INDOT Class C mix

- Normalized free shrinkage of standard-cured specimens as a function of cement replacement level
Resistance to Shrinkage Cracking

- **Method Used**: 2 Rings per mix/curing condition

Tested:
- **30FA/7SF - var. curing**
  - Time (days): 0, 28, 56, 84, 112, 140, 168, 196
  - Restrained shrinkage strain (microstrains)

  - **Restrained shrinkage strain (microstrains)**
    - -60
    - -50
    - -40
    - -30
    - -20
    - -10
    - 0
    - 10

  - **Air dry (1)**
  - **Air dry (2)**
  - **3 days burlap (1)**
  - **3 days burlap (2)**
  - **7 days burlap (1)**
  - **7 days burlap (2)**
  - **7 days cur. comp. (1)**
  - **7 days cur. comp. (2)**

- **30FA/5SF - var. curing**
  - Time (days): 0, 28, 56, 84, 112, 140, 168, 196
  - Restrained shrinkage strain (microstrains)

  - **Restrained shrinkage strain (microstrains)**
    - -60
    - -50
    - -40
    - -30
    - -20
    - -10
    - 0
    - 10

  - **Air dry (1)**
  - **Air dry (2)**
  - **3 days burlap (1)**
  - **3 days burlap (2)**
  - **7 days burlap (1)**
  - **7 days burlap (2)**
  - **7 days cur. comp. (1)**
  - **7 days cur. comp. (2)**

- **20FA/7SF - var. curing**
  - Time (days): 0, 28, 56, 84, 112, 140, 168, 196
  - Restrained shrinkage strain (microstrains)

  - **Restrained shrinkage strain (microstrains)**
    - -60
    - -50
    - -40
    - -30
    - -20
    - -10
    - 0
    - 10

  - **Air dry (1)**
  - **Air dry (2)**
  - **3 days burlap (1)**
  - **3 days burlap (2)**
  - **7 days burlap (1)**
  - **7 days burlap (2)**
  - **7 days cur. comp. (1)**
  - **7 days cur. comp. (2)**

- **20FA/5SF - var. curing**
  - Time (days): 0, 28, 56, 84, 112, 140, 168, 196
  - Restrained shrinkage strain (microstrains)

  - **Restrained shrinkage strain (microstrains)**
    - -60
    - -50
    - -40
    - -30
    - -20
    - -10
    - 0
    - 10

  - **Air dry (1)**
  - **Air dry (2)**
  - **3 days burlap (1)**
  - **3 days burlap (2)**
  - **7 days burlap (1)**
  - **7 days burlap (2)**
  - **7 days cur. comp. (1)**
  - **7 days cur. comp. (2)**

- **Class C INDOT - var. curing**
  - Time (days): 0, 28, 56, 84, 112, 140, 168, 196
  - Restrained shrinkage strain (microstrains)

  - **Restrained shrinkage strain (microstrains)**
    - -60
    - -50
    - -40
    - -30
    - -20
    - -10
    - 0
    - 10

  - **Air dry (1)**
  - **Air dry (2)**
  - **7 days burlap (1)**
  - **7 days burlap (2)**

- **INDOT Class C**
Resistance to Shrinkage Cracking

Age of Concrete at Cracking

Assessing Probability of Cracking Based on Free Shrinkage

Increasing Resistance to Shrinkage Cracking

<table>
<thead>
<tr>
<th>7 Days Curing Compound</th>
<th>3 Days Wet Burlap</th>
<th>Air Drying</th>
<th>7 Days Wet Burlap</th>
</tr>
</thead>
<tbody>
<tr>
<td>20FA/5SF</td>
<td>33.94</td>
<td>182.134</td>
<td>200\infty</td>
</tr>
<tr>
<td>20FA/7SF</td>
<td>\infty</td>
<td>\infty</td>
<td>23.40</td>
</tr>
<tr>
<td>30FA/5SF</td>
<td>20\infty</td>
<td>25.25</td>
<td>16.35</td>
</tr>
<tr>
<td>30FA/7SF</td>
<td>23.29</td>
<td>\infty</td>
<td>53.151</td>
</tr>
<tr>
<td>INDOT Class C</td>
<td>(620; 1.00)</td>
<td>(510; 0.83)</td>
<td>(430; 0.64)</td>
</tr>
</tbody>
</table>

Increasing Paste Content

56-day Free Shrinkage (microstrains)

- Probability of Cracking

- 20FA/5SF
- 20FA/7SF
- 30FA/5SF
- 30FA/7SF
- INDOT Class C
Relative Curing Efficiency (RCE) was calculated for each concrete property with respect to 7-d burlap method (assumed as a standard):

\[ RCE_i = \left( \frac{P_i}{P_{REF}} \right)^j \times 100\% \]

- STR – Compressive Strength
- SCA – Scaling Resistance
- RCP – Resistance to Chloride-Ion Penetration
- ABS – Absorptivity
- SHR – Shrinkage

Properties Most Affected:

<table>
<thead>
<tr>
<th>Age</th>
<th>Early</th>
<th>Late</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Drying</td>
<td>ABS, RCP</td>
<td>SCA, ABS, RCP, STR</td>
</tr>
<tr>
<td>7-D Cur. Comp.</td>
<td>SHR</td>
<td>ABS, STR, SHR</td>
</tr>
<tr>
<td>3-D Burlap</td>
<td>SCA, RCP</td>
<td>ABS</td>
</tr>
</tbody>
</table>

Sensitivity to Curing Conditions

- Properties Most Affected:
Freeze-Thaw Resistance

- Fresh Concrete Air Content 5.9-7.3%
- ASTM C666 Proc. A Used

<table>
<thead>
<tr>
<th>Testing Age (days)</th>
<th>14</th>
<th>56</th>
</tr>
</thead>
<tbody>
<tr>
<td>20FA/5SF</td>
<td>56</td>
<td>64</td>
</tr>
<tr>
<td>20FA/7SF</td>
<td>67</td>
<td>46</td>
</tr>
<tr>
<td>30FA/5SF</td>
<td>51</td>
<td>40</td>
</tr>
<tr>
<td>30FA/7SF</td>
<td>67</td>
<td>35</td>
</tr>
<tr>
<td>CLASS C INDOT</td>
<td>92</td>
<td>-</td>
</tr>
</tbody>
</table>
Two Hypotheses for Low F-T Resistance of OPC/FA/SF Concrete:

1. Use of frost-susceptible aggregate
   - Surface pop-outs
   - Cracking
   - But the same aggregate used in plain cement mix!

2. Need for more rigorous air-void system parameters for F-T resistant OPC/FA/SF concrete
   - Refined pore structure due to fine SF particles
   - More air bubbles needed to intercept the pores (Pigeon et al. 1986)
Air-Void System Requirements – Testing Procedure

1. **Manual Air-Void System Analysis**
   Using Modified Point-Count Method (ASTM C 457)

2. **Automatic Air-Void System Analysis**
   Using Flatbed Scanner and Image Analysis Techniques

3. **Freeze-Thaw Resistance**
   (ASTM C 666 Procedure A);
   Durability Factor after 300 F-T Cycles Calculated
Air-Void System Requirements – Critical Parameters (Manual)
## Air-Void System Requirements – Critical Parameters (Comparison)

### Comparison of Zone Boundaries for Manual and Automatic Methods

<table>
<thead>
<tr>
<th>Boundary</th>
<th>Method</th>
<th>Air Content (%)</th>
<th>Void Frequency (voids/mm)</th>
<th>Specific Surface (mm²/mm³)</th>
<th>Spacing Factor (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone I – II</td>
<td>Manual</td>
<td>4.5</td>
<td>0.21</td>
<td>14.4</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>Automatic</td>
<td>4.7</td>
<td>0.24</td>
<td>15.8</td>
<td>0.26</td>
</tr>
<tr>
<td>Zone II – III</td>
<td>Manual</td>
<td>8.0</td>
<td>0.28</td>
<td>19.4</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Automatic</td>
<td>6.8</td>
<td>0.28</td>
<td>23.6</td>
<td>0.20</td>
</tr>
</tbody>
</table>

### Comparison of Critical Air-Void System Parameters

<table>
<thead>
<tr>
<th>F-T Durable Concrete</th>
<th>Air Content (%)</th>
<th>Void Frequency (voids/mm)</th>
<th>Specific Surface (mm²/mm³)</th>
<th>Spacing Factor (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ternary Concrete (Current Study) – Manual Point-Count Method</td>
<td>8.0</td>
<td>0.28</td>
<td>19</td>
<td>0.20</td>
</tr>
<tr>
<td>Ternary Concrete (Current Study) – Automatic Technique Using Scanner</td>
<td>6.8</td>
<td>0.28</td>
<td>(0.04-0.06)×Air Content</td>
<td>0.20</td>
</tr>
<tr>
<td>Recommended as per Hover (1994)</td>
<td>na</td>
<td>(0.04-0.06)×Air Content</td>
<td>16-24</td>
<td>0.20</td>
</tr>
<tr>
<td>Recommended as per ASTM C 457</td>
<td>na</td>
<td>0.32</td>
<td>na</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Optimum Fly Ash and Silica Fume Contents

- Relative Performance Ranking for Laboratory Ternary Mixtures (1 – Best, 4 – Worst)

<table>
<thead>
<tr>
<th>Mixture Parameter</th>
<th>20FA/5SF</th>
<th>20FA/7SF</th>
<th>30FA/5SF</th>
<th>30FA/7SF</th>
<th>INDOT Class C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive Strength</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Resistance to Chloride-Ion Penetration</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Rate of Absorption</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Scaling Resistance</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>n/a</td>
</tr>
<tr>
<td>Freeze-Thaw Resistance</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Resistance to Shrinkage Cracking</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Cost ($/m$^3$)</td>
<td>126</td>
<td>136</td>
<td>128</td>
<td>139</td>
<td>123</td>
</tr>
</tbody>
</table>
Field Performance – Pilot INDOT HPC Bridge Deck

- Bridge deck on **SR 23** over **US 20** near South Bend, IN (202 ft. span)
- Mixture similar to **20FA/5SF** from lab study
- Laboratory Trial Batch (**LTB**)
- Trial Batch Demonstration (**TBD**): Oct. 5, 2004
- Phase 1 Construction (**BDC-1**): Nov. 3, 2004
- Phase 2 Construction (**BDC-2**): May 17, 2005

**PHASE 1 (BDC-1)**

**PHASE 2 (BDC-2)**
Field Performance
– Concrete Properties

**BDC-1 Temperature**
- Ambient
- Bridge deck

**Compressive Strength (MPa)**
- BDC-1 - field exposure
- BDC-2 - field exposure
- BDC-2 - moist cured
- LTB - moist cured
- FTB - moist cured (152×305 mm)

**Free Shrinkage (microstrains)**
- BDC-1
- BDC-2
- LTB
- FTB

**RCP (Coulombs)**
- BDC-1 - field exposure
- BDC-1 - cores
- BDC-2 - field exposure
- BDC-2 - moist cured
- LTB - moist cured
- FTB - moist cured (152×305 mm)
Field Performance
– Bridge Inspection (Dec. 2006)

• Scaling Comparison: BDC-1 📢; BDC-2 🍀
Conclusions

- Synergistic effects exist in ternary system mostly at later age (>7 days) and can be attributed to both physical and chemical interactions.

- All ternary concretes studied exhibit excellent transport properties (very low chloride penetrability and water absorptivity).

- To ensure adequate strength and good resistance to salt scaling, freeze-thaw and shrinkage cracking 20%FA, 5% SF & paste<25%.

- Good quality curing (≥3 days burlap) is critical to satisfactory performance.

- Properties most affected by lack of curing of ternary concrete include RCP, absorptivity, scaling (30% FA) and long-term strength.

- Ternary mixtures with 30% FA are more sensitive to lack of curing than 20% FA (wrt. strength and RCP) but less sensitive wrt. shrinkage.
Conclusions

• Air-void system of OPC/FA/SF concrete does not seem to require lower spacing factor, as long as slump < 190 mm

• Flatbed scanner can be efficiently used in lieu of manual method to discern between F-T durable and F-T non-durable concrete

• Field performance of ternary concrete was generally satisfactory, except for high initial RCP and low initial scaling resistance
Acknowledgments

• Joint Transportation Research Program FHWA/IN/JTRP-2008/29-2, High-Performance Concrete Bridge Decks: A Fast-Track Implementation Study