Selected Review of Current Structural Concrete Research at SMO (Durability, Mitigation of Cracking, PC-Slag Durability, and Cement Replacement Projects)

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Presented at the 2017 FTBA Construction Conference in Orlando, Florida
February 3, 2017
Mitigation of Cracking in Florida Structural Concrete; UF BDV31-977-47; PI-Tia and PM-DeFord.

Development of Calcined Clays as Pozzolanic Additions in Portland Cement Concrete Mixtures; USF; PI-Zayed and PM DeFord.

Effects of Blast Furnace Slag Characteristics on Durability of Cementitious Systems for Florida Concrete Structures; USF BDV25-977-28; PI-Zayed and PM-DeFord.

Durability Evaluation of Ternary Mix Designs for Extremely Aggressive Exposures; UF PI-Riding and PM-DeFord.

Performance Improvement of High Early Strength (HES) Concrete for Pavement Replacement Slabs; USF BDV25-977-23; PI-Zayed and PM-DeFord.
Proposed for Next Fiscal Year

- Improving Portland Cement Concrete Durability by Optimizing Paste Content; UF; PI-Tia and PM-DeFord

- Recycled and Repurposed Materials for Use in Concrete; UF; PI-Ferraro and PM DeFord.
Current Important Issues for SMO

Improve durability of FDOT concrete.
- Determine the most reliable test methods for measuring the properties that substantially influence concrete durability
- Use these test methods to evaluate the durability of concrete containing binary, ternary, and higher combinations of cementitious materials
- Determine which cementitious combinations are appropriate for use in extremely aggressive exposure conditions

Reduce usage of portland cement.
- Increase replacement of cement with pozzolans and fillers (including use of portland-limestone cement)
- Reduce concrete paste content
Focus of SMO Research Program

- **Ways to Improve Concrete Durability**
  - **Improve Resistance to Chemical Attack**
    - Optimize compositions, use of SCMs
    - Reduce permeability
  - **Reduce Permeability**
    - Increase resistance of concrete to ingress of deleterious substances (chlorides and sulfates)
  - **Mitigate Cracking**
    - Thermal and shrinkage cracking increase the effective permeability of the concrete
Focus of SMO Research Program

- **Ways to Reduce Use of PC**
  - Reduce excess paste content in concrete
  - Use Portland Cement – Limestone blends (IL) in place of Type I/II
  - Use of fillers and intermediate-sized aggregates to reduce the volume of paste needed to produce adequate slump/placement

- **Ways to Insure Long-Term Availability of Fly Ash and Other (SCMs)**
  - Develop / approve alternative SCMs
What is Concrete Durability?

- **ACI CT-16**: durability is defined as “the ability of a material to resist weathering action, chemical attack, abrasion, and other conditions of service.”

- Concrete durability refers to the long-term ability of concrete to maintain an acceptable level of performance by withstanding degradation from exposure to the in-service environment.

- Unlike material properties such as compressive strength, which can be described quantitatively by a measured value, **assessment of durability involves a performance-based, qualitative, composite property assessment**, based on measurement of multiple component properties.
Characteristics of a Good Durability Test

- The test method must produce results that can be directly correlated to long-term concrete durability (need benchmarks for comparison)
  - Use macro and microscopic evaluation of field samples taken from structures of various ages and conditions to qualitatively rate their levels of durability ("calibrate" test)
- The test method must be sensitive enough to distinguish between the different levels of durability encountered in service
  - Evaluate test methods based on their ability to produce results consistent with the levels of durability determined from the macro and microscopic evaluations
Measureable Indicators of Durability

- Important Properties used to Identify Durable Concrete
  - Strength sufficient for intended use
  - High resistance to external chemical attack, particularly chlorides and sulfates
  - Low permeability
  - High resistance to shrinkage cracking
  - High resistance to thermal cracking
There are many tests that give an indication of concrete permeability.
Cracking Potential Measurement Methods

Cracking

- Shrinkage Cracking Potential
  - Restained Shrinkage
  - Autogenous Shrinkage

- Thermal Cracking Potential
  - Heat of Hydration of Concrete
  - Adiabatic/Semi-Adiabatic Calorimetry of Concrete
  - Thermal Expansion of Concrete
  - Thermal Conductivity of Concrete
Important Properties To Consider for Durable Structural Concrete

- **Sufficient Strength**
  - Needs to be adequate for the intended use
  - Too often excess cementitious material is used in an attempt to get a more rapid increase in strength to speed construction

- **Low Permeability**
  - Greatly increases the diffusion path length - want to severely limit intrusion of substances that can degrade the performance and reduce durability

- **Low Cracking Potential**
  - Cracking greatly reduces the diffusion path length, effectively reducing or eliminating the benefits of the protective concrete cover
Typical Methods for Reducing the Permeability of Concrete

- **Use of High-Range Water-Reducing Admixtures**
  - Reduces w/cm which reduces porosity.

- **Addition of SCMs**
  - Additional cementitious material produced by pozzolanic reaction deposits on void and capillary surfaces, restricting capillary transport.

- **Reduce Paste and Optimize Aggregate Grading**
  - Reduces interstitial volume that would be occupied by paste, which reduces porosity and increases tortuosity.

- **Internal Curing**
  - Fills pores and capillaries with additional cementitious phase provided by additional internal water supplied to continue “saturated” curing after external surfaces are essentially sealed.
Typical Methods for Reducing the Cracking Potential of Concrete

- **Shrinkage Reducing Admixtures**
  - Reduce consolidation pressure by reducing the surface tension that drives capillary pressure

- **SCMs (Required for nearly all FDOT concrete)**
  - Reduce thermal cracking tendency by reducing Heat of Hydration due to reduction of cement content.

- **Reduce Paste Volume and Optimize Aggregate Gradation**
  - Reducing paste volume reduces thermal and shrinkage cracking by reducing aggregate interstitial volume. 
  - Reduces cement => reduces shrinkage, reduces temperature rise, reduces expansion-contraction (CTE)
Typical Methods for Reducing the Cracking Potential of Concrete

- **Internal Curing**
  - Reduces shrinkage cracking tendency by delaying onset of self-desiccation - reduces autogenous shrinkage.

- **Polymeric Fibers**
  - Help resist cracking, but when cracking occurs, they bridge cracks so that stress is relieved by formation of many microcracks (low permeability) instead of a few large cracks (high permeability).
Constructability versus Quality

- Changes to cement and concrete are driven by constructability issues, not quality, often leading to a reduction in durability
  - Contractors demand quicker strength gain for quicker constructability
  - Concrete producers respond by one or more of the following - increasing cement content, increasing cement fineness, and lowering w/cm
  - These changes typically lead to higher shrinkage and thermal cracking tendencies without significant changes in strength or strength gain
Paste Contents of FDOT Structural Concrete

- **Average paste content** of FDOT structural concrete mixes – about 33 vol% of concrete
- **Average paste content needed** for adequate placeability – 26-28 vol%, depending on aggregate gradation/packing density
- This indicates that at least 15-20 percent of paste (20% of cementitious material) could be replaced with aggregate without affecting the workability of the concrete (some admixture compensation needed)
- Thus 15-20% of cement is potentially wasted.
Benefits of Reducing Paste Content

• Reducing the volume fraction of cement paste
  - Reduces shrinkage - hydration products occupy less volume than reactants – causes plastic shrinkage followed by autogenous shrinkage after final set. Less paste ⇒ less shrinkage.
  - Reduces heat evolution / thermal gradients – total heat is a function of cement content. Less paste ⇒ less heat evolved, lower maximum temperatures and thermal gradients.
  - Reduces cracking tendency due to lower shrinkage and thermal stresses
  - Reduces total porosity / permeability – reducing paste content reduces water content which reduces the porosity formed by evaporation and hydration
Effect of Paste Reduction on SC Slump

Slump and Type F Content vs Paste Content for Standard Concrete (SC) Mix

Paste Content (vol%) vs Slump (in) and Type F (oz/cwt)

- SC 100
- SC 95
- SC 90
- SC 85
- SC 80

Paste Content: 33.3%, 32.6%, 31.3%, 29.3%, 27.5%

Slump: Decreases as paste content decreases

Type F Content: Increases as paste content decreases

Florida Department of Transportation
Effect of Paste Reduction on OAG Slump

Slump and Type F Content vs Paste Content for Concrete with Optimized Aggregate Gradation (OAG)

- OAG 100
- OAG 95
- OAG 90
- OAG 85
- OAG 80
- OAG 75
- OAG 70

Type F (oz/cwt)

- Paste Content (Vol%):
  - 33.3%
  - 32.6%
  - 31.3%
  - 29.3%
  - 27.5%
  - 25.6%
  - 23.7%

Slump (in)
### Effect of Paste Reduction on Properties

#### Class IV Concrete Mix Design

<table>
<thead>
<tr>
<th></th>
<th>Control Mix 2</th>
<th>Mix 2-OAG - No Paste Reduction</th>
<th>Mix 2-OAG - 15% Paste Reduction</th>
<th>Mix2-OAG - 25% Paste Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CM</strong></td>
<td>690 lb</td>
<td>690 lb</td>
<td>587 lb</td>
<td>518 lb</td>
</tr>
<tr>
<td><strong>Paste w/o air</strong></td>
<td>30.03 %</td>
<td>30.04 %</td>
<td>25.55 %</td>
<td>22.52 %</td>
</tr>
<tr>
<td><strong>Paste w/ air</strong></td>
<td>32.23 %</td>
<td>32.74 %</td>
<td>27.95 %</td>
<td>26.22 %</td>
</tr>
<tr>
<td><strong>28-day compressive strength</strong></td>
<td>8160 psi</td>
<td>7790 psi</td>
<td>8510 psi</td>
<td>8010 psi</td>
</tr>
<tr>
<td><strong>28-day flexural strength</strong></td>
<td>832 psi</td>
<td>832 psi</td>
<td>897 psi</td>
<td>840 psi</td>
</tr>
<tr>
<td><strong>28-day splitting tensile strength</strong></td>
<td>595 psi</td>
<td>520 psi</td>
<td>500 psi</td>
<td>600 psi</td>
</tr>
<tr>
<td><strong>28-day MOE</strong></td>
<td>5.25 Mpsi</td>
<td>5.05 Mpsi</td>
<td>5.50 Mpsi</td>
<td>5.85 Mpsi</td>
</tr>
<tr>
<td><strong>28-day CTE</strong></td>
<td>8.00E-06 in/in/°C</td>
<td>8.10E-06 in/in/°C</td>
<td>8.40E-06 in/in/°C</td>
<td>8.00E-06 in/in/°C</td>
</tr>
<tr>
<td><strong>28-day RCPT</strong></td>
<td>3533 C</td>
<td>3152 C</td>
<td>2630 C</td>
<td>2722 C</td>
</tr>
<tr>
<td><strong>28-day SR</strong></td>
<td>10.6 kΩ-cm</td>
<td>10.4 kΩ-cm</td>
<td>13.3 kΩ-cm</td>
<td>12.3 kΩ-cm</td>
</tr>
<tr>
<td><strong>Restrained Ring Time-To-Crack</strong></td>
<td>29 days</td>
<td>54 days</td>
<td>66 days</td>
<td>70 days</td>
</tr>
</tbody>
</table>

**Strength**: Comparable  
**CTE**: Comparable  
**Permeability**: Reduced  
**Cracking Tendency**: Reduced
Reduction of Paste Content Without Reducing Strength of Concrete (SC)

7-Day and 28-Day Compressive Strengths for SC
Reduction of Paste Content Without Reducing Strength of Concrete (OAG)

Can reduce paste volume by 20-25% of most FDOT concrete mix designs

Data from BDV31-977-47 Mitigation of Cracking in Florida Structural Concrete
Effect of Paste Reduction on Strength

Compressive and Flexural Strengths

- Compressive Strength
- Flexural Strength

Control Mix 2 | Mix 2-OAG - No Paste Reduction | Mix 2-OAG - 15% Paste Reduction | Mix 2-OAG - 25% Paste Reduction

Strengths:
- Compressive: 832 psi, 8160 psi, 897 psi, 840 psi
- Flexural: 832 psi, 7790 psi, 8510 psi, 8010 psi
Effect of Paste Reduction on “Permeability”

RCPT (Coulombs) and SR (kΩ-cm)

- Control Mix 2
- Mix 2-OAG - No Paste Reduction
- Mix 2-OAG - 15% Paste Reduction
- Mix 2-OAG - 25% Paste Reduction

Values:
- 3533 C
- 10.6 kΩ-cm
- 3152 C
- 10.4 kΩ-cm
- 13.3 kΩ-cm
- 2630 C
- 12.3 kΩ-cm
- 2722 C
### Reduction of Paste Content Without Reducing Strength or Increasing Set of HES Concrete

**Cylinder Crushing Strength (psi)**

<table>
<thead>
<tr>
<th>Percentage of Original Paste Volume</th>
<th>2550 psi @ 6 h</th>
<th>2050 psi @ 6 h</th>
<th>2000 psi @ 6 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>75.5% Paste w/c = 0.34</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>79.4% Paste w/c = 0.38</td>
<td>2000 psi @ 6 h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100% Paste w/c = 0.38</td>
<td></td>
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</tbody>
</table>

**High Early Strength (Accelerated) Concrete Mixes with Optimized Aggregate Gradation (#57 and #89)**

- **200 lb Reduction in cement content without loss of strength or delay in set**
- **500 psi increase in strength at 700 lb OPC by reducing w/cm from 0.38 to 0.34**

Data from BDV25-977-28 Effects of Blast Furnace Slag Characteristics on Durability of Cementitious Systems for Florida Concrete Structures
Effect of Paste Reduction on Restrained Shrinkage

Restrained Shrinkage - Days to Crack

- Control Mix 2
- Mix 2-OAG - No Paste Reduction
- Mix 2-OAG - 15% Paste Reduction
- Mix 2-OAG - 25% Paste Reduction
Mass Concrete Construction Issue: Rapid Temperature Rise and Very Slow Cooling

Peak of 179°F at 54 hours (50% slag)
5 days above 170°F
10 days above 160°F
Still > 50°F above ambient at 14 days
Mass Concrete Construction Issue: Rapid Temperature Rise and Very Slow Cooling

Peak of 176°F at 35 hours (60% slag)
66 hours above 170°F
120 hours above 160°F
> 11 days to reach < 50°F above ambient
Availability of Fly Ash for FDOT Concrete

**Current Situation in Florida**

- **Fly ash is required** in all DOT concrete mix designs and is a standard component of Ternary mixes.
- **Increasing demand** for fly ash.
- **Decreasing supply** of concrete-grade fly ash.
- **Local shortages** - SMO has issued seven Material Bulletins in the last three years concerning lack of fly ash availability in regions of Florida. Forecasts by Balmoral and AASHTO Fly Ash Task Force indicate that trend will continue
Potential Replacements for Fly Ash in FDOT Concrete

The following natural and recycled materials are available in Florida and development of these resources would help solve local supply shortages of SCMs and create jobs in Florida:

- Clays containing kaolin
- Recycled waste glass
- Sugarcane bagasse ash
- Glass sand (high purity silica sand)
- Commercial silica sand
Questions?