SELF CONSOLIDATING CONCRETE

Effect of Mix Design on Design and Performance of Precast/Prestressed Girders

Rigoberto Burgueño, Ph.D.
Assistant Professor of Structural Engineering

Department of Civil and Environmental Engineering
Michigan State University

BACKGROUND & MOTIVATION

- **Self-Consolidating Concrete (SCC):** a specially proportioned concrete that can flow easily into forms and around steel reinforcement without segregation.

- The benefits of SCC in reduced labor needs, increased rate of production and safety, and lower noise levels have generated great interest from the precast concrete industry.

- Considerable development in SCC technology has been made through the past decades particularly in Japan, Canada, and Europe, and its applications have become widespread.

SCC FRESH PROPERTY BEHAVIOR

- [Image of SCC fresh property behavior]
BACKGROUND & MOTIVATION

- **Self-Consolidating Concrete (SCC):** A specially proportioned concrete that can flow easily into forms and around steel reinforcement without segregation.

- The benefits of SCC include reduced labor needs, increased rate of production and safety, and lower noise levels, which have generated great interest from the precast concrete industry.

- Considerable development in SCC technology has been made through the past decades, particularly in Japan, Canada, and Europe, and its applications have become widespread.

SCC BENEFITS

- Use of SCC in the US has been limited due to concerns about design and construction issues that are perceived to influence the structural integrity.

- In spite of rapid developments in SCC technology, most of the work has focused on mix design development, rheology characterization, mechanical properties, and in-situ verification.

- Very limited information exists on issues related to structural design and performance.
SCC PROPORTIONING & BEHAVIOR

- Fluidity/Deformability
  - A. Increase paste deformability
    - use of HRWR
    - balanced w/c ratio
  - B. Reduce inter-particle friction
    - low coarse aggregate volume
    - use of continuous graded powder

- Key Flow/Low Blockage
  - A. Enhance cohesiveness
    - low w/c ratio
    - use of VMA
  - B. Compatible flow space and aggregate size
    - low coarse aggregate volume
    - use of high area powder

- Homogeneity/Stability
  - A. Reduce solids separation
    - limit aggregate content
    - reduce max. size aggregate
    - increase cohesion & viscosity
    - low w/c ratio
    - use of VMA
  - B. Minimize bleeding
    - low w/c ratio
    - use of high area powder
    - increase VMA

SCC MIX DESIGN DEVELOPMENT

- No commonly accepted procedure to proportion SCC.

- Methods are bounded by two approaches:
  1) High w/c ratios (e.g., 0.45) and use of HRWR and VMA.
  2) Lower w/c ratios (e.g., 0.33), high use of HRWR and no VMA

- Approach: Develop characteristic bounding SCC mix designs.

<table>
<thead>
<tr>
<th>Mix Design</th>
<th>w/c</th>
<th>HRWR</th>
<th>VMA</th>
<th>CAC</th>
<th>S/Pt</th>
<th>EA</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCC-1</td>
<td>0.35</td>
<td>+</td>
<td>–</td>
<td>less</td>
<td>more</td>
<td>+</td>
</tr>
<tr>
<td>SCC-2</td>
<td>0.40</td>
<td>+</td>
<td>–/–</td>
<td>less</td>
<td>more</td>
<td>+</td>
</tr>
<tr>
<td>SCC-3</td>
<td>0.45</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>NCC</td>
<td>0.40</td>
<td>+</td>
<td>–</td>
<td>more</td>
<td>less</td>
<td>–</td>
</tr>
</tbody>
</table>

MSU SCC RESEARCH – Part 1

- PCI Daniel P. Jenny Research Fellowship on “Structural Performance of PC/PS Girder Bridges using SCC”

- Objective:
  - To investigate the transfer and flexural bond length performance of prestressing strands in pc/ps bridge girders built using SCC to provide guidance on the construction and design of these elements with SCC.
MIX DESIGNS – PCI Project

<table>
<thead>
<tr>
<th>Constituents (lbs)</th>
<th>SCC1</th>
<th>SCC2A</th>
<th>SCC2B</th>
<th>SCC3</th>
<th>NCCB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>700</td>
<td>700</td>
<td>700</td>
<td>700</td>
<td>700</td>
</tr>
<tr>
<td>Sand</td>
<td>2 NS</td>
<td>1519</td>
<td>1426</td>
<td>1426</td>
<td>1273</td>
</tr>
<tr>
<td>Gravel</td>
<td>6 AA</td>
<td>1380</td>
<td>1380</td>
<td>1380</td>
<td>1435</td>
</tr>
<tr>
<td>Water (design)</td>
<td>245</td>
<td>280</td>
<td>280</td>
<td>315</td>
<td>280</td>
</tr>
<tr>
<td>Air</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>w/c Ratio</td>
<td>0.35</td>
<td>0.4</td>
<td>0.45</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Air Entraining</td>
<td>MB-AE™ 90</td>
<td>0.5</td>
<td>0.21</td>
<td>0.5</td>
<td>9.08</td>
</tr>
<tr>
<td>HRWR</td>
<td>Glenium® 3200 HES</td>
<td>6.29</td>
<td>8.49</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>VMA</td>
<td>Rheomac® VMA 358</td>
<td>0</td>
<td>5.94</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>Set Retardant</td>
<td>DELVO® Stabilizer</td>
<td>6.14</td>
<td>0</td>
<td>6.09</td>
<td>6</td>
</tr>
</tbody>
</table>

**Inverted Slump Flow and VSI Test**

<table>
<thead>
<tr>
<th>Slump Spread Flow</th>
<th>Visual Stability Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCC1</td>
<td>27°</td>
</tr>
<tr>
<td>SCC2a</td>
<td>25°</td>
</tr>
<tr>
<td>SCC2b</td>
<td>24.5°</td>
</tr>
<tr>
<td>SCC3</td>
<td>27°</td>
</tr>
</tbody>
</table>

Concrete had very low flowability

**J-Ring Test**

<table>
<thead>
<tr>
<th>J-Ring Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCC1</td>
</tr>
<tr>
<td>SCC2a</td>
</tr>
<tr>
<td>SCC2b</td>
</tr>
<tr>
<td>SCC3</td>
</tr>
</tbody>
</table>
**FRESH PROPERTIES – PCI Project**

**L-Box Test**

<table>
<thead>
<tr>
<th>Blocking Ratio</th>
<th>t1, t2 (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCC1</td>
<td>0.80</td>
</tr>
<tr>
<td>SCC2a</td>
<td>0.86</td>
</tr>
<tr>
<td>SCC2b</td>
<td>0.76</td>
</tr>
<tr>
<td>SCC3</td>
<td>0.69a</td>
</tr>
</tbody>
</table>

*Test was done too late

**CONSTITUTIVE PROPERTIES – f’c**

**CONSTITUTIVE PROPERTIES – f_{ct}**
CONSTITUTIVE PROPERTIES – $E_c$

TRANSFER AND DEVELOPMENT
LENGTH OF PRESTRESSING STRANDS

2 beams per concrete mix → 4 flexural bond tests per mix.
2 1/2-in. diameter strands - Stressed at ~ 0.75 $f_u$
38 ft in length.

Cross Section:
- 3 SCC mix designs that bound mix current design approaches
- 1 normally consolidated concrete (NCC) mix as a control mix
- SCC mix performance was to be evaluated

PRODUCTION PLAN
Casting Bed and Stressing Operation

Casting Operation with SCC Mix

Formwork Removal and Instrumentation
**Prestress Release Operation**

**TRANSFER LENGTH EVALUATION**

**Strand Draw-in Measurements**
Average Strain Profile for SCC1 Beams

Transfer Length Evaluation – PCI Phase 1

Transfer Length Evaluation – PCI Phase 2
Transfer Length Evaluation – Summary

<table>
<thead>
<tr>
<th>MIX TYPE</th>
<th>NCC</th>
<th>SCC1</th>
<th>SCC2</th>
<th>SCC3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer length (in.)</td>
<td>0</td>
<td>5</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Transfer length (mm)</td>
<td>0</td>
<td>100</td>
<td>200</td>
<td>300</td>
</tr>
</tbody>
</table>

Average ACI L₀ = 760.98 mm (29.96 in.)

DEVELOPMENT LENGTH EVALUATION

Development Length Test Setup
### Failure Modes

**Flexure Failure**

**Bond-Slip/Shear Failure**

### Typical Response with Flexure/Bond Failure

**Displacement at the section (in.)**

<table>
<thead>
<tr>
<th>Moment (kip-ft)</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement (mm)</td>
<td>0</td>
<td>25</td>
<td>50</td>
<td>75</td>
<td>100</td>
<td>125</td>
<td>150</td>
<td>175</td>
<td>200</td>
<td>225</td>
</tr>
</tbody>
</table>

**Lda = 103.0 in.**

**Mn = 116.87 kN-m (86.20 k-ft)**

**Slip Onset**

**Mn = 3.500 mm (0.137 in.)**

### Development Length Test Results – Phase 1

<table>
<thead>
<tr>
<th>ACI - 318</th>
<th>$M_m$</th>
<th>$L_{d, ACI}$</th>
<th>$L_{d, exp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCC1</td>
<td>1.06</td>
<td>1.07</td>
<td>1.03</td>
</tr>
<tr>
<td>SCC2A</td>
<td>1.11</td>
<td>1.09</td>
<td>1.04</td>
</tr>
<tr>
<td>SCC2B</td>
<td>1.01</td>
<td>1.21</td>
<td>1.17</td>
</tr>
<tr>
<td>SCC3</td>
<td>1.09</td>
<td>1.79</td>
<td>1.42</td>
</tr>
<tr>
<td>NCCB</td>
<td>1.04</td>
<td>1.06</td>
<td>0.97</td>
</tr>
</tbody>
</table>
### Development Length Test Results – Phase 2

<table>
<thead>
<tr>
<th></th>
<th>ACI - 318</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M_{\text{exp}}$</td>
</tr>
<tr>
<td>SCC1</td>
<td>1.06</td>
</tr>
<tr>
<td>SCC2</td>
<td>1.02</td>
</tr>
<tr>
<td>SCC3</td>
<td>1.05</td>
</tr>
<tr>
<td>NCC</td>
<td>1.11</td>
</tr>
</tbody>
</table>

### CONCLUSIONS – Part 1: PCI Project

- The presented studies are serving as an evaluation of SCC mix designs on the structural performance of precast SCC elements.
- SCC mix designs with moderate w/c ratios and moderate use of HRWR and VMA behave closer to NCC mixes without any chemical admixtures.
- Transfer lengths determined by draw-in and concrete strain measurements indicate that the ACI equation applies to SCC.
- Results from flexural tests indicate that development lengths for SCC mixes were slightly longer than code predicted values.

- The much longer development lengths found for SCC during the PCI Phase-1 project were verified to be due to poor strand quality.
- Development length tests using a pre-qualified strand, known to have very good properties, indicated that SCC mix designs do affect the flexural bond mechanism of prestressing strands but in a slight manner. A more definite position by the research team is under consideration.
- SCC mix proportioning seems to have different effects on the associated bond mechanisms controlling transfer and flexural bond length.
MDOT/FHWA IBRC Project: “Experimental Evaluation and Field-Monitoring of Bridge Precast/Prestressed Box-Girders made from Self-Compacting-Concrete”

Objective:
- To implement SCC in the precast/prestressed box beams of a demonstration bridge and to evaluate their short- and long-term performance against the behavior of beams from normally consolidated concrete.

MSU SCC RESEARCH – Part 2

M-50/US-127 Bridge Over the Grand River

Elevation View

Plan View

Bridge Deck

APPRAOCH

- Consider 3 SCC mix designs that bound current design approaches.
- Consider 1 normally consolidated concrete (NCC) mix as a control mix.
- The short-term flexure and shear performance of the SCC beams should be verified to be equal or better than that of the NCC beams through full-scale testing.
- The long-term performance of the SCC beams in comparison to the NCC beams to be continuously monitored for a year (or more?).
BEAM PRODUCTION

- 3 NCC and 3 SCC (one for each mix design) beams for demonstration bridge
- 2 NCC and 6 SCC (two of each mix design) for experimental evaluation
- 3 reserve NCC beams for bridge placement in case of unsatisfactory SCC performance
- Total: 17 Beams, 8 NCC and 9 SCC

MIX DESIGNS – IBRC Project

<table>
<thead>
<tr>
<th>Constituents (lbs)</th>
<th>Type</th>
<th>SCC1</th>
<th>SCC2</th>
<th>SCC3</th>
<th>SCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>Type-III</td>
<td>700</td>
<td>700</td>
<td>700</td>
<td>700</td>
</tr>
<tr>
<td>Sand</td>
<td>2 NS</td>
<td>1,591</td>
<td>1,513</td>
<td>1,320</td>
<td>1,277</td>
</tr>
<tr>
<td>Gravel</td>
<td>6 AA</td>
<td>1,350</td>
<td>1,350</td>
<td>1,450</td>
<td>1,600</td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td>256</td>
<td>285</td>
<td>320</td>
<td>280</td>
</tr>
<tr>
<td>Air (design)</td>
<td></td>
<td>0.37</td>
<td>0.41</td>
<td>0.46</td>
<td>0.40</td>
</tr>
<tr>
<td>Admixtures (oz/cwt)</td>
<td></td>
<td>54.1</td>
<td>32.9</td>
<td>47.7</td>
<td>44.4</td>
</tr>
<tr>
<td>Air Entraining</td>
<td>MBAE90</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>HRWR</td>
<td>Glenium® 3400</td>
<td>15</td>
<td>12</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>VMA</td>
<td>Rheomix® VMA</td>
<td>1</td>
<td>2</td>
<td>6</td>
<td>0</td>
</tr>
</tbody>
</table>

MIX DESIGN EVALUATION

- Strand Bond Evaluation
- Mock-up Production
- Fresh Property Evaluation
**BEAM CROSS SECTION**

16 Prestressing Strands
0.6" diameter

5 #4 Bars spaced at 6"

**BEAM PRODUCTION**

*NCC Beam Production*
- Cast in two operations
- Increased labor and time

*SCC Beam Production*
- Cast in one operation
- Reduced labor and time

**EXPERIMENTAL EVALUATION**
EXPERIMENTAL APPROACH

• Experimental evaluation was conducted at MSU’s Civil Infrastructure Laboratory

• Two test beams were cast for each concrete
  – One was to be evaluated for flexural response
    • Four total tests
  – One was to be evaluated for shear response
    • Four total tests

FLEXURAL EVALUATION

FLEXURAL TEST SETUP
FLEXURAL FAILURE MODE

FLEXURE TEST RESULTS

FLEXURE TEST RESULTS
### Achieved Flexural Capacities

<table>
<thead>
<tr>
<th></th>
<th>Maximum Total Moment (kip-ft)</th>
<th>Design Moment [AASHTO]* (kip-ft)</th>
<th>Actual to Design Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCC</td>
<td>1,649</td>
<td>1,499</td>
<td>1.10</td>
</tr>
<tr>
<td>SCC1</td>
<td>1,628</td>
<td>1,499</td>
<td>1.09</td>
</tr>
<tr>
<td>SCC2</td>
<td>1,593</td>
<td>1,499</td>
<td>1.06</td>
</tr>
<tr>
<td>SCC3</td>
<td>1,590</td>
<td>1,499</td>
<td>1.06</td>
</tr>
</tbody>
</table>

* According to AASHTO Standard Specifications – 17th Ed.

### Shear Evaluation

#### Shear Test Setup

- **Reaction Frame**
- **Actuator**
- **Shear Deformation Panel**
- **Support Block**
- **Reaction Floor**

- **NCC:** $L_v = 11$ ft
- **SCC:** $L_v = 9$ ft

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SHEAR FAILURE MODE

SHEAR TEST RESULTS

For all SCC Beams: \( L_v = 9 \) ft
For NCC Beam: \( L_v = 11 \) ft

AASHTO LRFD 2nd Ed.
Design Nominal Capacity
\[ \text{[Lv=9 ft]} \]

AASHTO LRFD 2nd Ed.
Design Nominal Capacity
\[ \text{[Lv=11 ft]} \]

Note: AASHTO 17th Ed.: 176 kip
Design Nominal Capacity

For all SCC Beams: \( L_v = 9 \) ft
For NCC Beam: \( L_v = 11 \) ft

Note: Design Nominal Capacity: 1546 kip-ft
AASHTO 17th Ed.
**SHEAR TEST RESULTS**

![Graph showing shear force vs. average shear strain]

**ACHIEVED SHEAR CAPACITIES**

<table>
<thead>
<tr>
<th>Material</th>
<th>Maximum Total Shear (kip)</th>
<th>Design Shear [AASHTO] (kip)</th>
<th>Actual to Design Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCC</td>
<td>128</td>
<td>116</td>
<td>1.11</td>
</tr>
<tr>
<td>SCC1</td>
<td>159</td>
<td>130</td>
<td>1.22</td>
</tr>
<tr>
<td>SCC2</td>
<td>146</td>
<td>130</td>
<td>1.12</td>
</tr>
<tr>
<td>SCC3</td>
<td>140</td>
<td>130</td>
<td>1.08</td>
</tr>
</tbody>
</table>

* According to AASHTO-LRFD Simplified Section Analysis Method

**BRIDGE CONSTRUCTION**

Beams placed: 9/15/05  
Open to traffic: Late October
FIELD MONITORING

Instruments per Girder:
- 8 Vibrating Wire Strain Gages
- 8 Thermocouples

System deployed: 12/20/05

CONCLUSIONS – Part 2: IBRC Project

- All beams exceeded design capacities and were implemented in the demonstration bridge.
- The capacities of the NCC beams were slightly higher than those of the SCC beams.
- The different SCC mix designs were seen to have an effect on flexural displacements as well as in the shear post-cracking behavior.
- The field-monitoring program is underway and an automated data reduction program with potential web broadcast is under development.

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