NCHRP Research Report 819: Self-Consolidating Concrete for Cast-in-Place Bridge Components

NCHRP Project 18-16
NCHRP is a State-Driven Program

- Sponsored by individual state DOTs who
  - Suggest research of national interest
  - Serve on oversight panels that guide the research.
- Administered by TRB in cooperation with the Federal Highway Administration.
Practical, ready-to-use results

- Applied research aimed at state DOT practitioners
- Often become AASHTO standards, specifications, guides, syntheses
- Can be applied in planning, design, construction, operations, maintenance, safety, environment
Previous NCHRP Publication Related to Self-Consolidating Concrete

- NCHRP Report 628: Self-Consolidating Concrete for Precast, Prestressed Concrete Bridge Elements

You can learn more about this publication by visiting www.trb.org
Added Considerations for Cast-in-Place Self-Consolidating Concrete

- Off-site, Third-Part Batching and Transit
- Constructability
- Material Performance/Properties in non-Prestressed Applications
Today’s Speaker

- Professor George Morcous
  University of Nebraska-Lincoln
SELF-CONSOLIDATING CONCRETE FOR CAST-IN-PLACE BRIDGE COMPONENTS

*NCHRP Project 18-16 (Report 819)*

*George Morcous, Ph.D., PE*

Professor, Durham School of Architectural Engineering and Construction

University of Nebraska- Lincoln

Omaha, NE

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Acknowledgments

NCHRP Staff
◦ Amir N. Hanna

Iowa State University (ISU)
◦ Kejin Wang
◦ Peter Taylor

Consultant
◦ Surendra P. Shah (NWU)

Graduate Students
◦ Micheal Asaad
◦ Xuhao Wang

Project 18-16 Panel
Donald J. Janssen, Seattle, WA (Chair)
Teck L. Chua, Vulcan Materials Company, Herndon, VA
Jugesh Kapur, Burns and McDonnell, Bismarck, ND
Kristin L. Langer, Pennsylvania DOT, Harrisburg, PA
Madhwesh Raghavendrachar, California DOT, Sacramento, CA
Anton K. Schindler, Auburn University, Auburn, AL
Brett S. Trautman, Missouri DOT, Jefferson City, MO
Susan N. Lane, FHWA Liaison
Frederick Hejl, TRB Liaison
M. Myint Lwin, Olympia, WA
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1. Definition
2. Problem Statement
3. Research Objectives and Scope
4. Research Approach (chapter 1)
5. Research Results (chapter 2)
6. Conclusions (chapter 3)
Definition

“SCC is a specially proportioned hydraulic cement concrete that enables fresh concrete to flow easily into the forms and around steel reinforcement without segregation and without any mechanical consolidation” (NCHRP 819)

Key workability properties of SCC:

- Filling Ability
- Passing Ability
- Stability
Problem Statement

• SCC has limited use in cast-in-place (CIP) bridge construction due to:
  – Lack of design specifications
  – Lack of construction guidelines
  – Concerns about design and construction issues affecting structural integrity
Problem Statement

- The use of SCC in precast/prestressed concrete bridge components has been growing in US since early 2000.

- Several studies focused on the use of SCC in the controlled condition of precast/prestressed concrete plants.

- Cast-in-place bridge components differ with respect to:
  - Compressive strength (4 – 8 ksi)
  - Constituent materials (aggregate type, NMSA, SCM/filler, w/cm, etc.)
  - Component geometric characteristics
  - Conditions of transporting, placing, and curing
  - Properties, such as bond, time of setting, workability retention, formwork pressure, etc.
Research Objectives and Scope

OBJECTIVES:

1. Develop guidelines for the use of SCC in CIP bridge components
2. Recommend changes to AASHTO LRFD Bridge Design and Construction Specifications

SCOPE:

- Project focused on bridge substructure and superstructure components
- Bridge deck, approach slab, and drilled shafts were not considered.
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1. Definition
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Research Approach

1- Literature Review
   ◦ NCHRP 628
   ◦ ACI 237R-07 ETS Document
   ◦ PCI TR-6-15 Guidelines for the Use of SCC in Precast/Prestressed Concrete
   ◦ European and Japanese Guidelines and Recommendations
   ◦ RILEM State of the Art Report (228-MPS-14)
   ◦ State DOT Sponsored Research Projects
   ◦ Published Research Articles

Outcome:
   ◦ SCC properties relevant to design and construction of CIP components
Research Approach

2- Surveys:

- NDDOT Project Survey (Mamaghani, et al., 2010)
- National Concrete Consortium (NCC) Survey

Outcomes:

- SCC Applications
- Constituent Materials
- Mix Proportioning
- Performance Requirements
## Research Approach

### Coarse Aggregate

<table>
<thead>
<tr>
<th>Type</th>
<th>NMSA (in.)</th>
<th>SCC Mixtures</th>
<th>CVC Mixtures</th>
<th>Number of Mixtures</th>
</tr>
</thead>
</table>
### Research Approach

#### 3- Workability Targets

<table>
<thead>
<tr>
<th>Workability Property</th>
<th>Class</th>
<th>Value/Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Filling Ability (FA)</strong></td>
<td>FA1</td>
<td>22 in. ≤ Slump Flow &lt; 26 in.</td>
</tr>
<tr>
<td></td>
<td>FA2</td>
<td>26 in. ≤ Slump Flow ≤ 30 in.</td>
</tr>
</tbody>
</table>
| **Passing Ability (PA)** | PA1   | 80% > Filling Capacity ≥ 70%  
2 in. < J-Ring ΔD ≤ 4 in.  
0.6 in. < J-Ring ΔH ≤ 0.8 in. |
|                      | PA2   | Filling Capacity ≥ 80%  
J-Ring ΔD ≤ 2 in.  
J-Ring ΔH ≤ 0.6 in. |
| **Segregation Resistance (SR)** | SR1   | 10% < Column Segregation ≤ 15%  
0.5 in. < Penetration ≤ 1 in.  
VSI = 1 |
|                      | SR2   | Column Segregation ≤ 10%  
Penetration ≤ 0.5 in.  
VSI = 0 |

<table>
<thead>
<tr>
<th>Component Geometric Characteristic</th>
<th>Class</th>
<th>Value/Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length</strong></td>
<td>Low</td>
<td>≤ 33 ft</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>&gt; 33 ft</td>
</tr>
<tr>
<td><strong>Depth</strong></td>
<td>Low</td>
<td>≤ 16 ft</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>&gt; 16 ft</td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
<td>Low</td>
<td>≤ 8 in.</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>&gt; 8 in.</td>
</tr>
<tr>
<td><strong>Shape Intricacy</strong></td>
<td>Low</td>
<td>Concrete flows in a single direction</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>Concrete flow around corners and cutouts</td>
</tr>
<tr>
<td><strong>Formed Surface Quality</strong></td>
<td>Low</td>
<td>Unexposed to the travelling public</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>Exposed to the travelling public</td>
</tr>
<tr>
<td><strong>Level of Reinforcement</strong></td>
<td>Low</td>
<td>Large spacing between bars (≥ 3 in.)</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>Small spacing between bars (&lt; 3 in.)</td>
</tr>
</tbody>
</table>
3- Workability Targets

Is component shape intricate/high formed surface quality needed?

- **NO**
  - Is component deep/long?
    - **NO**
      - Is reinforcement level high/component thin?
        - **NO**
          - 111
        - **YES**
          - 112
    - **YES**
      - Is reinforcement level high/component thin?
        - **NO**
          - 121
        - **YES**
          - 122

- **YES**
  - Is component deep/long?
    - **NO**
      - Is reinforcement level high/component thin?
        - **NO**
          - 211
        - **YES**
          - 212
    - **YES**
      - Is reinforcement level high/component thin?
        - **NO**
          - 221
        - **YES**
          - 222
## Research Approach

### 23 Mixtures with Crushed Limestone

<table>
<thead>
<tr>
<th>Mixture Type</th>
<th>SCC Mixtures</th>
<th>CVC Mixtures</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCMs/Fillers</td>
<td>Low slump flow</td>
<td>High slump flow</td>
</tr>
<tr>
<td>Cement Type I/II, lb/cy</td>
<td>1542 1462 1518 1439 1334</td>
<td>1542 1462 1518 1439 1334</td>
</tr>
<tr>
<td>Natural Sand, lb/cy</td>
<td>1262 1297 1242 1276 1334</td>
<td>1262 1297 1242 1276 1334</td>
</tr>
<tr>
<td>HRWRA, oz/cwt</td>
<td>12.0 14.0 12.0 16.0 13.0</td>
<td>12.0 10.0 18.0 16.0 15.0</td>
</tr>
<tr>
<td>VMA, oz/cwt</td>
<td>0.0 0.0 6.0 0.0 0.0</td>
<td>0.0 0.0 3.0 0.0 0.0</td>
</tr>
<tr>
<td>AEA, oz/cwt</td>
<td>1.5 1.5 1.5 1.5 1.5</td>
<td>1.5 1.5 1.5 1.5 1.5</td>
</tr>
<tr>
<td>Total Weight, lb/cy</td>
<td>3792 3767 3797 3772 3756</td>
<td>3792 3767 3797 3772 3756</td>
</tr>
<tr>
<td>Total Aggregate, lb/cy</td>
<td>2804 2759 2760 2714 2669</td>
<td>2804 2759 2760 2714 2669</td>
</tr>
<tr>
<td>Total Powder, lb/cy</td>
<td>708 713 757 763 783</td>
<td>708 713 757 763 783</td>
</tr>
<tr>
<td>W/P Ratio</td>
<td>0.40 0.41 0.37 0.39 0.39</td>
<td>0.40 0.41 0.37 0.39 0.39</td>
</tr>
<tr>
<td>S/A Ratio</td>
<td>0.45 0.47 0.45 0.47 0.50</td>
<td>0.45 0.47 0.45 0.47 0.50</td>
</tr>
<tr>
<td>Paste Volume %</td>
<td>37.0% 38.0% 38.0% 39.0% 40.0%</td>
<td>37.0% 38.0% 38.0% 39.0% 40.0%</td>
</tr>
<tr>
<td>Coarse Agg. Vol. %</td>
<td>34.4% 32.6% 33.9% 32.1% 29.8%</td>
<td>34.4% 32.6% 33.9% 32.1% 29.8%</td>
</tr>
</tbody>
</table>
## 4- Testing of Lab-Mixed Concrete Specimens

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Standard/Source</th>
<th>Target Values/Ranges</th>
<th>Time(s) of Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive Strength</td>
<td>Compressing 4x8 in. Cylinders</td>
<td>AASHTO T 22</td>
<td>min 4,000 - 6,000 psi</td>
<td>7, 14, 28, 56 days</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>Compressometer for 4x8 in. Cylinders</td>
<td>ASTM C469</td>
<td>AASHTO LRFD 5.4.2.4</td>
<td>28 days</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>Splitting 4x8 in. Cylinders</td>
<td>AASHTO T 198</td>
<td>AASHTO LRFD 5.4.2.7</td>
<td>28 days</td>
</tr>
<tr>
<td>Modulus of Rupture</td>
<td>Simple Beam with Third-Point Loading</td>
<td>AASHTO T 97</td>
<td>AASHTO LRFD 5.4.2.6</td>
<td>28 days</td>
</tr>
<tr>
<td>Bond Strength</td>
<td>Pull-out of Vertical Bars</td>
<td>RILEM/CEB/FIB. 1970</td>
<td>Comparison to CVC</td>
<td>28 days</td>
</tr>
<tr>
<td></td>
<td>Pull-out of Horizontal Bars</td>
<td>RILEM/CEB/FIB. 1970</td>
<td>Comparison to CVC</td>
<td>28 days</td>
</tr>
<tr>
<td>Shear Resistance</td>
<td>Push-off Test</td>
<td>Mattock and Hawkins, 1972</td>
<td>AASHTO LRFD 5.8.4.1</td>
<td>28 days</td>
</tr>
<tr>
<td></td>
<td>Beam Test</td>
<td>Lachemi, et al, 2005</td>
<td>AASHTO LRFD 5.8.3.3</td>
<td>28 days</td>
</tr>
<tr>
<td>Shrinkage</td>
<td>Drying Shrinkage</td>
<td>AASHTO T 160</td>
<td>AASHTO LRFD 5.4.2.3.3</td>
<td>7, 14, 28, 56 days</td>
</tr>
<tr>
<td></td>
<td>Restrained Shrinkage</td>
<td>ASTM C1581</td>
<td>Comparison to CVC</td>
<td>28 days</td>
</tr>
<tr>
<td>Creep</td>
<td>Two 6x12 in. Cylinders</td>
<td>ASTM C512</td>
<td>AASHTO LRFD 5.4.2.3.2</td>
<td>28 - 365 days</td>
</tr>
<tr>
<td>Air Void System</td>
<td>Linear-Traverse Method</td>
<td>ASTM C457</td>
<td>For Comparison Only</td>
<td>28 days</td>
</tr>
<tr>
<td>Surface Resistivity</td>
<td>Four Point Wenner Array Probe</td>
<td>AASHTO TP 95</td>
<td>For Comparison Only</td>
<td>28 days</td>
</tr>
</tbody>
</table>
Research Approach

5- Testing of Ready-Mixed Concrete Full-Scale Specimens
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5. Research Results (chapter 2)
   • Small-scale specimens
   • Full-scale specimens
6. Conclusions (chapter 3)
Research Results

- **From Small-Scale Lab-Mixed Concrete Specimens:**
  - Fresh concrete properties
  - Early-age concrete properties
  - Hardened concrete properties

- **From Full-Scale Ready-Mixed Concrete Specimens:**
  - Constructability
  - Structural Performance
Rheology

SCC has lower yield stress than CVC and wide range of viscosity.

Concrete Rheometer

Mortar Rheometer

Plastic Viscosity (Pa-s)

Dynamic Yield Stress (Pa)

Slope (N-m-s)

Yield Torque (N-m)

SCC (Limestone)
SCC (Gravel)
CVC (Limestone)
CVC (Gravel)

Concrete
Rheometer

SCC has lower yield stress than CVC and wide range of viscosity.
Filling Ability (AASHTO T347)

![Graph showing slump flow for different mixtures]
Passing Ability *(AASHTO T345)*

![Graph showing passing ability](image)

- J-Ring ∆D (in.)
- Slump Flow (in.)

- 3/4” NMSA
- 1/2” NMSA
- 3/8” NMSA
Filling Capacity *(AASHTO T349)*

---

### Slump Flow (in.)
- 3/4” NMSA
- 1/2” NMSA
- 3/8” NMSA

The graph shows the relationship between slumping flow and filling capacity (in %) for different sizes of NMSA aggregates.
Static Stability

**ASTM C1712**

- Penetration (in.): 0.00, 0.25, 0.50, 0.75, 1.00, 1.25
- Slump Flow (in.): 22, 23, 24, 25, 26, 27, 28, 29, 30, 31

**ASTM C1610**

- Column Segregation (%): 0%, 5%, 10%, 15%, 20%, 25%, 30%
- Slump Flow (in.): 22, 23, 24, 25, 26, 27, 28, 29, 30, 31
Static Stability

Visual Stability Index (VSI)

AASHTO T351

Hardened Visual Stability Index (HVSI)

AASHTO PP 58
Dynamic Stability

Lange, et al. (2008)

Modified

Dynamic Segregation (%)

Slump Flow (in.)

△ 3/4” NMSA
〇 1/2” NMSA
● 3/8” NMSA

Lange, et al. (2008) Modified
Workability Retention

WRA should be used for extended workability

\[ y = 0.60x - 10.71 \]

\[ R^2 = 0.86 \]
Formwork Pressure

**SCC has higher formwork pressure than CVC**

\[
y = -10.04x + 99.51 \\
R^2 = 0.89
\]

\[
y = -1.93x + 101.27 \\
R^2 = 0.82
\]

- SCC has higher formwork pressure than CVC.
Heat of Hydration

Semi-adiabatic calorimetry

No difference in HOH
Delay in reaching peak value

Isothermal calorimetry (ASTM C1702)
Time of Setting (AASHTO T197)

 Depends on SCM, Slump Flow, and temperature

- T = 80°F
  \[ y = 0.3x - 0.5 \]
  \[ R^2 = 0.4 \]
- T = 60°F
  \[ y = 0.9x - 14.2 \]
  \[ R^2 = 0.7 \]

Penetration Stress (psi) vs. Time (min)

Penetration Stress (psi) vs. Slump Flow (in.)

- LS121F
- LS221F
- LS121S
- LS221S
- LS121C
- LS221C
- LS121FP
- LS221FP
- CVC

Time of Initial Setting (hr.) vs. Slump Flow (in.)

- T = 80°F
  \[ y = 0.9x - 14.2 \]
  \[ R^2 = 0.7 \]
- T = 60°F
  \[ y = 0.3x - 0.5 \]
  \[ R^2 = 0.4 \]
Compressive Strength (AASHTO T22)

\[ y = 1.12x \quad R^2 = 0.96 \]
\[ y = 0.88x \quad R^2 = 0.90 \]
\[ y = 0.77x \quad R^2 = 0.89 \]

T (days) | Predicted Ratio According to ACI 209 | Measured Ratio for SCC
---|---|---
7 | 0.70 | 0.77
14 | 0.88 | 0.88
56 | 1.09 | 1.12

*No Modification*
Modulus of Elasticity (MOE) (ASTM C469)

\[ E = 33,000 \, K_1 \, w_c^{1.5} \sqrt{f_c} \]

AASHTO LRFD 5.4.2.4-1

\[ y = 0.96x \]
\[ R^2 = 0.78 \]

0.96 Modification Factor
Splitting Tensile Strength (AASHTO T198)

\[ f_t = 0.23 \sqrt{f_c} \]

AASHTO LRFD C5.4.2.7

\[ y = 0.79x \]

\[ R^2 = 0.60 \]

Measured Splitting Tensile Strength (ksi) vs. Predicted Splitting Tensile Strength (ksi)

0.8 Modification Factor
Modulus of Rupture (MOR) *(AASHTO T97)*

\[ \text{MOR} = 0.24 \sqrt{f_c} - 0.37 \sqrt{f_c} \]

AASHTO LRFD C5.4.2.6

\[ y = 0.34x \quad R^2 = 0.63 \]

\[ y = 0.24x \]

---

No Modification
Bond Strength

Pullout Test PHASE I (Rilem/CEB/FIB, 1970)

36 block specimens (18 SCC + 18 CVC) with #6 vertical bars (Lab Mixed)

SCC
\[ y = 2.20x - 2.51 \]
\[ R^2 = 0.89 \]

CVC
\[ y = 2.32x - 2.12 \]
\[ R^2 = 0.69 \]

SCC Bond is 30% lower than that of CVC for vertical bars
Bond Strength

Pullout Test PHASE II (Rilem/CEB/FIB, 1970)

54 tests to evaluate bond and top bar effect of horizontal bars in wall specimens (Ready Mixed)

- Average Bond Strength / √fc (ksi/ksi1/2)
- SCC (high slump flow)
- SCC (low slump flow)
- CVC

Top bar effect in SCC depends on slump flow
Shear Resistance

- Push off Tests for interface shear (Mattock and Hawkins, 1972)
  - 24 specimens (12 CVC+ 12 SCC) with 2#3 reinforcement - Lab mixed

\[
y = 0.62x - 0.60 \quad R^2 = 0.50
\]

\[
y = 0.73x - 0.88 \quad R^2 = 0.72
\]
Shear Resistance

**Ignore c when $f_c < 6$ ksi**

**With Reinforcement**

**Without Reinforcement**

\[ V_{ni} = c A_{cv} + \mu (A_{vf} f_y + P_c) \]  
AASHTO LRFD 5.8.4.1-3
Shear Resistance

18 Beam tests (6 CVC + 6 low slump SCC + 6 high slump SCC)

- Measured for SCC (high slump flow)
- Measured for SCC (low slump flow)
- Measured for CVC
- Predicted for CVC (per AASHTO LRFD)

No Modification
Drying (Free) Shrinkage (AASHTO T160)

AASHTO LRFD 5.4.2.3.3-1

Several Modification Factors:
1.6 for C Ash
1.4 for GGBFS
1.3 for F Ash
Restrained Shrinkage (ASTM C1581)

Average and standard deviation of stress rate (psi/day)

<table>
<thead>
<tr>
<th>SCM/Filler Type</th>
<th>C Fly Ash</th>
<th>F Fly Ash</th>
<th>GGBFS</th>
<th>F Ash + LP</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCM</td>
<td>SCC</td>
<td>CVC</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

No Difference

Restrained Shrinkage (µ-strain) vs. Square Root of Age (day^{1/2})
Creep (ASTM C512)

Modification Factor 1.2 for LSP

AASHTO LRFD 5.4.2.3.2-1

SCC with LSP
\[ y = 1.17x \]
\[ R^2 = 0.93 \]

SCC without LSP
\[ y = 0.98x \]
\[ R^2 = 0.95 \]
Air Void System (ASTM C457)

- **Spacing Factor (mm)**
  - Y-axis: [0.00, 0.25]
  - X-axis: Air Content (%)
- **Specific Surface (mm²/mm³)**
  - Y-axis: [0, 54]
  - X-axis: Air Content (%)

- SCC Mixtures
- CVC Mixtures

Result: No Difference
Surface Resistivity (AASHTO TP 95)

Depends on SCM/Filler

- Limestone Mixtures
- Gravel Mixtures

- CVC + class F fly ash
- SCC + class C fly ash
- SCC + class F fly ash + LP
- SCC + class F fly ash
- SCC + GGBFS

28-Day Surface Resistivity (kΩ-cm)
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Research Results

- From Small-Scale Lab-Mixed Concrete Specimens:
  - Fresh concrete properties
  - Early-age concrete properties
  - Hardened concrete properties

- From Full-Scale Ready-Mixed Concrete Specimens:
  - Constructability
  - Structural Performance
Full-Scale Substructure Component

Section C-C

Section D-D

Section B-B

Section A-A
### Full-Scale Substructure Component

<table>
<thead>
<tr>
<th>Component</th>
<th>NMSA (in.)</th>
<th>Ordered Quantity (cy)</th>
<th>Required Quantity (cy)</th>
<th>Duration of Casting (min.)</th>
<th>Placement</th>
<th>Method</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Footing</td>
<td>3/4</td>
<td>7</td>
<td>6.2</td>
<td>5</td>
<td>Truck Chute</td>
<td>1.3 cy/min.</td>
<td></td>
</tr>
<tr>
<td>First Column</td>
<td>1/2</td>
<td>3</td>
<td>2.05</td>
<td>35</td>
<td>Bucket and Tremie Pipe</td>
<td>26 ft/hr (0.06 cy/min)</td>
<td></td>
</tr>
<tr>
<td>Second Column</td>
<td>1/2</td>
<td>3</td>
<td>2.05</td>
<td>15</td>
<td>Bucket (free fall)</td>
<td>60 ft/hr (0.14 cy/min)</td>
<td></td>
</tr>
<tr>
<td>Pier Cap</td>
<td>1/2</td>
<td>4</td>
<td>3.15</td>
<td>45</td>
<td>1/2 cy Bucket</td>
<td>0.07 cy/min</td>
<td></td>
</tr>
</tbody>
</table>
Formwork Pressure

Distance from the bottom of the column form (ft) vs. Pressure (psf)

- **Hydrostatic Pressure**
- - Measured Pressure (R=26 ft/hr)
- --- Measured Pressure (R=60 ft/hr)
# Surface Void Ratio

**ACI 347.3R-13 Guide to Formed Concrete Surfaces**

<table>
<thead>
<tr>
<th>Formed Concrete Surface</th>
<th>Max. Void Diameter ($D_{\text{max}}$), in.</th>
<th>% of $D_{\text{max}}$</th>
<th>Total % of void area</th>
<th>Surface Void Ratio Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Footing (short side)</td>
<td>3/8</td>
<td>27.6%</td>
<td>0.16%</td>
<td>SVR3</td>
</tr>
<tr>
<td>Footing (long side)</td>
<td>3/8</td>
<td>14.0%</td>
<td>0.31%</td>
<td>SVR3</td>
</tr>
<tr>
<td>First Column (at 1.5 ft from the bottom)</td>
<td>3/8</td>
<td>35.3%</td>
<td>0.14%</td>
<td>SVR3</td>
</tr>
<tr>
<td>First Column (at 11.3 ft from the bottom)</td>
<td>3/8</td>
<td>8.7%</td>
<td>0.25%</td>
<td>SVR3</td>
</tr>
<tr>
<td>Second Column (at 8.5 ft from the bottom)</td>
<td>5/8</td>
<td>78.3%</td>
<td>0.19%</td>
<td>SVR2</td>
</tr>
<tr>
<td>Second Column (at 10 ft from the bottom)</td>
<td>5/8</td>
<td>14.0%</td>
<td>0.31%</td>
<td>SVR2</td>
</tr>
<tr>
<td>Pier Cap (at the pour Line)</td>
<td>5/8</td>
<td>12.0%</td>
<td>0.68%</td>
<td>SVR2</td>
</tr>
<tr>
<td>Pier Cap (away from the pour Line)</td>
<td>5/8</td>
<td>8.1%</td>
<td>0.54%</td>
<td>SVR2</td>
</tr>
</tbody>
</table>
### Stability

**HVSI AASHTO PP 58**

<table>
<thead>
<tr>
<th>Location</th>
<th>Bottom</th>
<th>Middle</th>
<th>Top</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First Column</strong></td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
</tr>
<tr>
<td><strong>Second Column</strong></td>
<td><img src="image4" alt="Image" /></td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
</tr>
</tbody>
</table>
Stability

HVSI AASHTO PP 58

\[ \text{HVSI} = 0 \quad \text{and} \quad \text{HVSI} = 1 \]
Strut-and-Tie Resistance

![Strut-and-Tie Resistance Graph](image)

- Load (lb) vs. Deflection (in.)
- Load limit of 380,000 lb
Flexural Resistance

![Concrete structure image]

![Graph showing lateral load vs. lateral displacement]
Full-Scale Superstructure Component

ELEVATION

END DIAPHRAGM 8” THICK

No. 5 Spiral Rebar
Min. grade 60 steel

8½” HARDWARE ANCHOR

ANCHORAGE DETAILS

PT CORRUGATED METAL DUCT

[Diagram with dimensions and annotations]
## Full-Scale Superstructure Component

<table>
<thead>
<tr>
<th>Component</th>
<th>NMSA (in.)</th>
<th>Ordered Quantity (cy)</th>
<th>Required Quantity (cy)</th>
<th>Duration of Casting (min.)</th>
<th>Placement Method</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Box Girder</td>
<td>3/8</td>
<td>7</td>
<td>5</td>
<td>40</td>
<td>Pumping (2&quot; and 3&quot; hose)</td>
<td>0.13 cy/min</td>
</tr>
<tr>
<td>Top Flange</td>
<td>3/8</td>
<td>7</td>
<td>3.35</td>
<td>25</td>
<td>Pumping (3&quot; hose)</td>
<td>0.13 cy/min</td>
</tr>
<tr>
<td>Formed Concrete Surface</td>
<td>Max. Void Diameter (D&lt;sub&gt;max&lt;/sub&gt;)</td>
<td>% of D&lt;sub&gt;max&lt;/sub&gt;</td>
<td>Total % of void area</td>
<td>Surface Void Ratio Class</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------------------------------------</td>
<td>--------------------------------------</td>
<td>----------------------</td>
<td>-----------------------</td>
<td>--------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top of the Girder (pouring side)</td>
<td>1/2</td>
<td>16.1%</td>
<td>0.40%</td>
<td>SVR3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bottom of the Girder (pouring side)</td>
<td>1/2</td>
<td>37.2%</td>
<td>0.51%</td>
<td>SVR3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bottom of the Girder (opposite side)</td>
<td>1/4</td>
<td>10.8%</td>
<td>0.20%</td>
<td>SVR4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Girder End (at the construction joint)</td>
<td>1/4</td>
<td>25.0%</td>
<td>0.02%</td>
<td>SVR4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Stability  
HVSI AASHTO PP 58

$HVSI = 0$
Flexural Resistance

297,000
Shear Resistance

![Image of a structural beam under load]

The graph shows the relationship between load (lb) and deflection (in.) for a structural component. The data indicates that the shear resistance reaches approximately 353,000 lb at a deflection of 1.5 inches.
## Air Void System

### Table: Air Void System in Hardened Concrete

<table>
<thead>
<tr>
<th>Batch ID</th>
<th>% Air Content in fresh concrete at plant*</th>
<th>Additional dosage of HRWRA (oz/cwt)</th>
<th>% Air Content in fresh concrete at site</th>
<th>Placement Method</th>
<th>Air Void System in Hardened Concrete</th>
<th>Measured from 4x8 Cylinders</th>
<th>Measured from Extracted Cores</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Air content, %</td>
<td>Spacing factor, mm</td>
</tr>
<tr>
<td>Footing</td>
<td>4.5</td>
<td>2.3</td>
<td>2.5</td>
<td>Truck Chute</td>
<td></td>
<td>4.1</td>
<td>0.17</td>
</tr>
<tr>
<td>First Column</td>
<td>4.5</td>
<td>2.0</td>
<td>4.0</td>
<td>Bucket and Tremie Pipe</td>
<td></td>
<td>5.7</td>
<td>0.17</td>
</tr>
<tr>
<td>Second Column</td>
<td>6.2</td>
<td>1.0</td>
<td>4.0</td>
<td>Bucket (free fall)</td>
<td></td>
<td>4.9</td>
<td>0.15</td>
</tr>
<tr>
<td>Pier Cap</td>
<td>6.4</td>
<td>4.0</td>
<td>4.0</td>
<td>1/2 cy Bucket</td>
<td></td>
<td>4.3</td>
<td>0.22</td>
</tr>
<tr>
<td>Box Girder</td>
<td>6.0</td>
<td>1.5</td>
<td>4.5</td>
<td>Pumping (2 and 3 in. hose)</td>
<td></td>
<td>4.0</td>
<td>0.16</td>
</tr>
<tr>
<td>Top Flange</td>
<td>4.5</td>
<td>1.5</td>
<td>3.5</td>
<td>Pumping (3 in. hose)</td>
<td></td>
<td>5.0</td>
<td>0.13</td>
</tr>
<tr>
<td>Average</td>
<td><strong>5.35</strong></td>
<td><strong>2.05</strong></td>
<td><strong>3.75</strong></td>
<td>-</td>
<td></td>
<td><strong>4.7</strong></td>
<td><strong>0.17</strong></td>
</tr>
</tbody>
</table>

*Measured by plant technician
Table of Content

1. Definition
2. Problem Statement
3. Research Objectives and Scope
4. Research Approach (chapter 1)
5. Research Results (chapter 2)
6. Conclusions (chapter 3)
## Conclusions

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<th>SCC Workability Targets</th>
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<td>Pile Cap</td>
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<td></td>
<td>Wing Wall</td>
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<td></td>
<td>Abutment Wall</td>
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<tr>
<td></td>
<td>Pier Wall</td>
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<tr>
<td></td>
<td>Pier Column</td>
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<td>Strut or Tie</td>
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<td></td>
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<tr>
<td></td>
<td>Pier Cap</td>
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<td></td>
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<td>Superstructure</td>
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<td>Floor Beam</td>
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<tr>
<td></td>
<td>Girder</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Arch</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* For deep/long components, SR1 could be acceptable if free-fall height/free-travel distance are controlled (e.g., tremie pipe).
Conclusions

1. SCC mixtures for CIP bridge components can be proportioned with:
   - water-powder ratio 0.37 – 0.44
   - powder content 650 – 760 lb/cy
   - sand-to-aggregate ratio 0.45 – 0.5
   - NMSA 3/4, 1/2, 3/8 in. (limestone and gravel)
   - SCM/filler: C ash, F ash, GGBFS, Limestone powder

2. The rate of workability loss of SCC mixtures is directly proportional to the initial slump.

3. Time of initial setting of SCC mixtures depends on temperature, SCM/filler, and slump flow.

4. Heat of hydration of SCC mixture is similar to that of CVC, but with slight delay in reaching the peak temperature/energy.

5. Formwork pressure of SCC mixture is less than full hydrostatic pressure depending on the placement rate, thixotropy, and yield stress.
Conclusions

6. ACI 209 adequately predict SCC compressive strength development.
7. AASHTO LRFD slightly overestimates SCC MOE.
8. AASHTO LRFD overestimates SCC splitting tensile strength.
9. AASHTO LRFD adequately predict SCC MOR.
10. SCC has lower bond strength with vertical bars than CVC.
11. SCC top bar effect depends on slump flow and could be less than that of CVC.
12. AASHTO LRFD overestimates interface shear resistance for low strength SCC.
13. SCC has similar nominal shear resistance to that of CVC at different reinforcement levels, which can be accurately predicted by AASHTO LRFD.
Conclusions

14. Drying shrinkage of SCC is higher than predicted by AASHTO LRFD and highly depended of the type of SCM/filler used.

15. Restrained shrinkage of SCC is highly depended of the type of SCM/filler used, but not significantly different from that of CVC.

16. Creep coefficient of SCC can be accurately predicted by AASHTO LRFD except SCC mixtures containing LSP (higher creep coefficient).

17. Air void system of SCC is not significantly different from that of CVC. However, variations in HRWRA dosage can result in differences between fresh and hardened conditions.

18. Surface resistivity of SCC is highly depended of the type of SCM/filler used, but not significantly different from that of CVC.
Thank You

George Morcous, Ph.D., P.E.
Durham School of Architectural Engineering and Construction
College of Engineering
University of Nebraska - Lincoln
1110 South 67th Street, PKI 105B
Omaha, NE, 68182-0571
Tel. (402) 554-2544
E-mail: gmorcous2@unl.edu