Development of SCC Performance Criteria

Developed in Japan in the late 1980's

Flows into formwork without vibration or mechanical consolidation

Flowable properties achieved with:

- Ultra high-range water reducer (polycarboxylate)
- Viscosity Modifying Admixture (VMA)
- High cementitious materials or powder content
- Small coarse aggregate and higher sand fraction

ACI 237 ETS Report
Potential benefits of SCC

- Improved consolidation
- Reduced labor cost
- Accelerated construction
- Reduced noise

Performance Requirements
- Flowability into formwork and through reinforcement
- Stability (resistance to segregation)
- **but what about hardened concrete properties?**
Database of SCC proportions shows a departure from “normal” OPC
Workability and Rheology

Workability: “The ease with which [concrete] can be mixed, placed, consolidated, and finished to a homogenous condition.”
SCC Flow Characteristics

Slump flow test (ASTM C1611)
Prestressed Engineering Corp, Blackstone, IL, USA

Flowing into double T beam forms
ACI 237 ETS Report
Standard tests have been developed
J-ring test for passing ability (ASTM C1621)

Test is performed using a standard slump cone

Difference in diameter
Rheology is the study of the flow of matter.

A concrete rheometer determines resistance to shear flow at various rates.

Bingham model:
- **Yield stress**: minimum stress to initiate or maintain flow (slump)
- **Plastic viscosity**: the resistance to flow once yield stress is exceeded (stickiness)

Slump, slump flow, stability, segregation, are concrete rheology terms.

The Bingham Model

- **Yield stress** ($\tau_0$)
- **Slope**: plastic viscosity ($\mu$)

Conventional Concrete

SCC
How to approximate rheological behavior

Stability and Cohesion of SCC
How do we evaluate segregation?

**Hardened Visual Stability Index (VSI) Rating Criteria for Concrete Cylinder Specimens**

<table>
<thead>
<tr>
<th>Rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td><strong>Stable</strong></td>
</tr>
<tr>
<td></td>
<td>No paste or mortar layer visible at top of cylinder, no apparent difference in the size and area percentage of coarse aggregate through depth</td>
</tr>
<tr>
<td>1</td>
<td><strong>Stable</strong></td>
</tr>
<tr>
<td></td>
<td>No paste or mortar layer visible at top of cylinder, slight difference in the size and area percentage of coarse aggregate through depth</td>
</tr>
<tr>
<td>2</td>
<td><strong>Unstable</strong></td>
</tr>
<tr>
<td></td>
<td>Slight paste or mortar layer visible (&lt;1”), slight difference in coarse aggregate through depth</td>
</tr>
<tr>
<td>3</td>
<td><strong>Unstable</strong></td>
</tr>
<tr>
<td></td>
<td>Significant paste or mortar layer visible (&gt;1”), obvious difference in the size and area percentage of coarse aggregate through depth</td>
</tr>
</tbody>
</table>
Segregation Resistance

\[
SI = \frac{M4 - M1}{\sqrt[1/2]{(M4 + M1)}}
\]

\[
\tau_0 \geq \frac{4}{3} g (\rho_{sphere} - \rho_{fluid}) R
\]

Gravitational Force
- density & size

Buoyancy + Resisting Force
- Paste rheology & density
- Aggregate shape & texture
- Aggregate lattice effect

The Segregation Probe

**Applicability:**
- Rapid surface segregation measurement
- Sensitive to small changes in stability of SCC
- Suitable for field measurement

**Procedure:**
- Cast fresh concrete into 6 x 12” cylinder
- Wait for 15 min, avoid excessive disturbance
- Put ring on surface gently
- Wait for at least 2 min until ring stops settling
- Take reading
Design for Segregation Resistance

Segregation resistance increased with:
- Higher yield stress (static and dynamic yield stress assumed equal initially)
- Higher plastic viscosity
- Higher thixotropy

Reduce Flow

Use smaller aggregate

Use more paste

SCC Formwork Pressure

SCC approaches full hydrostatic pressure during rapid placement.

Will SCC change the way we design formwork?

Pressure decrease is a combination of physical (internal friction) and chemi-physical (gelation) phenomena.

Internal friction is a function of the aggregate content and the workability of concrete.

Set modifying admixtures will affect formwork pressure.

Initial pressure drop is independent of cement hydration.

Temperature is a significant factor.
Models are needed to describe pressure for design

The coefficient alpha describes different pressure decay rates over time.

\[ C = \frac{C_0}{(Bt^2 + 1)^\alpha} \left( e^{-\sqrt{(t^2 + b)} - t} \right) \]

\[ P(t) = \gamma (R\Delta t) \sum_{i=1}^{n} C_i(t) \]
Formwork Pressure

Formwork pressure is related to concrete rheology
- Pressure increases with slump
- SCC exhibits high formwork pressure due to high fluidity

Concrete at rest in forms, static yield stress is relevant
- Static yield stress is affected by dynamic yield stress and thixotropy
- SCC is placed in lifts, which takes advantage of thixotropy

SCC must be designed to flow under its own mass and exert low formwork pressure
- Low dynamic yield stress (self flow)
- Fast increase in static yield stress (reduced formwork pressure) – gelation or structural build up

Place concrete in lifts to allow build-up of thixotropic structure

Limit pour heights and rates based on concrete rheology

Do not vibrate concrete
Early Age Cracking

0.016” (0.4 mm)
Stress development in SCC indicates cracking risk

Autogenous shrinkage in low w/c materials generates significant stress at early age.

A minimum w/c ratio can reduce early age cracking in restrained concrete.
Early age shrinkage causes cracking risk

Typical Concrete – “Safe Zone”? 

Free Shrinkage (x10^-6)

| OPC1, w/c = 0.40 |
| SCC1, w/c = 0.39 |
| SCC2, w/c = 0.33 |
| SCC3, w/c = 0.41 |
| SCC5, w/c = 0.34 |

Age (days)

w/b, paste%

0.40, 32%
0.41, 33%
0.34, 34%
0.39, 37%
0.33, 40%
Low w/c drives autogenous shrinkage

Typical Concrete – “Safe Zone”? w/b, paste%

0.41, 33%
0.40, 32%
0.39, 37%
0.34, 34%
0.33, 40%

OPC1, w/c = 0.40
SCC1, w/c = 0.39
SCC2, w/c = 0.33
SCC3, w/c = 0.41
SCC4, w/c = 0.32
NEED: Measurement of cracking tendency

ASTM C1581

• Concrete shrinks around the steel ring causing tensile stress in concrete
• Stress relaxes due to tensile creep
• Strain measurements in steel are proportional to stress in concrete
• When tensile stress exceeds strength, cracking occurs
Cracking time is improved with higher w/cm, and/or lower paste content.

- w/cm = 0.42, 33% paste
- w/cm = 0.40, 35% paste
- w/cm = 0.37, 37% paste

Strain, in/in x 10^-6

Concrete Age, days
NEED: Concrete temperature rise

25% fly ash
NEED: Shrinkage and cracking mitigation

SRA – Shrinkage reduction through chemistry
SLA – Shrinkage reduction through internal curing
Optimization – Reduce cement paste %
SCMs – Reduce autogenous, temperature, modulus
Preventing SCC cracking

Some SCC mixtures have high risk for cracking, specs should utilize performance tests

Mechanical properties controlled by paste content and w/cm

Autogenous shrinkage is early age issue

Recommendations:

◦ Use the lowest possible cement paste content that still achieves desired flow characteristics
◦ Avoid low w/b ratios that lead to high autogenous shrinkage
Back to Specifications...

What is the “real performance” we need to ensure?
  ◦ More that strength

Spec writers need to assert more control
  ◦ Example: SCC needs limits on segregation, shrinkage cracking, min. aggregate content, min. w/c
  ◦ Limit temperature rise for mass concrete applications
  ◦ Modulus and Creep
  ◦ Ring test for cracking
Suggestions for Practice
Acceptance Criteria: w/cm ratio

0.42 eliminates autogenous shrinkage

Application specific limits

- High Restraint: 0.42
- Med Restraint: 0.38
- Low Restraint: 0.32
Water-cementitious ratio “safe zone”

Below 0.32 autogenous shrinkage can cause severe cracking when concrete is restrained.

Above 0.50, drying shrinkage is a concern.

Strength and durability also affected.

Good range for minimum “total” shrinkage is 0.38 to 0.44.
Acceptance Criteria: Paste Content

IDOT max cement factor: 7.05 cwt/yd³

At 705 lb/yd³, 0.44 w/cm = 34% paste

Below 32%, SCC has questionable fresh properties

Application specific limits
- High Restraint: 30%
- Med Restraint: 34%
- Low Restraint: 36%

**TABLE 4.3 – From ACI 237 ETS**

<table>
<thead>
<tr>
<th>Trial Mix Parameters</th>
<th>28% - 32%</th>
<th>34% - 40%</th>
<th>68% - 72%</th>
<th>0.32 – 0.45</th>
<th>650* – 800 pounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse aggregate by volume</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paste Content by volume</td>
<td>34%</td>
<td>40%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mortar Fraction by volume</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typical w/cm</td>
<td>0.32</td>
<td>0.45</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typical powder content</td>
<td>650*</td>
<td>800</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Graph:**

- **Autogenous Shrinkage (28d)**
- **Total Shrinkage (28d)**

**Paste Content by Volume**

Paste Content by Volume: 30% - 42%

Autogenous Shrinkage Strain (x10⁻⁶)
Aggregate gradation analysis

- Sieve Size (inches)
- Percent Retained

Min, OPC1, SCC1, SCC2, SCC3, SCC5, Max

Percent Retained:
- Min: 15%
- OPC1: 5%
- SCC1: 0%
- SCC2: 5%
- SCC3: 5%
- SCC5: 10%

Sieve Size (inches):
- 1
- 3/4
- 5/8
- 1/2
- 3/8
- 1/4
- 1/8
- 1/16
- 1/30
- 1/50
- 1/100
- 1/200
- Pan
Shrinkage reduced through aggregate optimization

- Free Shrinkage ($\times 10^{-6}$)
- Age (d)

Graph showing the relationship between Free Shrinkage and Age for OPC 42 and DOC 42 with w/cm = 0.42.

 OPC 42:
- Free Shrinkage decreases significantly with age.
- The data points show a trend indicating lower shrinkage compared to DOC 42.

 DOC 42:
- Similar trend to OPC 42, with a slower decrease in Free Shrinkage.
- The data points show a trend indicating higher shrinkage compared to OPC 42.

Legend:
- OPC 42
- DOC 42

- w/cm = 0.42
- 22% paste
- 32% paste
Recommendations

Place limits on maximum paste content

Place lower limit on w/cm

Use well graded aggregates to reduce the need for high paste%

Recommend supplementary cementitious materials to replace cement

Recommend autogenous shrinkage test for w/cm below 0.38
SCC: Bridging Research and Practice

SCC has many benefits
- Improved consolidation for tight forms or bar spacing
- Labor cost savings
- Aesthetic finish
- Rapid placement

Research is available to help solve problems
- Rheology testing is becoming more common
- Avoid segregation problems with proper testing in the lab and field
- Pressure models assist formwork design
- Cracking can be avoided through careful mixture development or mitigation

Specifications must
- Limit w/b and paste content or utilize mitigation to avoid cracking
- Use performance testing for rheological characterization, avoid segregation, form pressure, and pumpability problems