Performance Based Tests and Criteria for Concrete Durability

ACI Fall Convention
October 2016
For successful performance specification

- Need test procedure/criteria to select mixtures with desired resistance to
  - Chlorides
  - Freeze thaw
  - Sulfates
    - Physical salt attack (PSA)
Physical Salt Attack

- Salt Crystals
- Aggregate

Evaporative Front/Salt Crystalization

Salt Solution Migration
Requirements for PSA

- No ASTM tests
- ACI 201
  - Recommends w/cm < 0.50 for PSA
## Material Characteristics

<table>
<thead>
<tr>
<th>Item</th>
<th>Type I</th>
<th>Type II</th>
<th>Type V1</th>
<th>Type V2</th>
<th>Slag Cement</th>
<th>Fly Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cement Type</strong></td>
<td>I</td>
<td>II</td>
<td>V-1</td>
<td>V-2</td>
<td>SL</td>
<td>FA</td>
</tr>
<tr>
<td>Silicon oxide (SiO$_2$), %</td>
<td>19.3</td>
<td>20.6</td>
<td>22.2</td>
<td>20.7</td>
<td>-</td>
<td>60.5</td>
</tr>
<tr>
<td>Aluminum oxide (Al$_2$O$_3$), %</td>
<td>5.9</td>
<td>5.0</td>
<td>3.7</td>
<td>4.4</td>
<td>11.8</td>
<td>29.1</td>
</tr>
<tr>
<td>Iron oxide (Fe$_2$O$_3$), %</td>
<td>1.9</td>
<td>3.2</td>
<td>4.1</td>
<td>4.0</td>
<td>-</td>
<td>2.9</td>
</tr>
<tr>
<td>Calcium oxide (CaO), %</td>
<td>62.3</td>
<td>62.8</td>
<td>64.7</td>
<td>64.8</td>
<td>-</td>
<td>0.7</td>
</tr>
<tr>
<td>Sulfur trioxide (SO$_3$), %</td>
<td>3.9</td>
<td>2.9</td>
<td>2.1</td>
<td>2.5</td>
<td>2.40</td>
<td>0</td>
</tr>
<tr>
<td>Total Alkali (as Na$_2$O eq), %</td>
<td>0.94</td>
<td>0.53</td>
<td>0.41</td>
<td>0.30</td>
<td>0.49</td>
<td>0.54</td>
</tr>
<tr>
<td>Tricalcium Silicate (C$_3$S), %</td>
<td>53</td>
<td>53</td>
<td>58</td>
<td>64</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dicalcium silicate (C$_2$S), %</td>
<td>16</td>
<td>-</td>
<td>20</td>
<td>11</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tricalcium Aluminate (C$_3$A), %</td>
<td>12</td>
<td>8</td>
<td>3</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tetracalcium Aluminoferrite (C$_4$AF), %</td>
<td>6</td>
<td>-</td>
<td>12</td>
<td>12</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Mixture Proportions

- ASTM C33 No. 57 crushed coarse aggregate
- ASTM C33 natural sand
- w/cm = 0.40 to 0.60
- Type I, II, V-1, V-2
- Class F (15-30%), slag cement (25-50%)
- Non-air-entrained
- ASTM C494 Type A with 3 oz/cwt. (200 ml/100 kg)
- Type F varied for target slump of 4-7 in. (125-175 mm)
Tests Conducted

- Fresh properties, strength, RCPT, sorptivity, absorption
- PSA test
  - 3 x 3 x 11 ¼ in. prisms
  - Specimen moist cured for 28 d + 28 d air drying
  - Partial immersion (5 in.) in 10% sodium sulfate
  - Lab environment (73°F and 60% RH)
  - After 12 months started weekly cycling with hot room (100°F and 30% RH)
  - Temp and RH measured at 1 in. above surface
Sodium sulfate conversion
Test set up
Measurements

- Scaling distance
  - From solution surface upwards
- Scaling visual rating
- Mass loss
Results

![Graph showing the relationship between age and average scaling distance for different conditions.](chart.png)

- **0.4SL25-I**
- **0.6SL25-I**
- **0.4FA15-I**
- **0.6FA15-I**

**Axes:**
- **Y-axis:** Avg. Scaling Distance, inches
- **X-axis:** Age, months

The graph illustrates the increase in average scaling distance over time for different conditions, indicating growth patterns that may be relevant for studies or comparisons in related fields.
0.4SL25

0.6SL25
Terminated @ 23 months

0.4FA15

0.6FA15
0.5PC-I
Terminated @ 23 months

0.5PC-II

Results

<table>
<thead>
<tr>
<th>Age, months</th>
<th>Avg. Scaling Distance, inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>5</td>
<td>1.00</td>
</tr>
<tr>
<td>10</td>
<td>2.00</td>
</tr>
<tr>
<td>15</td>
<td>3.00</td>
</tr>
<tr>
<td>20</td>
<td>4.00</td>
</tr>
<tr>
<td>25</td>
<td>5.00</td>
</tr>
</tbody>
</table>

0.5PC-I

Age, months

0.5PC-II

Avg. Scaling Distance, inches

Graph showing the comparison of Avg. Scaling Distance between 0.5PC-I and 0.5PC-II with respect to Age, months.
Results
Results
Effect of SCMs on PSA

Average Scaling Distance, in.

0.5PC-I 0.5PC-II 0.4FA15-I 0.6FA15-I 0.4SL25-I 0.6SL25-I

0.45PC-V1 0.45PC-V2 0.40FA20-II 0.40FA30-V1 0.40SL35-II 0.40SL50-V1
Petrography (Micro-chem)
Petrography (Micro-chem)

Stereomicroscope, thin section analysis
- Lesser secondary gypsum in exposed area
  - Scaling initiated by PSA
- Aggregate particles in exposed area cracked and degraded
  - Symptom of PSA
## Resistance to PSA Categorization based on Scaling Distance

<table>
<thead>
<tr>
<th>Resistance to Physical Salt Attack</th>
<th>Mixtures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>0.5PC-I, 0.5PC-II, 0.6FA15-I, 0.4FA20-II, 0.6FA20-II, 0.6FA30-V1, 0.4SL50-V1, 0.6SL25-I, 0.6SL35-II, 0.6SL50-V1</td>
</tr>
<tr>
<td>High</td>
<td>0.45PC-V1, 0.45PC-V2, 0.4FA15-I, 0.4FA30-V1, 0.4SL25-I, 0.4SL35-II</td>
</tr>
</tbody>
</table>

Low – 16 m scaling distance >3.0 in.
High – 16 m scaling distance ≤3.0 in.
Suggested criteria for PSA

<table>
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<tr>
<th>Resistance to Physical Salt Attack</th>
<th>Prescriptive option</th>
<th>Performance Option, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>w/cm ≤ 0.45</td>
<td>Compressive Strength ≥ 4500*</td>
</tr>
</tbody>
</table>

*for air entrained concrete. For non-air-entrained concrete increase by 20%
An accelerated PSA test

- Daily cycling (16h in 73°F/80% RH and 8h in 100°F/30% RH)
  - Tested 4x8 in. cylinders
  - Partial immersion in 3 in. of 10% Na$_2$SO$_4$ solution
  - Accumulated scaled mass, scaling distance, visual rating every 10 cycles – 50 cycles
Results
Results

Type II Mixtures

Type V Mixtures

Accumulated Scaled Mass, g

50 Cycles

- 0.4FA20-II
- 0.5FA20-II
- 0.6FA20-II
- 0.4SL35-II
- 0.5SL35-II
- 0.6SL35-II
- 0.4FA30-V1
- 0.5FA30-V1
- 0.6FA30-V1
- 0.4SL50-V1
- 0.5SL50-V1
- 0.6SL50-V1

0.45PC
Conclusions

- Mixtures with high resistance to PSA
  - W/CM < 0.45 or $f'_c > 4500$ psi
- Cement types, SCMs did not greatly impact resistance to PSA
- Accelerated PSA test procedure (50 days) shows promise
  - Results consistent with 2 year test
Thank you