Recent Advances in ASR Test Methods and Understanding Mitigation Mechanisms, Part 2

ACI Spring 2012 Convention
March 18 – 21, Dallas, TX

R. Doug Hooton is an ACI Fellow, the 2011 Arthur R. Anderson Award winner, and a member of numerous ACI committees including C232 on fly ash and C201 on durability. He is also a Fellow of ASTM, and the Engineering Institute of Canada. He is a professor and NSERC/Cement Association of Canada Senior Industrial Research Chair in Concrete Durability and Sustainability in the Department of Civil Engineering at the University of Toronto. His research over the last 38 years has focused on the durability performance of cementitious materials in concrete.

The Kingston Outdoor Exposure Site for Mitigating ASR After 20 Years

ACI Dallas, March 2012

R. D. Hooton & T. Ramlochan
C.A. Rogers & C. A. MacDonald

Site Established in Kingston, Ontario in 1991
6 different concrete mixtures reinforced and non reinforced blocks and slab for each mix
Spratt coarse aggregate and local non-reactive fine aggregate

Sept. 1991 Kingston Site

<table>
<thead>
<tr>
<th>Binder</th>
<th>Mix 1</th>
<th>Mix 2</th>
<th>Mix 3</th>
<th>Mix 4</th>
<th>Mix 5</th>
<th>Mix 6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50% Slag 58% HAPC</td>
<td>10% Fly Ash 82% HAPC</td>
<td>50% Slag 77% HAPC</td>
<td>25% Slag+13% SF 77% HAPC</td>
<td>100% LAPC</td>
<td>100% HAPC</td>
</tr>
<tr>
<td>W/cm</td>
<td>0.4</td>
<td>0.39</td>
<td>0.39</td>
<td>0.38</td>
<td>0.37</td>
<td>0.34</td>
</tr>
<tr>
<td>Alkali Loading (kg/m³)</td>
<td>1.84</td>
<td>2.67</td>
<td>2.67</td>
<td>2.54</td>
<td>1.91</td>
<td>3.28</td>
</tr>
</tbody>
</table>

All mixes had total CM = 415 kg/m³
All made with ASR Spratt Reactive Coarse Aggregate (siliceous Limestone)

Aggregates

- The alkali-silica reactive coarse aggregate (5-20mm) was the Spratt aggregate from a quarry near Ottawa, Ontario.
- The aggregate had been crushed in 1985 and placed in a 120-tonne stockpile.
- Spratt aggregate is a Middle Ordovician, medium-grey, fine crystalline limestone. The material is slightly siliceous (9% SiO₂) and has been used as a convenient alkali-silica reactive aggregate for investigating alkali-silica reaction expansion tests
- The fine aggregate was local non-reactive natural sand composed of igneous and high-grade metamorphic rocks and derived minerals with a long history of satisfactory performance in concrete made with high-alkali cement.
Concrete was batched in Ready Mix Plant, truck mixed and discharged within 0.5 to 1 hour of mixing.

Concrete cured with wet burlap and plastic for 4 days.

### Compressive Strengths (MPa) and Alkali Loading

<table>
<thead>
<tr>
<th>Mix</th>
<th>60% Slag</th>
<th>18% F-Ash</th>
<th>25% Slag</th>
<th>25% slag +3.8%SF</th>
<th>LAPC</th>
<th>HAPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/cm</td>
<td>0.38</td>
<td>0.37</td>
<td>0.39</td>
<td>0.34</td>
<td>0.40</td>
<td>0.39</td>
</tr>
<tr>
<td>28 d</td>
<td>40.0</td>
<td>39.0</td>
<td>41.8</td>
<td>47.9</td>
<td>39.6</td>
<td>35.6</td>
</tr>
<tr>
<td>82 d</td>
<td>44.9</td>
<td>50.0</td>
<td>42.7</td>
<td>52.8</td>
<td>46.2</td>
<td>44.3</td>
</tr>
<tr>
<td>1 y</td>
<td>49.7</td>
<td>52.4</td>
<td>50.9</td>
<td>63.2</td>
<td>54.9</td>
<td>49.2</td>
</tr>
<tr>
<td>7.25y</td>
<td>58.5</td>
<td>60.4</td>
<td>59.0</td>
<td>61.8</td>
<td>62.2</td>
<td>57.9</td>
</tr>
<tr>
<td>Alkaline Loading (kg/m³)</td>
<td>1.64</td>
<td>2.67</td>
<td>2.46</td>
<td>2.34</td>
<td>1.91</td>
<td>3.28</td>
</tr>
</tbody>
</table>

**Accelerated Mortar Bar Test**

CSA A23.2-25A       ASTM C 1260

<table>
<thead>
<tr>
<th>Binder Type and Proportions</th>
<th>Aggregate/cementitious material = 2.25</th>
<th>W/CM = 0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mortar bars, 25 x 25 x 250 mm, stored in 1M NaOH at 80°C for <strong>14 days</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Concrete Prism Test**

CSA A23.2-14A       ASTM C 1293

<table>
<thead>
<tr>
<th>Binder Type and Proportions</th>
<th>Mortar Bar Expansion in Per Cent</th>
<th>Concrete Prisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>420 kg/m³ cementitious material</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NaOH added to yield 1.25% Na₂Oₑ by mass of Portland cement</td>
<td>0.42 ≤ W/CM ≤ 0.45</td>
<td></td>
</tr>
<tr>
<td>Concrete prisms 75 x 75 x 250 mm (min)</td>
<td>Stored over water at 38°C (and nominally 100% RH) for 2 years</td>
<td></td>
</tr>
</tbody>
</table>
38°C Concrete Prism Expansions to 9 Years (but not boosted to 1.25% alkali)

Inside containers, prisms were sealed in bags with 100ml water

- High-alkali PC
- Low-alkali PC
- 25% Slag
- 18% Fly Ash
- 50% Slag
- 3.8% SF + 25% Slag

20-year old 0.6x0.6x2.0 m concrete beams exposed outdoors in Kingston (mixes: 415kg/m³)

Cracking in large beams noticed at ~0.04-0.07% expansion—similar to 38°C concrete prisms

- 14-year old 0.6x0.6x2.0 m concrete beams
- Exposed outdoors in Kingston (mixes: 415kg/m³)

- Cracking in large beams noticed at ~0.04-0.07% expansion—similar to 38°C concrete prisms

Block 2, 18% type F fly ash (14-years)

End of block 3R 25% slag

End of block 5R 100% LAPC

Block 6, 100% HAPC
Top end block 6

16-year Reinforced Beam Expansions
Area of steel = 1.41%
(4-25M and 8-20M bars)

- High-alkali PC
- Low-alkali PC
- 25% Slag
- 18% Fly Ash
- 3.8% SF + 25% Slag
- 50% Slag

20-year Pavement Slab Expansions

Mix 6: High-alkali Cement Concrete
Lab vs 20-Year Field Exp’n

- High-alkali PC
- 18% Class F Fly Ash
- 25% Slag
- Low-alkali PC
- 3.8% SF + 25% Slag
- 50% Slag

Damage Rating Index of Cores at 14-years
(thanks to P. Grattan-Bellew)

- 50% slag
- 18% Fly Ash
- 25% Slag
- Slag + SF
- LAPC
- HAPC

Low-Alkali Cement Concrete

- Crack in coarse aggregate filled with ASR product “Okenite”?
- Only found in aggregate not in adjacent cement paste
- First described in 1986 by Fournier /Berube/Vezina for Ordovician carbonates of St Lawrence Lowlands

Okenite (Ca10Si18O46·6H2O)
High-Alkali Cement Concrete

12-year cores

- ASR in air
- Void
- and in crack
- Cracks ranged from about 5 \( \mu \text{m} \) to 200 \( \mu \text{m} \) in width on 30-50\% of all aggregate particles

0.7mm

- ASR in crack inside limestone aggregate on right, extending into paste on left.

0.7mm

100\% HAPC Concrete with Spratt reactive aggregate
ASR cracking paste and filling cracks

Spratt aggregate is a limestone with \~5\% reactive silica.

T. Ramlochan,
U. of Toronto

100\% PC Concrete: K/Ca changes as ASR Gel moves from aggregate(1, 4) to paste (2, 3)

Calcium appears to play a role in altering ASR gel, raising its viscosity, increasing swelling pressure and recycling alkalis to continue ASR

18\% F Ash Concrete
Summary 1

- The concrete made with high-alkali cement and no protective measures cracked at an age of 5 years when stored outdoors in the Canadian climate.
- Low-alkali cement did not prevent cracking, it delayed it until ~7 years even at 1.91 kg/m³ alkali loading.
- The expansion levels at the time of cracking ranged from 0.04 to 0.07%.
- This is similar to the 0.04% limit used for the 38°C Concrete prism test.

Summary 2

- When the high-alkali cement was replaced with various amounts of supplementary cementing materials or low-alkali cement, expansion was considerably less and only very minor cracking occurred at 16 years.
- When sufficient SCMs were used, there was no sign of ASR or cracking at 20 years.

Summary 3

- Damage Rating Index was performed on cores at 12 years.
- DRI values of 54-58, coincided with minor visible cracking in outdoor beams and slabs.
- The uncracked Slag+SF mix DRI = 5.
- The uncracked 50% Slag mix DRI = 51.
- The severely cracked HAPC DRI = 194.

Summary 4

- The data confirm the advice given in CSA standards that, when mortar bars give less than 0.10% expansion at 14 days with a reactive aggregate and a supplementary cementing material, the material in the proportion used will prevent deleterious alkali-silica reaction in concrete.
<table>
<thead>
<tr>
<th>Summary 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>- The concretes with SCMs also had superior chloride resistance properties to the pure Portland cement mixtures, as measured by both bulk diffusion (ASTM C 1556) and ASTM C 1202 coulomb results.</td>
</tr>
</tbody>
</table>