Alkali-aggregate Reactions in Concrete

- A review -

Benoit Fournier
AAR → one of many deleterious mechanisms affecting the durability of concrete

(Mehta and Monteiro 1999)
First report of AAR

- 1930’s in the Monterey and Los Angeles counties (Californie)
- Thomas Stanton, Caltrans
Structures affected by AAR all around the world

- China
- Australia
- Holland
- Japan
- USA
- South Africa
- Brazil
- Scotland
- Norway
- Canada
13 international conferences since 1974
Thousands of papers, reports, specifications, guidelines
Pore fluid in concrete:

- Mainly composed of K+, Na+ and OH- $\rightarrow$ pH $\geq$ 12.4

- Some mineral phases unstable in ↑ pH conditions $\rightarrow$ alkali-aggregate reactions

(Diamond 1989)

(Mehta and Monteiro 1999)
• Alkalis from ≠ sources:
  ➢ Cement (mainly)
  ➢ Aggregates (~ long term)
  ➢ Other cementitious materials
  ➢ Chemical admixture
  ➢ sea water, deicing chemicals
Alkali-Silica Reaction

- Most common form of AAR

- Reaction between concrete pore fluid (↑ pH) and siliceous phases from aggregates
Alkali-Silica Reaction

- Deleterious reaction produces secondary reaction product → alkali-silica gel
- Gel swells in the presence of moisture
Alkali-Silica Reaction

- Internal expansion forces → cracking and distress of concrete
Alkali-Carbonate Reaction

- Limited cases from Canada, USA, China, Austria
- “Classical” ACR in Canada: argillaceous dolomitic limestone
Time for Distress Due to AAR

- Less than 2 to more than 25 years
- Depends on various factors

Reactive Material in the aggregates

How serious is the problem??

Sufficient Alkali

Sufficient Moisture
AAR – the Problem

- Very few cases of structures demolished essentially because of AAR
AAR – the Problem

- Extensive cracking $\rightarrow$ durability issues (rebar corrosion)
- Differential expansion and movements in critical structures (bridges, dams) $\rightarrow$ operational issues $\rightarrow$ repairs and $$$$

![Image of a dam with visible cracking]
Paulo Afonso Hydro Generating Complex, Brazil
ASR Damage Channel Islands - USA

Built in 1989 - $14M to Rebuild
(Photos c. 1993, courtesy ANG)

Sherman (2006)
AAR Must be Prevented !!

In 2010, there is no excuse to construct a structure at risk of AAR!

1. Properly recognize the potential alkali-reactivity of aggregate
2. Select and use appropriate preventive action(s) in the presence of reactive aggregates
Lab Testing

- $T^o$ increases
- alkali content increases
- particle size decreases

25 years

14-28 days

3-24 months

50 years
AASHTO
Designation PP 65-10

Proven history of satisfactory field performance?
  No → Petrographic examination
  No → Aggregate potentially reactive?
    Yes → Petrographic examination
    No → Is the rock a quarried carbonate?
    No → Chemical examination (CSA A23.2-26A)
      Composition → ACR?
      No → Concrete Prism Test, ASTM C 1105
        Expansion < limits?
        No → Accelerated Mortar Bar Test (ASTM C 1260)
          Is 14-day expansion > 0.10%?
          No → Concrete Prism Test, ASTM C 1293
            Is 1-year expansion < 0.04%?
            No → Type of reaction
              Expansion due to ACR or ASR?
              No → Alkali-silica reactive
                Take preventive measures or do not use?
              Yes → Alkali-carbonate reactive
                Reject from use
          Yes → Not reactive
            Accept for use.
            No precautionary measures necessary.
      Yes → Concrete Prism Test, ASTM C 1293
        Is 1-year expansion < 0.04%?
        No → Type of reaction
          Expansion due to ACR or ASR?
          No → Alkali-silica reactive
            Take preventive measures or do not use?
          Yes → Alkali-carbonate reactive
            Reject from use
      No → Not reactive
        Accept for use.
        No precautionary measures necessary.
  Yes → Accelerated Mortar Bar Test (ASTM C 1260)
    Is 14-day expansion > 0.10%?
    No → Concrete Prism Test, ASTM C 1293
      Is 1-year expansion < 0.04%?
      No → Type of reaction
        Expansion due to ACR or ASR?
        No → Alkali-silica reactive
          Take preventive measures or do not use?
        Yes → Alkali-carbonate reactive
          Reject from use
      Yes → Not reactive
        Accept for use.
        No precautionary measures necessary.
    No → Concrete Prism Test, ASTM C 1105
      Expansion < limits?
      No → Accelerated Mortar Bar Test (ASTM C 1260)
        Is 14-day expansion > 0.10%?
        No → Concrete Prism Test, ASTM C 1293
          Is 1-year expansion < 0.04%?
          No → Type of reaction
            Expansion due to ACR or ASR?
            No → Alkali-silica reactive
              Take preventive measures or do not use?
            Yes → Alkali-carbonate reactive
              Reject from use
          Yes → Not reactive
            Accept for use.
            No precautionary measures necessary.
AASHTO
Designation PP 65-10

Proven history of satisfactory field performance?

- No
  - Petrographic examination
    - Aggregate potentially reactive?
      - No
      - Yes
        - Petrographic examination
          - Is the rock a quarried carbonate?
            - No
            - Yes
              - Chemical examination
                - (CSA A23.2-26A)
                  - Composition → ACR?
                    - Yes
                    - No
                      - Either
                        - Concrete Prism Test, ASTM C 1105
                          - Expansion < limits?
                            - Yes
                            - No
                              - Accelerated Mortar Bar Test (ASTM C 1260)
                                - Is 14-day expansion > 0.10%?
                                  - Yes
                                  - No
                                    - Concrete Prism Test, ASTM C 1293
                                      - Is 1-year expansion < 0.04%?
                                        - Yes
                                        - No
                                          - Type of reaction
                                            - Expansion due to ACR or ASR?
                                              - Yes
                                              - No
                                                - Alkali-silica reactive
                                                  - Take preventive measures or do not use?
                                                    - Yes
                                                    - No
                                                      - Alkali-carbonate reactive
                                                        - Reject from use
                                                          - No precautionary measures necessary.
                                                            - Not reactive
                                                              - Accept for use.
                                                                - Either
                                                                  - Yes
                                                                  - No
                                                                    - No
                                                                      - No
                                                                        - No
                                                                             - Yes
                                                                                 - No
                                                                                     - Yes
                                                                                       - No
                                                                                        - Yes
                                                                                             - No
                                                                                                 - Yes
                                                                                                     - No
                                                                                                         - Yes
                                                                                                             - No
                                                                                                                 - No
                                                                                                                     - Yes
                                                                                                                         - No
                                                                                                                             - Yes
                                                                                                                                - No
                                                                                                                                    - Yes
                                                                                                                                 - No
                                                                                                                                               - Yes
                                                                                                                                                    - No
                                                                                                                                                           - Yes
                                                                                                             - ACR
                                                                                               - ASR
                                                                                     - Not reactive
                                                                                       - Accept for use.
                                                                                         - No precautionary measures necessary.
                                                                       - Not reactive
                                                                             - Accept for use.
                                                                                 - No precautionary measures necessary.
Field Performance Survey of AAR

- Structure > 10 years old
- Structure incorporating high alkali levels
- Structure exposed to severe conditions (moisture)
- No “preventive measures” used (pozzolans, etc.)
Proven history of satisfactory field performance? 

Petrographic examination
Aggregate potentially reactive?

Chemical examination (CSA A23.2-26A)
Composition \(\rightarrow\) ACR?

Concrete Prism Test, ASTM C 1105
Expansion < limits?

Accelerated Mortar Bar Test (ASTM C 1260)
Is 14-day expansion > 0.10%?

Concrete Prism Test, ASTM C 1293
Is 1-year expansion < 0.04%?

Type of reaction
Expansion due to ACR or ASR?

Alkali-silica reactive
Take preventive measures or do not use?

Alkali-carbonate reactive
Avoid reactive component or do not use?

Not reactive
Accept for use. No precautionary measures necessary.
Petrographic Examination

- **Essential step:**
  - Nature of aggregate (ACR, ASR)
  - Select best test to perform

- Risky to accept/reject aggregates based on petrographic examination only.
Proven history of satisfactory field performance?

Petrographic examination
Aggregate potentially reactive?

Chemical examination
(CSA A23.2-26A)
Composition → ACR?

Concrete Prism Test, ASTM C 1105
Expansion < limits?

Accelerated Mortar Bar Test (ASTM C 1260)
Is 14-day expansion > 0.10%?

Concrete Prism Test, ASTM C 1293
Is 1-year expansion < 0.04%?

Type of reaction
Expansion due to ACR or ASR?

Alkali-silica reactive
Take preventive measures or do not use?

Alkali-carbonate reactive
Avoid reactive component or do not use?

Not reactive
Accept for use. No precautionary measures necessary.
Proven history of satisfactory field performance?

No

Petrographic examination Aggregate potentially reactive?

No

Chemical examination (CSA A23.2-26A) Composition → ACR?

Yes

Concrete Prism Test, ASTM C 1105 Expansion < limits?

Yes

Accelerated Mortar Bar Test (ASTM C 1260) Is 14-day expansion > 0.10%?

No

Concrete Prism Test, ASTM C 1293 Is 1-year expansion < 0.04%?

Yes

Type of reaction Expansion due to ACR or ASR?

ASR

Alkali-silica reactive Take preventive measures or do not use?

No

ACR

Alkali-carbonate reactive Avoid reactive component or do not use?

Not reactive Accept for use. No precautionary measures necessary.
Accelerated Mortar Bar Test → ASR

- Mortar bars, 25 x 25 x 285 mm in size
- Particle size: 0.15 – 4.75mm
Accelerated Mortar Bar Test → ASR

- Immersed 1N NaOH @ 80°C for 14 days
- Severe test conditions;
  ~ good screening test
  ➢ Not to be used for rejecting aggregates
Accelerated Mortar Bar Test (AMBT)

- **Time in the 1N NaOH solution (days)**
- **Expansion (%)**

**Aggregate potentially reactive** ➔ run CPT

**Exp. Limit** ➔ 0.10 – 0.20%

**Aggregate non reactive**
Proven history of satisfactory field performance?

Petrographic examination
Aggregate potentially reactive?

Petrographic examination
Is the rock a quarried carbonate?

Chemical examination
(CSA A23.2-26A)
Composition \(\rightarrow\) ACR?

Concrete Prism Test, ASTM C 1105
Expansion < limits?

Accelerated Mortar Bar Test (ASTM C 1260)
Is 14-day expansion > 0.10%?

Concrete Prism Test, ASTM C 1293
Is 1-year expansion < 0.04%?

Type of reaction
Expansion due to ACR or ASR?

Alkali-silica reactive
Take preventive measures or do not use?

Alkali-carbonate reactive
Avoid reactive component or do not use?

Not reactive
Accept for use. No precautionary measures necessary.
Concrete Prism Test → ASR & ACR

- Concrete prisms, 75 x 75 x 300-400 mm in size
- Cement content of 420 kg/m³
- Particle size: -20 + 5 mm
- Alkalis boosted to 1.25% Na₂Oeq, by cement mass
Concrete Prism Test ➔ ASR & ACR

- Prisms stored at 38°C and R.H. > 95%

Test Method (CSA, ASTM, RILEM)
Concrete Prism Test (CPT)

Expansion (%)

Aggregate potentially reactive ⇒ select preventive measure

Exp. Limit ⇒ 0.040%

Aggregate non reactive

Time at 38°C and R.H. > 95% (months)
Storage Conditions (60°C) – “Reactor”

“Reactor” and Steel boxes

“Reactor” and Plastic pails
The graph illustrates the comparison between ACPT (60°C) and Conventional (38°C) CPT (Cone Penetration Testing) for one-year and three-month expansion percentages.

The equation fitted to the data is:

\[ y = 0.8457x + 0.0041 \]

with a coefficient of determination \( R^2 = 0.861 \).

The data points are categorized as follows:
- Tremblay et al. [10]
- Murdock & Blanchette [4]
- Touma et al. [7]
- DeGrosbois and Fontaine [6]
- Fournier et al. 2006 [62]
Proven history of satisfactory field performance?

Petrographic examination
Aggregate potentially reactive?

Chemical examination (CSA A23.2-26A)
Composition → ACR?

Concrete Prism Test, ASTM C 1105
Expansion < limits?

Accelerated Mortar Bar Test (ASTM C 1260)
Is 14-day expansion > 0.10%?

Concrete Prism Test, ASTM C 1293
Is 1-year expansion < 0.04%?

Type of reaction
Expansion due to ACR or ASR?

Alkali-silica reactive
Take preventive measures or do not use?

Alkali-carbonate reactive
Avoid reactive component or do not use?

Not reactive
Accept for use. No precautionary measures necessary.
Preventive Measures Against ASR

Reactive Material in the aggregates

Sufficient Alkali

Sufficient Moisture
Preventive Measures Against ASR

- Use non-reactive aggregate

  » Not always possible; not available; transport NR aggregates over long distances → $$, GHG emissions!

  » Selective quarrying

  » Aggregate beneficiation
Limiting the alkali content in concrete

![Graph showing the relationship between concrete alkali content and expansion](image)

- **Concrete alkali content** (kg/m³):
  - 3 kg/m³
  - 5 kg/m³

- **Expansion limit**:
  - Expansion limit is indicated by a horizontal line at 0.04%.

- **Concrete prism expansion** (1 yr), %:
  - The graph shows the expansion of concrete with different alkali contents over a period of 1 year.
Preventive Measures

- Control the alkali content of the concrete mixture

Internal contribution from sea-dredged sand

Internal contribution from aggregates
Preventive Measures Against ASR

- Use a sufficient amount of efficient SCM(s)

GGBFS

Blast furnace

Fly ash
Field Performance of FA Concrete

- Hydraulic dams (Northern Ontario, Canada)

Frederic House River Dam

Conventional concrete → no SCMs
Field Performance of FA Concrete

- Hydraulic dams (Northern Ontario, Canada)

High-alkali cement + 30% Class F FA
Field Performance of FA Concrete

- Lower Notch dam (Northern Ontario, Canada)
Pavement sections (New Mexico, USA) (1992)

Source: www.google.maps.com
## Pavement sections (New Mexico, USA)

<table>
<thead>
<tr>
<th>East</th>
<th></th>
<th>West</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grevey aggregate pit</td>
<td>Shakespeare aggregate pit</td>
<td></td>
</tr>
<tr>
<td>507.8'</td>
<td>307.4'</td>
<td></td>
</tr>
<tr>
<td>200.4'</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Grevey Aggregates
- **East Section**: 20.4'
  - Class C fly ash
  - 1% LiOH
  - Control
  - Class C fly ash
- **West Section**: 28.7'
  - Class C fly ash
  - Blended C + F fA
  - Class F fly ash
  - Class F fly ash
  - 0.5% LiOH
  - 1% LiOH

### Shakespeare Aggregates
- **East Section**: 20.4'
  - Class C fly ash
  - 1% LiOH
  - Control
  - Class F fly ash
- **West Section**: 28.7'
  - Class C fly ash
  - Blended C + F fA
  - Class F fly ash
  - Class F fly ash
  - Lomar at 20 ounces per 100wt
  - 0.5% LiOH
  - 1% LiOH

Source: USDOT, 2006
Field performance of fly ash concrete

- Pavement sections (New Mexico, USA) (15 years)

Testing site

Mix of Class C & F fly ashes

Class C fly ash
Field performance of fly ash concrete

- Pavement sections (New Mexico, USA) (15 years)
Effect of FA Composition on ASR Expansion

- Mixtures with 25% fly ashes

![Graph showing the effect of fly ash composition on ASR expansion](image)

Spratt limestone (highly-reactive)

- **Fly Ash CaO / Na₂Oe**
  - 30.0/2.26
  - 15.9/8.46
  - 21.5/1.94
  - 13.6/3.77
  - 5.57/2.30

Control

(Thomas, UNB)
Effect of FA Composition on ASR Expansion

Spratt limestone (highly-reactive)

Control

Fly Ash
CaO / Na₂Oe
30.0/2.26
15.9/8.46
21.5/1.94
13.6/3.77
5.57/2.30

Expansion (%)

Age (Weeks)

(Thomas, UNB)

Efficacy against ASR ↓ with ↑ %CaO and %Na₂Oe
Effect of FA Composition & Proportion on ASR Expansion

Spratt limestone

- Fly ash: 27.7% CaO
- Fly ash: 20.6% CaO
- Fly ash: 12.4% CaO
- Fly ash: 6.4% CaO

CSA expansion Limit at 2 years

(Thomas et al. 1999)
Effect of fly ash composition on the chemistry of the concrete pore solution

*Cement paste with high-alkali cement & 25% FA*

<table>
<thead>
<tr>
<th>Fly ash CaO / Na$_2$O$_e$</th>
<th>Control CaO / Na$_2$O$_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.7 / 1.65</td>
<td>27.7 / 1.65</td>
</tr>
<tr>
<td>17.5 / 1.68</td>
<td>17.5 / 1.68</td>
</tr>
<tr>
<td>13.6 / 3.77</td>
<td>13.6 / 3.77</td>
</tr>
<tr>
<td>6.38 / 1.41</td>
<td>6.38 / 1.41</td>
</tr>
</tbody>
</table>

(Shehata and Thomas, U. of Toronto)
Silica Fume against ASR

Fournier et al. 1995
Metakaolin against ASR

Moderately-reactive aggregate

Highly-reactive aggregate

Ramlochan et al. 2000
Effect of Slag on ASR Expansion

Expansion at 2 Years (%)

Slag Level (%)

Siliceous Limestone
Greywacke
Sandstone
Granite

(Thomas & Innis 1998)
Preventive Measures Against ASR

- Use a sufficient amount of a chemical admixture (lithium-based product)
Lithium-based admixtures
History and Background

McCoy and Caldwell (1951) → lithium compounds (LiF, Li₂CO₃, LiCl et LiNO₃) can suppress expansion due to ASR.

Renewed interest in lithium compounds, starting late 1980’s

Little research on using lithium to control ASR…

Adapted from Thomas & Folliard (2002)
Factors Influencing the Effectiveness of Lithium to Reduce ASR Expansion

- Alkali loading and nature of the reactive aggregate

- The main factor is the ratio lithium : alkali content of the concrete mixture

  i.e. Molar ratio $\left[ \text{Li} \right] / \left[ \text{Na} + \text{K} \right]$
Factors Influencing the Effectiveness of Lithium to Reduce ASR Expansion

- Alkali loading and nature of the reactive aggregate
- The main factor is the ratio of lithium to alkali content of the concrete mixture, i.e., Molar ratio $\frac{[\text{Li}]}{[\text{Na} + \text{K}]}$

Earlier research $\Rightarrow [\text{Li}] / [\text{Na} + \text{K}]$ of 0.74 is OK with a large number of reactive aggregates $\Rightarrow$ “Standard Dosage”
Lithium-based Admixtures

Standard Dosage ➞ molar ratio of 0.74

- 1 kg of LiOH•H₂O / kg of Na₂Oeq in the concrete
- 4.6 L of LiNO₃ solution / kg of Na₂Oeq in the concrete
Use of Lithium to control ASR expansion
Exposure blocks

New Mexico Reactive aggregate

- NM control
- NM LiOH 1.0
- NM LiNO$_3$ 1.0
- NM LiNO$_3$ 1.25
- NM LiOH 1.50

Expansion (%) vs Time (years)
Preventive Measures Against ASR

- Amount of lithium-based product needed varies depending on the reactive aggregate

(Tremblay et al. 2007)
Accelerated testing for lithium dosage

• CPT is the preferred test → 2-year, 0.04% exp limit)

• **Modified** version of AMBT
  • Lithium to be added in the bar and the soak solution
  • Expansion limit ~ 0.10% @ 28 days

To control leaching, ASTM C 1260 is modified by adding Li to the soak solution

Mortar Bars Immersed in Water or 1N NaOH
Modified AMBT – proposed approach

Begin by Testing the Aggregate with the following two mixtures:

1. Control mixture (Expansion at 28 days = E1)
2. Mixture with lithium: $[\text{Li}]/[\text{Na+K}] = 0.74$ in bar and $[\text{Li}]/[\text{Na}] = 0.148$ in soak solution (Expansion at 28 days = E2)

Is the $((E2-E1)/E1) < 0.1$

- **Yes**
  - Use the following equation:
    
    $1.0 + 0.7 \times ((E2-E1)/E1) = \text{Ratio}$
    
    The $\text{Ratio} = [\text{Li}]/[\text{Na+K}]$ to use in concrete

- **No**
  - Use concrete prisms test to evaluate the ratio to use

Tremblay et al. (2008)
Modified AMBT – proposed approach

Tremblay et al. (2008)
How does lithium help?

- Formation of a “stable” lithium silicate that “protects” the silica from attack by the alkali and hydroxil ions.

- Presence of lithium ions would reduce the dissolution of silica from reactive material.

- Formation of a non-swelling lithium-based reaction product (gel)
Summary on Preventing AAR

- For assuring long-term performance of concrete infrastructures → risk of deleterious expansion and cracking in concrete due to AAR should be prevented

- Preventing ACR → reject the aggregate !!

- Preventing ASR:
  - Use of non-reactive aggregates
  - Use appropriate amount of fly ash (minimum 20-30% Class Fly ash), slag (minimum 35%) or combinations of the above (ternary systems !!); better concrete !!
  - Use appropriate amount of chemical admixture (e.g. LiNO₃) → aggregate type, long term ?; $$
Summary on Preventing AAR

Select preventive measures:

- **Prescriptive approach → risk analysis**
  - Reactivity of the aggregate
  - Nature of the structure (includes design life)
  - Exposure conditions

- **Performance approach → testing in the laboratory**
How and When to Repair AAR-affected Concrete Structure???
Selecting the right time and the right method for mitigation

- Control of moisture
- Chemical treatments
- Strengthening
- Stress relief

Humidity

Reactive silica, Alkalis

Treat the cause ➔

Control the effect ➔ expansion
Evaluation of Mitigating measures in concrete structures affected by ASR (FHWA, USA)
Protocol for Selecting Alkali-Silica Reaction (ASR)-Affected Structures for Lithium Treatment

Publication No. FHWA-HRT-06-071
FHWA Contact: Fred Magdanz, HPO-11, 202-493-3976, fred.magdanz@fhwa.dot.gov

Objective
This TechBrief describes a protocol for evaluating damaged concrete structures to determine whether they are suitable candidates for lithium treatment to address alkali-silica reaction (ASR). A major part of the TechBrief’s source document, Protocol for Selecting Alkali-Silica Reaction (ASR)-Affected Structures for Lithium Treatment (FHWA-HRT-03-113), deals with the approaches that can be used to determine whether ASR is the principal cause, or only a contributing factor to, the observed deterioration (diagnosis); determine the extent of deterioration due to ASR in the structure; and evaluate the potential for future expansion due to ASR (progress). A full version of the report is available through the Federal Highway Administration (FHWA).

Introduction
Three conditions are necessary to initiate and sustain ASR in concrete (as shown in Figure 1):

- A sufficient amount of reactive silica (fines) must be present in the aggregate.
- The concentration of alkali hydroxides (NaOH, OH−, potassium (K+), hydraulic (CEM) in the concrete pore solution must be high enough.
- Sufficient moisture must be present.

Figure 1. The three necessary components for ASR-initiated damage in concrete.
Georgetown – Delaware (June 23-25, 2009)

Highway 113 North of Georgetown
Concrete pavement (Delaware)
Ettringite

ASR

Ettringite
Monitoring efficacy in-situ \(\rightarrow\) crack mapping

<table>
<thead>
<tr>
<th>Interval</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Base length (m)</th>
<th># cracks</th>
<th>Total cumulative</th>
<th>Avg. / crack</th>
<th>Avg. / m</th>
<th>Global Average (CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>Crack opening (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OA</td>
<td>0.1</td>
<td>0.1</td>
<td>0.8</td>
<td>--</td>
<td>--</td>
<td>1.9</td>
<td>1</td>
<td>6</td>
<td>4.8</td>
<td>0.8</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OB</td>
<td>0.05</td>
<td>0.05</td>
<td>0.9</td>
<td>0.03</td>
<td>0.05</td>
<td></td>
<td>1</td>
<td>7</td>
<td>0.8</td>
<td>0.11</td>
<td>0.8</td>
</tr>
<tr>
<td>OC</td>
<td>--</td>
<td>--</td>
<td>0.3</td>
<td>0.05</td>
<td>0.4</td>
<td>0.3</td>
<td>1.4</td>
<td>7</td>
<td>5.6</td>
<td>0.8</td>
<td>4.0</td>
</tr>
<tr>
<td>AB</td>
<td>0.5</td>
<td>0.2</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.3</td>
<td>1.4</td>
<td>8</td>
<td>5.05</td>
<td>0.63</td>
<td>3.6</td>
</tr>
</tbody>
</table>
Dimensional changes measurements
Georgetown – Delaware (June 23-25, 2009)

Topical application of LiNO$_3$ on about 25 km
- Water application (1 gal/1000 ft$^2$)
- 30% - LiNO$_3$ solution @ 1.5 gal/1000 ft$^2$
- Water application d’eau (1 gal/1000 ft$^2$) \[ \times 2 \]
Treatment → LiNO₃ application (3 gal / 1000 ft²) → limited penetration depth
Maine: I395 (Bangor / Brewer)

- I395 over Main
- I395 over Penobscot River
- 5th Parkway (Robertson) over I395
- South Parkway over I395
- Green Point Road over I395
- Rte 1A over 395
- Rte 1A over railroad
South Parkway over I 395

Site 1

Site 3
Damage Rating Index (DRI)
# ASR Petrographic Features & Associated Factors

<table>
<thead>
<tr>
<th>Petrographic feature</th>
<th>Abbreviation</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse aggregate with crack</td>
<td>CA</td>
<td>0.25</td>
</tr>
<tr>
<td>Open crack in coarse aggregate</td>
<td>OCA</td>
<td>4</td>
</tr>
<tr>
<td>Coarse aggregate with crack and gel</td>
<td>CA+G</td>
<td>2</td>
</tr>
<tr>
<td>Debonding coarse aggregate</td>
<td>DCA</td>
<td>3</td>
</tr>
<tr>
<td>Reaction rim</td>
<td>RR</td>
<td>0.5</td>
</tr>
<tr>
<td>Cement paste with crack</td>
<td>CP</td>
<td>2</td>
</tr>
<tr>
<td>Cement paste with crack and gel</td>
<td>CP+G</td>
<td>4</td>
</tr>
<tr>
<td>Gel in air void</td>
<td>V+G</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Grattan-Bellew and Danay (1992)
South Parkway over I 395

<table>
<thead>
<tr>
<th>S P 1</th>
<th>S P 2</th>
<th>S P 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
</tbody>
</table>

- CrCA
- OCrCA
- Cr+RPCA
- CrCP
- Cr+RPCP
- CAD
- RR
- RPAV

- 0
- 100
- 200
- 300
- 400
- 500
- 600
- 700
- 800
- 900

- 152
- 203
- 531
South Parkway over I395

Wrapping
Control
Control
Silane
Lithium (electro-chemical)
Control
South Parkway over I395

Electrochemical treatment
(LiNO$_3$)
South Parkway over I395

Wrapping
Hydro-Québec
Electrical towers
Québec City
Hydro-Québec Electrical towers Québec City

- Symptoms of deterioration
Concrete tower foundations - Québec city area
Expansion results according repair method

- Unrepaired (0.019%/year)
- Membrane (0.017%/year)
- Post-tensioned and membrane (0.012%/year)
- Splitted and encapsulation (0.006%/year)

(Durand 2000)
Management Actions on AAR Affected Concrete Structures

- Hydro-Québec Electrical towers Québec City
Median (Jersey) barriers, Leominster, MA
Median (Jersey) barriers, Leominster, MA

- Control sections
- Vacuum impregnation (LiNO$_3$)
- Topical application (silane, LiNO$_3$)
Median (Jersey) barriers → vacuum impregnation
Median (Jersey) barriers \(\rightarrow\) topical application (silane, LiNO\(_3\))
Topical applications (silane, LiNO$_3$), June 2005 → May 2010

2x Lithium topical + silane

Control

Silane (40%)
Topical applications (silane, LiNO₃), June 2005 → May 2010

4x Lithium topical

Control

2x Lithium topical + silane
Median (Jersey) barriers → sampling (Li profiling)
Median (Jersey) barriers $\rightarrow$ efficacy vacuum treatment
Median (Jersey) barriers → 4 LiNO₃ topical treatments
Use of Sealers
(Quebec City, Canada) – early 1990’s

![Graph showing internal humidity over time for sections sealed with and without sealers.]

Courtesy of M.A. Bérubé
early 1990’s

Control

Treated

Courtesy of M.A. Bérubé
Bridge structure – Houston, TX (USA) (2005)
Vacuum impregnation LiNO$_3$

Electrochemical treatment
Column #45
Penetration depth after vacuum treatment
Column #46-1 - Electrochemical treatment

8-week treatment before sampling over rebars
Profiles for Li, Na & K ions in the column (electrochemical treatment)
Conclusions

- Strong measures should be applied to prevent AAR in new concrete constructions
  - Testing of aggregate combinations
  - Application of appropriate preventive measures

- Critical challenge for engineers → how to manage concrete structures affected by AAR !?
  - Proper diagnosis of the source of the problem
  - Establish prognosis → expansion to date and for future → select appropriate management action
Thank you very much for your attention !!
Muito obrigado !!
Mactaquac Dam, Eastern Canada

- Intake
- Main Dam
- Diversion sluiceway
- Main spillway
- Powerhouse
Mactaquac Dam, Eastern Canada

- Aggregate accepted for use based on ASTM C 227 !!!!
- Vertical growing of the intake structure → ~ 18 cm
- Deformation rate → ~ 120 to 150 με/ano
- Expenses for ASR-related repairs → ~ $6M / year (> 75M$)
- 1 Billion $ to rebuild (2020)
Mactaquac Dam, Eastern Canada

Intake structure
Stress relief

Temporary solution for structures where AAR has not ceased → recutting often required