Alkali-Aggregate Reaction (AAR) of Concrete Structures
Outline

• What is AAR?

• How does AAR work?

• How to assess AAR?

• How to minimise AAR risk in new concrete structures?
AAR

• Alkali-silica Reaction (ASR):
  - only type of AAR occurred in HK

• Alkali-silicate Reaction

• Alkali-carbonate Reaction
Concrete failure due to ASR
Concrete failure due to ASR
Effect of ASR

- **Concrete Quality**
  - Loss of strength, stiffness, impermeability
  - Affect concrete durability and appearance
  - Premature failure of concrete structures

- **Economic Costs**
  - Maintenance cost increased
  - The life of concrete structure is reduced

- **Overall Result**
  - No concrete structures had collapsed due to ASR damage
  - Some concrete structures/members were demolished because of ASR
Example: Daqing Railway Bridge, China

- Railway Bridge built in 1987
- Precast prestressed concrete beams cast at Gaogezehuang, North of Beijing
Example: Daqing Railway Bridge, China
Example: Daqing Railway Bridge, China
Local Example in HK

Shek Wu Hui Treatment plant

Built in early 1980s
ASR was reported in 1991
Local Example in HK

Shek Wu Hui Treatment plant
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Shek Wu Hui Treatment plant
## Local Examples of ASR

### Structures Affected by ASR:

<table>
<thead>
<tr>
<th>Site</th>
<th>Year constructed</th>
<th>Year ASR reported</th>
<th>Approx. time for ASR to develop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shek Wu Hui Treatment Works</td>
<td>1980 - 1983</td>
<td>1991</td>
<td>about 9 - 12 years</td>
</tr>
<tr>
<td>Fan Ling Footbridges</td>
<td>1982</td>
<td>1998</td>
<td>16 years</td>
</tr>
<tr>
<td>North Point Govt. School</td>
<td>1987</td>
<td>about 1999</td>
<td>about 12 years</td>
</tr>
<tr>
<td>Hill Road Flyover</td>
<td>1982</td>
<td>1997</td>
<td>15 years</td>
</tr>
</tbody>
</table>
Local History of ASR

Background

• ASR was first diagnosed in HK (1991)
• AAR Sub-Committee under SCCT was set up

• **Hong Kong Specification**

• WBTC 14/94 issued
  3 Kg/m³ limit on reactive alkali content in concrete

• Quality Scheme for the Production and Supply of Concrete (QSPSC)
  Cl. 7.1.1(e) Use of chemical method ASTM C289

• Increasing use of AMBT (included in PS) in major concrete structures
How to assess ASR
Test for Potential ASR

- Reaction of alkali with silica is slow
- ASR can be accelerated by:
  - increasing temperatures,
  - increasing moisture availability,
  - increasing alkali concentrations
Common Test Methods to assess ASR

- Petrographic Examination
- Chemical Test
- Accelerated Mortar Bar Test (AMBT)
- Concrete Prism Test (CPT)
- Accelerated Concrete Prism Test (ACPT)
# Common Test Methods to assess ASR

<table>
<thead>
<tr>
<th>Test Method</th>
<th>RILEM</th>
<th>ASTM Standard</th>
<th>Canadian Standard</th>
<th>British Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petrographic Examination</td>
<td>AAR-1</td>
<td>ASTM C295</td>
<td>---</td>
<td>BS 812:Part 104</td>
</tr>
<tr>
<td>Accelerated Mortar Bar Test (AMBT)</td>
<td>AAR-2</td>
<td>ASTM C1260</td>
<td>CSA A23.2-25A</td>
<td>DD 249: 1999</td>
</tr>
<tr>
<td>Concrete Prism Test (CPT)</td>
<td>AAR-3</td>
<td>ASTM C1293</td>
<td>CSA A23.2-14A</td>
<td>BS 812:Part 123</td>
</tr>
<tr>
<td>Accelerated Concrete Prism Test (ACPT)</td>
<td>AAR-4</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Chemical Method</td>
<td></td>
<td>ASTM C289</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Petrographic examination of concrete cores from Shek Wu Hui Treatment Plant

Crack running through aggregate particle and into surrounding cement paste
Use of Chemical Method (ASTM C289)

**FIG. 2** Illustration of Division Between Innocuous and Deleterious Aggregates on Basis of Reduction in Alkalinity Test
Use of AMBT in HK

- PWL CON 5.5 Method
- RILEM AAR-2
- Others: ASTM C1260, CSA A23.2-25A
**Public Works Central Laboratory**

**Flow Chart for Rilem TC-106-2**

- **Cure at 20 ± 1°C and RH >90%**
- **Immerse in distilled water at room temp and put in oven at 80 ± 2°C**
- **Immerse in 1M NaOH at 80 ± 2°C**

**CASING**

- **CASTING**
- **1 DAY**
- **2 DAY**
- **3 DAY**
- **7 DAY**
- **9 DAY**
- **14 DAY**
- **16 DAY**

**Demould**

- **(L₁)**
- **(L₀)**

**Ln**

- **1 day**
- **4 days**
- **2 days**
- **5 days**
- **2 days**

**Expansion (%) = \( \frac{L_n - L_0}{Gauge \ length} \times 100\% \)**

**gauge length = L₀ - 2studs length**
AMBT Results of Local & Reference Aggregate
AMBT Results of Local & Reference Aggregate
Cure at 20 ± 2 °C and RH ≥ 90% under moist covers

Cure inside the container in environment of 20 ± 2 °C

Cure inside the container in environment of 38 ± 2 °C, 24 hours before each measurement, allow container with prism to cool at 20 ± 2 °C.

Measurement of weight (W_n) and length comparator reading (R_n).

24 ± 0.5 hours 24 hours 5 days 1 week 2 weeks 9 weeks 13 weeks 26 weeks

Demould, wrapped with cotton cloth, polyethylene tubing, and polyethylene bag, stored in container.

Measure initial length (L_i), initial weight (W_2) & length comparator reading (R_2)

Measurement at day 7 (R_7, W_7)

Measurement at 2 weeks (R_14, W_14)

Measurement at 4 weeks (R_28, W_28)

Measurement at 13 weeks (R_91, W_91)

Measurement at 26 weeks (R_182, W_182)

Measurement at 52 weeks (R_364, W_364)

Percentage increase in weight ( % ) = \( \frac{W_n - W_2}{W_2} \times 100\% \)

Where W_n is the weight at n days age.

Percentage increase in length ( % ) = \( \frac{L_n - L_i}{L_i} \times 100\% \)

Where L_n is the length of prism with studs at n days age.

(L_n = R_n + calibrated length of reference bar)

1 week 2 weeks 4 weeks 13 weeks 26 weeks 52 weeks
Steel Mould for Casting
Concrete Prism
CPT: RILEM AAR-3

• Steel Mould with Gauge Studs
CPT: RILEM AAR-3
Concrete Prism

CPT: RILEM AAR-3
Container for Storing Concrete Prism
CPT: RILEM AAR-3

- Interior of Container
CPT: RILEM AAR-3

- Interior of Oven
Measurement of Prism with Length Comparator
ACPT

- A Faster test when compared with CPT
- Determination of alkali threshold limit
- Performance test for concrete mix

- Development of ACPT will be the next task of PWCL
ASR Testing Methods

- Hong Kong Experience
  - Chemical test is not reliable
  - AMBT show reliable result
  - CPT is under development by PWCL
  - Development of ACPT will be the next task
Preventive Measures against ASR
in New Concrete Structures
Factors affecting ASR Reactivity

- Reactivity of the siliceous material
- Total alkali content of the concrete
- Supply of moisture
Preventive Measures against ASR

- **Cements**

  - Limiting the alkali content of the mix, means that a low-alkali cement have to be used
  
  - most countries adopted the limit of 0.60% Na$_2$O equivalent
Preventive Measures against ASR

- **Restriction of alkali level in concrete**

<table>
<thead>
<tr>
<th>Country, Region</th>
<th>Alkali Level (Kg/m³ Na₂O equivalent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada, Denmark</td>
<td>1.8 to 3.0 Kg/m³ Na₂O equivalent, depending on information about AAR reactivity of aggregate and the level of risk</td>
</tr>
<tr>
<td>South Africa</td>
<td>2.0 to 4.5 Kg/m³ Na₂O equivalent, depending on information about AAR reactivity of aggregate</td>
</tr>
<tr>
<td>New Zealand</td>
<td>2.5 Kg/m³ Na₂O equivalent</td>
</tr>
<tr>
<td>UK</td>
<td>2.5 to 5.0 Kg/m³ Na₂O equivalent, depending on information about AAR reactivity of aggregate</td>
</tr>
<tr>
<td>Belgium, China, Japan, USSR</td>
<td>3.0 Kg/m³ Na₂O equivalent</td>
</tr>
<tr>
<td>France</td>
<td>3.0 to 3.5 Kg/m³ Na₂O equivalent, depending on information about variability of cement alkalis</td>
</tr>
<tr>
<td>Ireland</td>
<td>4.0 Kg/m³ Na₂O equivalent but 4.5 Kg/m³ Na₂O equivalent if reactive aggregate is only Carboniferous chert</td>
</tr>
</tbody>
</table>
Preventive Measures against ASR

- Supplementary Cementitious Materials (SCM)
- Pulverized-fuel ash (PFA)
- Ground granulated blastfurnace slag (GGBS)
- Microsilica, also called silica-fume
Preventive Measures against ASR

• **Use of Cementitious Replacement Materials**

• PFA, GGBS used in most countries

• microsilica used in Australia, Belgium, Canada, Denmark, Iceland, New Zealand, South Africa & USA

• **Usual Range of Replacement Levels**
  – 15 to 40% PFA
  – 25% to 70% GGBS
  – 7% to 15% microsilica
Preventive Measures against ASR

• Aggregates

• If the aggregate is non-reactive, no other precautions are necessary

• If not, a variety of precautions are invoked

• Preclusion of reactive aggregates from particular uses.
Preventive Measures against ASR

• **Moisture**

• Reduce the access of moisture and maintain the concrete in a sufficiently dry state
Preventive Measures against ASR

• Others

• Modify the properties of any gel such that it is non-expansive, e.g. using lithium salts
Review of International Practice with ASR

- **3 Basic Approaches**

  - (1) aggregates are classified as reactive or innocuous; mitigation measures are prescribed for use with reactive aggregates.

  - (2) the reactivity of an aggregate is first classified; mitigation measures are prescribed for use of the aggregate according to the nature of the structure and the environment it is in.

  - (3) consideration starts with the nature of structure to be constructed and the service environment; aggregate reactivity is considered for the choice of supply sources and the mitigation measures needed to prevent AAR.
Typical Framework

- Determination the level of precaution
- Characterisation of the structural needs
- Characterisation of the environment
Classes of Structures

• Structures classified by risk category

• S1 – some deterioration from AAR is acceptable, e.g. temporary or short service life structures, easily replaceable elements

• S2 – minor AAR and resulting cosmetic cracking is acceptable, e.g. most building and civil engineering structures

• S3 – no AAR damage is acceptable, even if only cosmetic - long service life or highly critical structures, e.g. nuclear installations, dams, tunnels, exceptionally important bridges or viaducts, structures retaining hazardous materials
Classes of Environment

• Characterisation of the environment

• E1 – protected from external moisture, e.g. internal concrete within buildings, external concrete protected by cladding

• E2 – exposed to external moisture, e.g. internal concrete within buildings where humidity is high (laundries, swimming pools), external concrete exposed to atmosphere

• E3 – exposed to external moisture + aggravating factors such as de-icing salts, freezing and thawing or a marine environment
### Level of Precaution

- An example of Level of Precaution
- P1 – no special precautions against ASR
- P2 – normal level of precaution
- P3 – special level of precaution

<table>
<thead>
<tr>
<th>Environment Category</th>
<th>E1</th>
<th>E2</th>
<th>E3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category of Structure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>P1</td>
<td>P1</td>
<td>P1</td>
</tr>
<tr>
<td>S2</td>
<td>P1</td>
<td>P2</td>
<td>P2</td>
</tr>
<tr>
<td>S3</td>
<td>P2</td>
<td>P3</td>
<td>P3</td>
</tr>
</tbody>
</table>
Example of Control Framework: RILEM: Draft International Specification to Minimise Damage from ASR in Concrete

• **Level of Precaution**
  - **P1** – no special precautions against ASR
  - **P2** – normal level of precaution
    - M1: Restrict the alkalinity of pore solution, e.g. limit the alkali content of concrete, use of low alkali cement, include PFA, GGBS, etc.
    - M2: Avoid the presence of a critical amount of reactive silica, e.g. identify non-reactive aggregate
    - M3: reduce the access of moisture and maintain the concrete in a sufficiently dry state, e.g. use external cladding or tanking
    - M4: modify the properties of any gel such that it is non-expansive, e.g. use lithium salts

• **P3** – special level of precaution
  Combined application of at least two of the precautionary measures from level 2
What shall we do?

What we know:

• Which reactants involved and their sources
• How alkali-silica gel is created
• ASR prevention can be achieved by using low alkali cement and non-reactive aggregate
• Cement replacement such as PFA, GGBS and microsilica help mitigate ASR damage

What we don’t know:

• Cement Replacement: its mechanism of inhibition, which compounds work best, how much of each compound is needed to prevent expansion, its long term performance
• Which test method most suit local aggregate
What shall we do?

- SCCT: Review of Concrete Related Standards
  - (1) Cement Standard
  - (2) Aggregate Standard
  - (3) Unifying Concrete Specification
  - (4) CS1 - Concrete Testing
  - (5) CS2 – Reinforcement Bar

- Proposed framework for controlling risk of ASR in Hong Kong is being prepared and will be circulated to relevant parties
THANK YOU