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Degradation of ASR and DEF in concrete with International case studies

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Contents

Alkali silica reactions (ASR) in concrete

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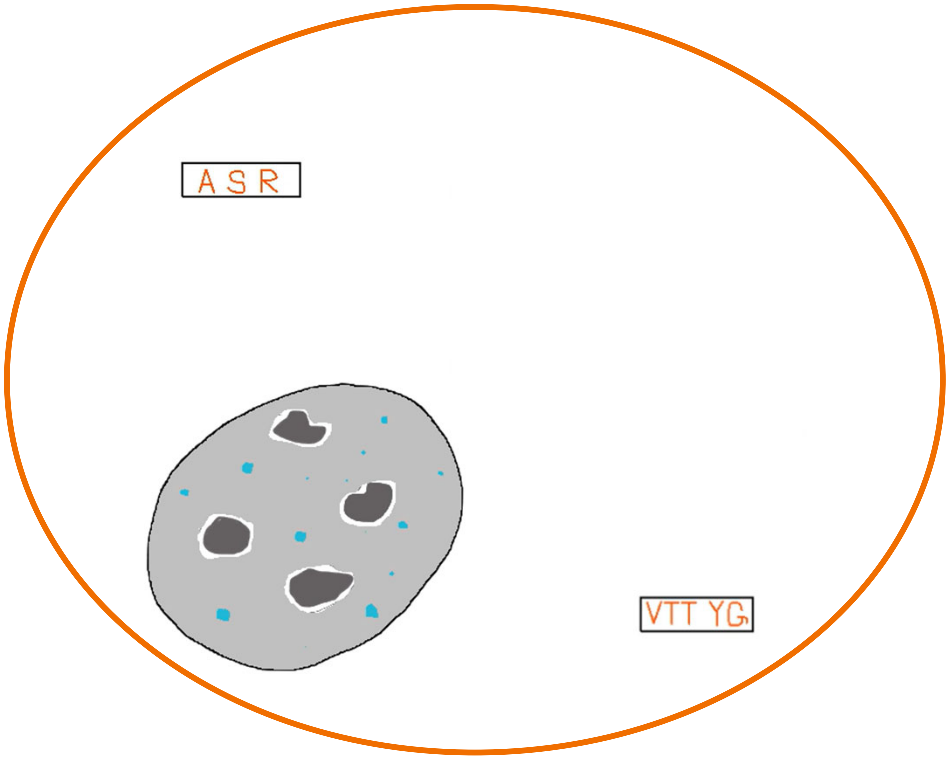
What is ASR?
ASR is a harmful deterioration mechanism caused by the reaction between reactive **silica** in aggregates and **alkali** hydroxides (Na+, K+, OH-) in concrete pore solution.

Reactive Aggregates

Na^{+}, K^{+}, Ca^{2+}, OH-
Ions are dominated in concrete pore solution

In presence of **reactive silica**, the **Na^{+}, K^{+}** and OH^{-} react with **SiO_2**

Alkali Silica Gel
formed around and within the aggregate structure



Alkali silicate hydrate gel (expansion)
The gel absorb water then expands and swelling gel over time

ASR Concrete degradation

Cracks,
Loss of strength/stiffness,
Serviceability issues in bridges, dams, and other concrete structures.

Delayed ettringite formation (DEF) in concrete

What is DEF?
DEF is an internal swelling reaction (ISR) caused by the late formation of **ettringite** (AFt) in hardened concrete. AFt forms after an initial **high-temperature** phase has dissolved early-age AFt.

Cement with **sulfate content**

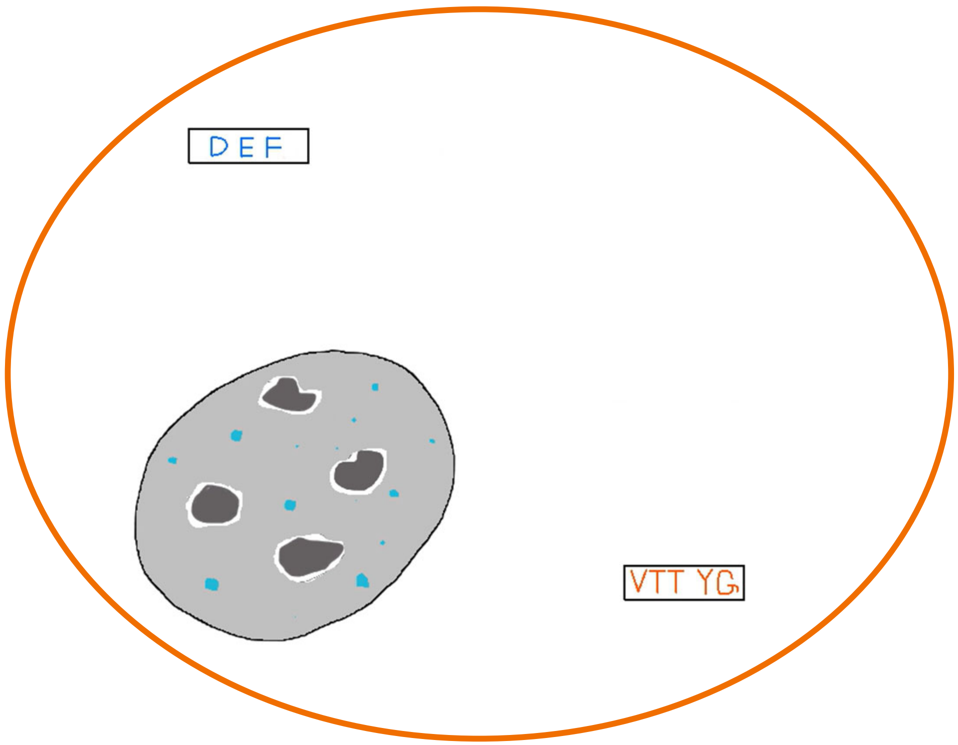
Temperature exceeds **~65°C**

Primary Aft dissolution

Followed by a **cooling**

Precipitation of AFt

Moisture availability



Ettringite formation (expansion)
The supersaturation pressure of Aft in pore solution drives concrete to expand

DEF Concrete degradation

Internal expansion, cracking, loss of stiffness, and potential durability performance of massive concrete structures.

Case study 1 – Monitoring of a Hydraulic Structure affected by ASR

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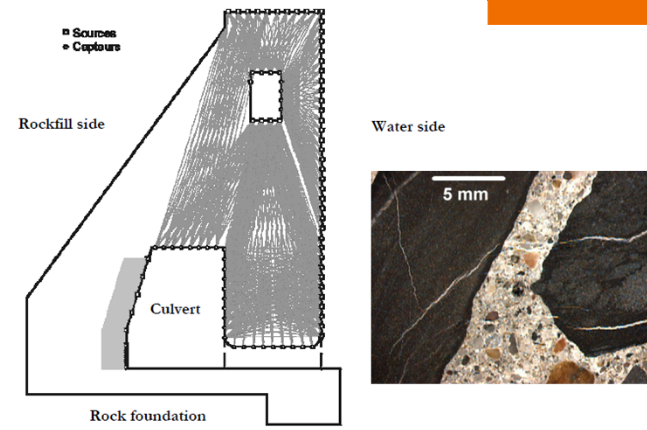
Background
- Large hydraulic structure in Eastern Canada – ASR active for 30+ years
- Issue observed: cracking, surface deterioration, horizontal displacement
- Goal: assess condition + understand extent of ASR damage

Key Findings
- Major deterioration concentrated in upper 2 m of concrete
- Lower structure remains structurally sound with good mechanical properties
- Major tensile crack identified running from gallery toward surface
- ASR progression is slow, deep concrete largely unaffected



Identification & Assessment Methods
1. Stress Measurements
- Strain-relief + flat-jack method
- Showed:
  - Longitudinal compressive stresses: 2-3.5 MPa
  - Transverse stress ~0 MPa (unrestrained expansion)

Identification & Assessment Methods
2. Seismic Tomography
- P-wave velocity mapping to identify internal defects
- Revealed:
  - Two low-velocity zones
  - Major tensile crack

Identification & Assessment Methods
3. Mechanical Testing (on drilled Cores D80mm)
- Compressive strength: 19.7-45.2 MPa (lower near surface); Indirect tensile strength: 2.4-4.3 MPa
- Young's modulus: 13.9-26.2 GPa
- ASR damage + freeze-thaw most evident near surface

Rivard, P., Ballivy, G., Gravel, C., Saint-Pierre, F. (2010): Monitoring of an hydraulic structure affected by ASR: A case study. Cement and Concrete Research (40): 676-680.

Case study 1 – Monitoring of a Hydraulic Structure affected by ASR

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Identification & Assessment Methods
4. Ultrasonic Pulse Velocity (on drilled cores)
- Compression-wave: 3000-5095 m/s
- Shear-wave: 1660-3440 m/s
- Lower velocities near surface; increase with depth

Identification & Assessment Methods
5. Petrography (Damage Rating Index (DRI))
- DRI values: 160-480 (significant ASR)
- High values due to cracks filled with gels
- Highest deterioration in top 1 m

Implications for Repair & Management
Monitoring Strategy
- Repeat tomography every 5 years
- Track crack development + ASR progression

Repair Focus
- Target upper 2 m of concrete
- Remove/replace deteriorated surface material
- Apply moisture-control or protective systems

Structural Condition
- Deeper concrete remains strong; large-scale structural repair unnecessary

Summary
- ASR damage is significant but mostly near the surface
- Structure retains good mechanical integrity at depth
- Seismic tomography was critical in locating internal cracking
- Combined methodology provides a comprehensive long-term monitoring approach

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Case study 2 – Characterisation of an ASR-affected concrete structure

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Background
- Rapid-des-Iles (RDI) hydro-electric dam in Quebec, Canada.
- Built between 1965-1967.
- Affected by moderately severe ASR, with vertical expansion around 1mm/y.

Key Findings
- Misalignment of turbine-generator units
- Map-cracking and structural cracking
- Long-term premature aging of concrete infrastructure

Identification & Assessment Methods
1. Concrete Coring and Mechanical Testing
Over 90 cores were extracted from the dam.
- Compressive strength + Indirect tensile strength;
- Elastic modulus: E; Poisson’s ratio

Major finding:
E of the in-service concrete decreased by ~68% 50+ years, showing significant ASR-related degradation.

Identification & Assessment Methods
2. Residual expansion (RE) and Ultimate expansion (UE)
Performed on 150 mm cores under:
- 100% RH at 38 °C (RE)
- 1M NaOH at 38 °C (UE)

Findings:
- RE approached an asymptote after ~1100 days
- UE did not reach an asymptote

3. Expansion under different stresses
- Free conditions,1-d, 2-d, and 3-d confinement

Key results:
- Higher vertical confinement restricted expansion; and lateral confinement had a strong effect on strain.
- ASR expansion continued even under 10 MPa stress, showing the reaction is not halted by in-situ stress.

Argouges, Matthieu, et al. "Characterization of an ASR-Affected Hydraulic Concrete Structure for Numerical Study." International Conference on Alkali-Aggregate Reaction in Concrete. Cham: Springer Nature Switzerland, 2024.

Case study 2 – Characterisation of an ASR-affected concrete structure

Identification & Assessment Methods
4. Creep Tests
Long-term creep tests (2028-2023) under 10 MPa load showed:

- Higher creep in new GORDI mixtures compared to RDI cores
- Asymptotic strain rates similar for all mixtures
- Elastic recovery proportion higher in older concrete

Identification & Assessment Methods
5. Fracture Energy Tests
Using wedge splitting tests with digital image correlation on large concrete blocks.
Findings:

- Fracture energy does not always decrease with ASR due to multi-cracking patterns
- Casting direction influences fracture behavior
- Numerical modelling of AAR with 3D scanning detecting heterogeneous swelling in mass concrete cylinders
- DRI correlated well with fracture energy and expansion

Argouges, Matthieu, et al. "Characterization of an ASR-Affected Hydraulic Concrete Structure for Numerical Study." International Conference on Alkali-Aggregate Reaction in Concrete. Cham: Springer Nature Switzerland, 2024.

Identification & Assessment Methods
6. ASR kinetics and stress-state Testing

- Accelerated mortar bar tests to evaluate reaction kinetics.
- Investigations of alkali availability
- Influence of particle size, silica content, and aggregate

Findings:

- ASR expansion strongly influenced by humidity
- Anisotropy observed in expansion
- Expansion continued even with significant applied stress
- Concrete in the dam exhibited more severe damage than newly prepared blocks at equivalent expansion levels

Implications for Repair & Management
Use of FEM Modelling for LT management

- Advanced FEM tools help predict structural performance and guide repair decisions

Improved diagnostic tools for repair planning:

- Damage Rating Index (DRI)
- Swelling Detection Testing (SDT)
- 3D laser scanning
- Fracture energy evaluation

Case study 3 – DEF identification in a RC bridge

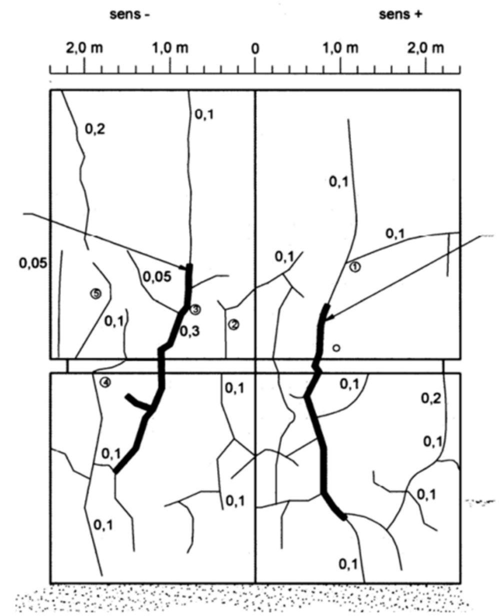
Background

- DEF in a massive reinforced-concrete bridge pier column (France, 2003)
- Observed widespread cracking several years after construction
- Visual surveys reported map-cracking, crack coalescence along restrained zones, and measurable displacements consistent with internal swelling.

Investigation & Identification methods
1. Crack mapping & displacement monitoring:
Established spatial patterns and progression, highlighting restraint-driven crack orientations and zones of higher swelling.

Investigation & Identification methods
2. Residual expansion on drilled cores:
Cores stored at high humidity/temperature showed continued expansion potential, supporting an internal swelling mechanism consistent with DEF.

Investigation & Identification methods
3. Petrography/SEM:
Identification of ettringite infilling microcracks/voids and interfacial transition zones, with absence of external sulfate attack features; these microstructural signatures are characteristic of DEF.



Cracking at the surface of the pier P1 (the thick lines correspond to injected cracks – crack width in mm).

Godart, Bruno, et al. "The effects of delayed ettringite formation on the expansion of a massive bridge pier and a precast prestressed concrete beam of a bridge." Proceedings of the 15th International Conference on Alkali Aggregate Reaction. 2016.

Case study 3 – DEF identification in a RC bridge

Investigation & Identification methods

4. Thermal assessment + FEM:

Estimated peak temperatures in the massive member, and used finite-element modeling to reproduce displacement /stress fields from swelling, aligning with observed damage.

Findings:

- The bridge pier's distress was consistent with DEF-driven internal swelling: map-cracking, expansion-induced displacements, and core residual expansion.
- Exposure conditions (high humidity/wetting) and elevated early temperatures significantly influenced the observed movements and stress redistribution.
- FEM results reinforced the diagnosis by matching measured displacement fields with swelling inputs calibrated from residual expansion data.

Repair/Management methods

- Moisture control to slow further ettringite growth
  - Enhance waterproofing and drainage; protect exposed faces to reduce water ingress.
- Targeted concrete repairs where damage is severe
  - Localized removal of highly cracked cover and patch repair with low-heat, sulfate-resistant repair materials; careful curing to avoid re-creating high temperature conditions.
- Structural assessment & strengthening
  - Use FEM to identify critical stress paths; apply strengthening (e.g., external reinforcement) if serviceability or ultimate capacity is threatened by stiffness loss or crack-induced durability risks.
- Long-term monitoring plan
  - Periodic crack width surveys, displacement/tilt monitoring, and repeat residual-expansion or core testing to track the kinetics of swelling and to trigger interventions early.

Case study 4 – Lessons learned from structures damaged by DEF

In France, several massive cast-in-place concrete structures — developed deterioration linked to DEF.

	Ondes 1955	Bourgogne 1990	Lodève 1980	Bellevue 1988	Beynost 1982	Cheviré 1988/89
Structural part	Cap beam	Base of pylon	Cap beam	Pier	Cap beam	Base of pier
DEF Occurrence	27 yrs	6 yrs	9 yrs	10 yrs	10 yrs	8 yrs
Environment	Waterproofing Problem	Immersed & variable imme.	Lack of drainage	Immersed & variable imme.	Exposure to rains	Rains and capillarity
T max (°C)	80	79	80	80	69	75
W/C ratio	0.50	0.45	0.47	0.54	0.49	0.48
Cement type	CEM I	CEM I	CEM I	CEM II/A	CEM I	CEM II/A
Cement (kg/m³)	430	400	400	380	350	385
SO3 (%)	2.5	2.8	2.6	2.5	3.4	2.5
C3A (%)	11.2	8.2	9.8	7.0	10.4	7.0
	Finnsementti CEM I 42.5 N SR 3 C3A (%) ≤ 3%					

Godart, Bruno, and Loïc Divet. "Lessons learned from structures damaged by delayed ettringite formation and the French prevention strategy." Fifth international conference on Forensic Engineering, Institution of Civil Engineers. 2013.

Case study 4 – Lessons learned from structures damaged by DEF

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Observed Symptoms

Engineers observed the following damage patterns across several affected structures:

- Widespread map-cracking in exposed faces
- Cracking in zones of restraint, such as re-entrant corners and embedded components
- Progressive expansion-induced displacement
- Cracks without a clear relation to mechanical loading
- No evidence of external sulfate sources

Investigation & Identification Methods

1. Petrographic Examination:

- Ettringite in cracks and voids
- Secondary ettringite forming after hardening
- No ASR gel or reaction rims
- No signs of external sulfate attack

These observations confirmed DEF as the primary mechanism.

Investigation & Identification Methods

3. Crack mapping and monitoring

- Crack widths
- Extent of expansion
- Later propagation under moisture cycles

Patterns consistent with DEF expansion were documented

Investigation & Identification Methods

2. Temperature history analysis

Thermal calculations and construction records showed:

- Internal temperature in massive placements could reach >65 °C
- Concrete placed during high ambient temperature (summer) was especially vulnerable.

Godart, Bruno, and Loïc Divet. "Lessons learned from structures damaged by delayed ettringite formation and the French prevention strategy." Fifth international conference on Forensic Engineering, Institution of Civil Engineers. 2013.

Case study 4 – Lessons learned from structures damaged by DEF

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Repair & Management Measures
1. Moisture reduction
- Improving drainage
- Applying waterproof barriers
- Reducing wetting cycles on exposed faces

Repair & Management Measures
2. Surface repair and crack treatment
- Removal of severely cracked cover concrete
- Replacement with low-heat, sulfate-resistant repair materials
- Strict curing controls to avoid renewed overheating

Key lessons:

- DEF can occur without steam curing, purely from the heat of hydration in mass concrete.
- Early-age temperatures above ~65°C pose significant risk.
- Moisture presence is essential for DEF progression.
- Prevention through thermal control is more effective than repair.
- Long-term monitoring is crucial for affected structures.

Repair & Management Measures
3. Structural monitoring and preventive strategy
France developed a national DEF prevention strategy:
- Mandatory thermal modelling for massive pours
- Limiting peak concrete temperature to 65°C
- Adjusting cement composition and binder choice
- Monitoring programs for structures with suspected DEF risk

Repair & Management Measures
4. Long-term condition assessment
Periodic:
- Crack mapping
- Stiffness evaluation
- Deformation tracking

Helping detect acceleration of DEF-related expansion.

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Conclusion

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1. A combination of measurements and simulation tools provides a reliable methodology for assessing ASR/DEF effects and predicting future behaviour.

2. Repair efforts should focus on the ASR/DEF-affected concrete, with removal of severely cracked cover and patch restoration using more resistant materials.

- Non-reactive aggregates for ASR;
- Sulfate-resistant cement for DEF.

3. Moisture-control or protective methods have been suggested as an efficient way to mitigate ASR/DEF deterioration effects.

4. Continuous monitoring and periodic safety evaluations remain crucial.

VTT competences on ASR & DEF

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Failure analyses
on core samples

Coupled
Chemo-Mechanical-Damage
model at multi-scales

RILEM AAR tests:
Alkali-reactivity of aggregates;
Concrete prism tests at 38 & 60 °C;
Concrete prism tests with external
alkali supply (60 °C).

Mineralogical phase
characterizations
SEM-EDS, XRD

ASR

DEF

RILEM AAR tests:
Performance concrete prism
tests at 38 & 60 °C.

Expansion
Measurements

Models assessing the
impact of
environmental factors

Upscalling
modelling

Thanks for your attention!