16th ICAAR LISBOA 2020-2022

16th International Conference on Alkali-Aggregate Reaction in Concrete

Lisboa | LNEC | Portugal | 31 May - 2 June 2022

consortium CONCRETE

RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

IRSN
INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

INTERNAL SWELLING REACTIONS IN MASSIVE STRUCTURES: MULTI-SCALE EXPERIMENTAL APPROACH

Jacques Jabbour, Aveline Darquennes, Loic Divet, Rachid Bennacer, Jean-Michel Torrenti, Georges Nahas

Email : jacques.jabbour@irsn.fr

LABORATÓRIO NACIONAL DE ENGENHARIA CIVIL

Industrial Context

- Extension of the operating life of nuclear power plants (LTO)
  - Safety assessment of nuclear civil engineering structures in terms of stability and confinement
  - The impact of ageing on the structures?
- Internal Swelling Reactions (ISR) are part of the concrete pathologies detected “recently”
- In nuclear structures, the probability of ISR can not be ruled out (massive structures/high early-age temperature, potential use of reactive aggregates).
- Multiple Nuclear Power Plants (NPP) have already been diagnosed with ISR, for instance:
  - Gentilly-2 (Canada) with ASR; Seabrook (USA) with ASR; Tihange-2 (Belgium) with ASR, DEF & carbonatation;

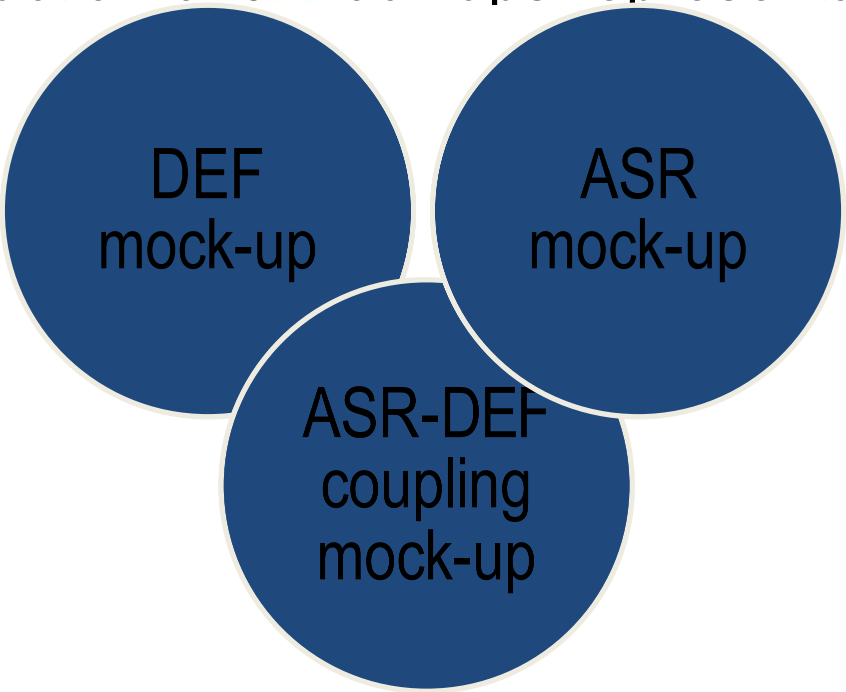
Scientific Context

- Swelling pathologies act at different scales: microscopic, mesoscopic and macroscopic.
- Laboratory studies of internal swelling reaction are usually realized on relatively small size samples.
- Those laboratory samples do not allow to reproduce real conditions to which is submitted the real concrete in its environment, in terms of kinetics, volume/surface ratio, thermal conditions especially in massive structures.
- There's a gap between conventional laboratory samples and the behavior of real scale massive structures.
- Therefore, an experimental protocol to accelerate internal swelling reactions of concrete on a structural scale has been developed at IRSN to allow a multi-scale experimental investigation of swelling reactions.

New experimental approach to accelerate the development of internal swelling reactions (ISR) in massive concrete structures;
Construction and Building Materials ; December 2021; https://doi.org/10.1016/j.conbuildmat.2021.125388

Conception of the project

- Construction of 3 mock-ups representative of massive structures



Concrete composition :
- **Representatif** of nuclear civil engineering structures
- **Equivalent chemical composition**
- **ASR: Calcareous non-reactive sand + siliceous reactive coarse aggregates**
- **DEF: Calcareous non-reactive sand + Calcareous non-reactive aggregates**

Early age thermal profile and aggregates type

DEF mock-up
heated at 80˚C for 3 days then cooled
non-reactive aggregates

ASR mock-up
Tmax < 65° C
reactive aggregates

ASR-DEF mock-up
heated at 80˚C for 3 days then cooled
Optimized granular composition
reactive aggregates

Conservation environnment

Water renewal each month for 14 months

DEF mock-up
Submerged at **20˚C**

ASR mock-up
Submerged at **38˚C**

ASR-DEF mock-up
Submerged at **38˚C**

Fabrication process

Device used for the early age heat treatement

Concrete mix (9 batch 400 L, 20-25 Min/batch)

Acquisition thermocouples/sensors

Cure

Conservation Environment

Non-reinforced structures
→ metallic support

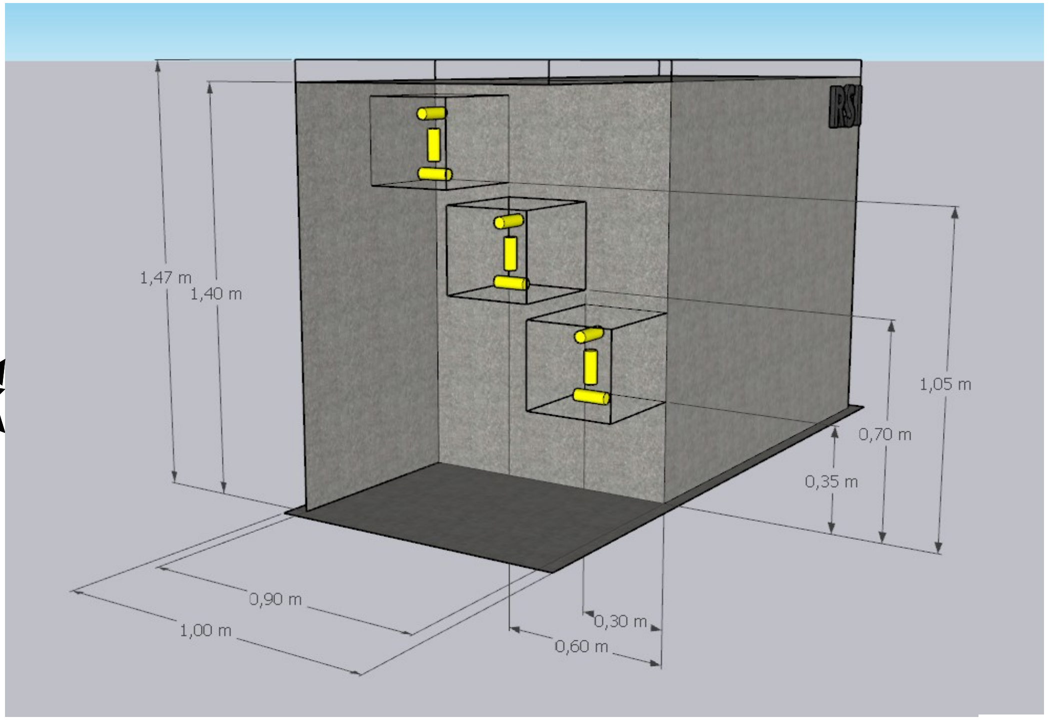
Conservation Environment:
→ submerged in a pool
→ water maintained at constant temperature
→ pool emptied monthly

Instrumentation of the mock-ups

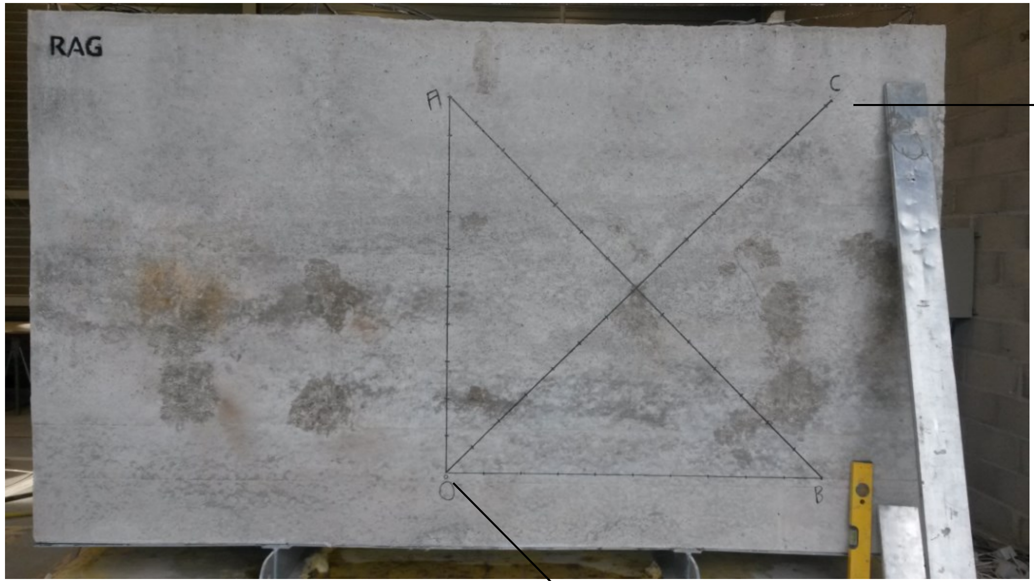
Instrumentation support system

16 thermocouples

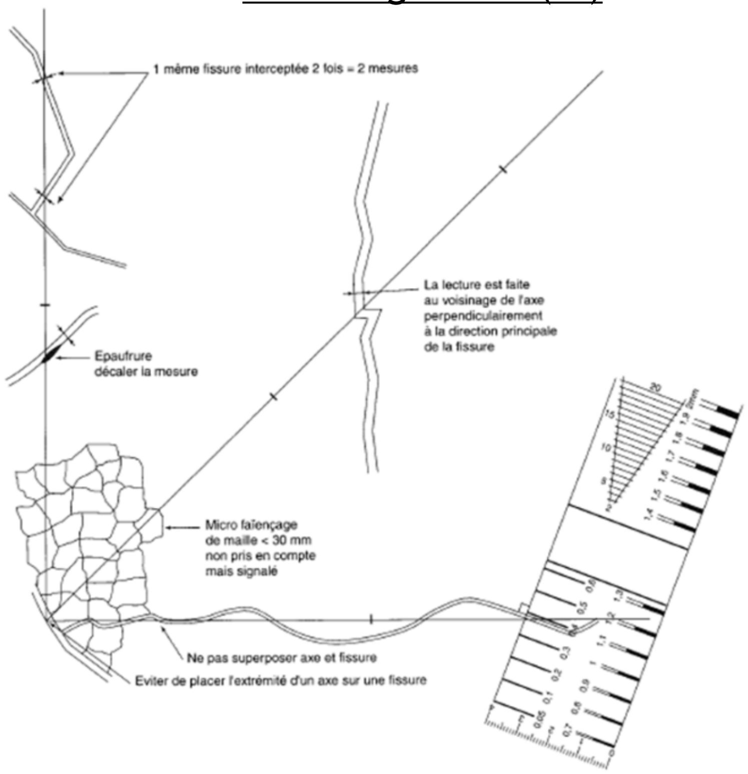
9 vibrating wire extensometers (3D)



Macroscopic follow-up of the cracking



Cracking Index (IF)



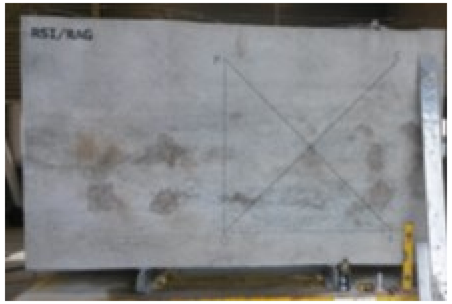
(Méthode d'essai des Laboratoires des Ponts et Chaussées, n°47)

IF = average crack opening per 1 m^2

Multi-scale Experimental campaign

Structural Scale: mock-ups

- Monitoring swelling
- Monitoring cracks (Damage Index)

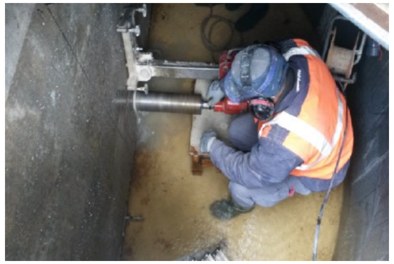


Specimen Scale: reconstituted concrete

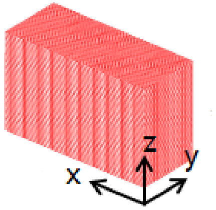
- Early age thermal profil: *identical as the mockups*
- Conservation environement: *equivalent to the pools*

Specimen Scale: Coring

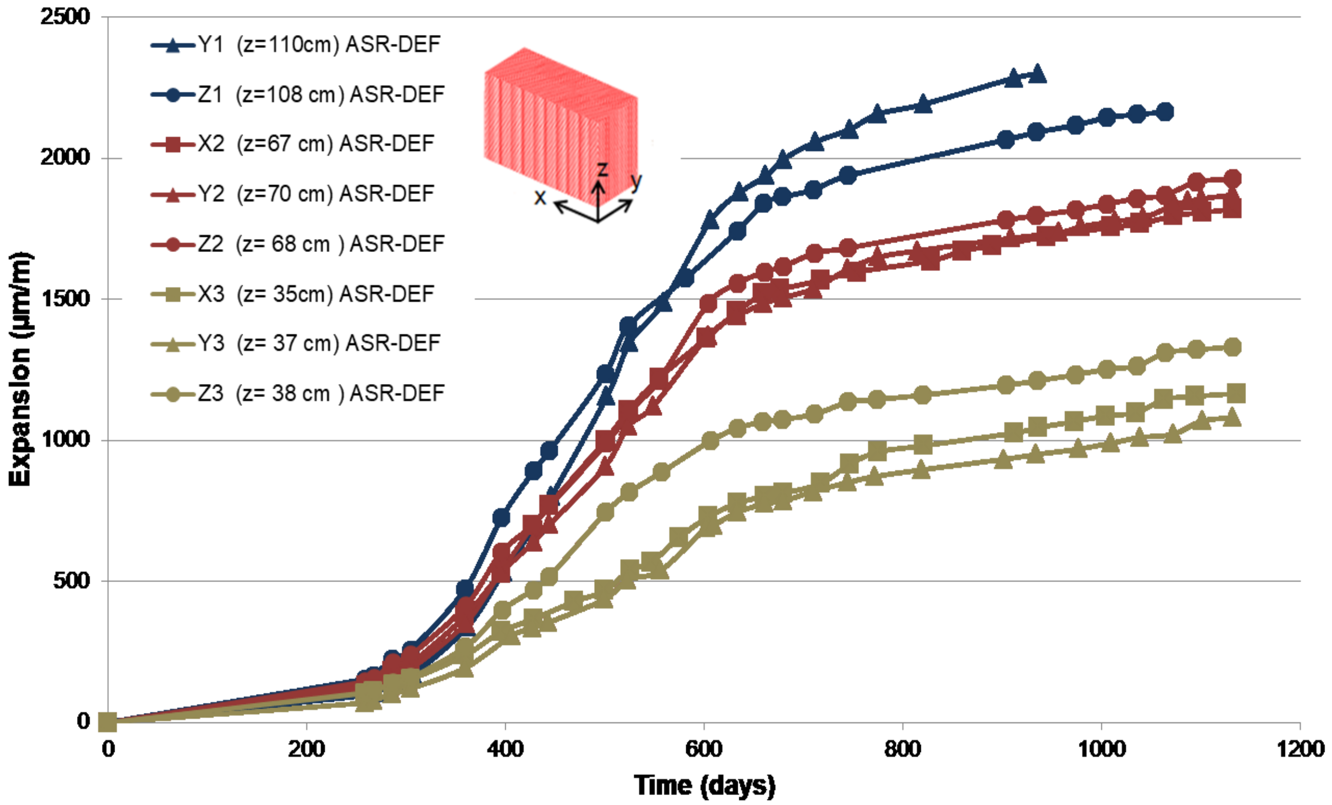
- 3 corings per mockup
- *Méthode d'essais LCPC 67*
- *Méthode d'essais LCPC 44*
- Résidual Swelling

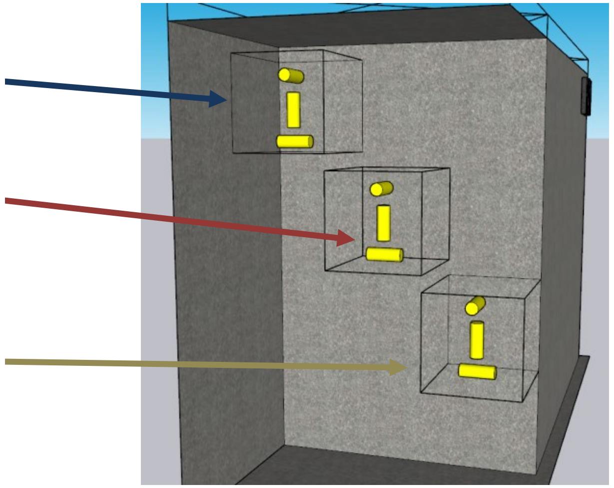


Structural Scale: mock-ups



- Strain evolution in the massive specimen until t = 1150 days



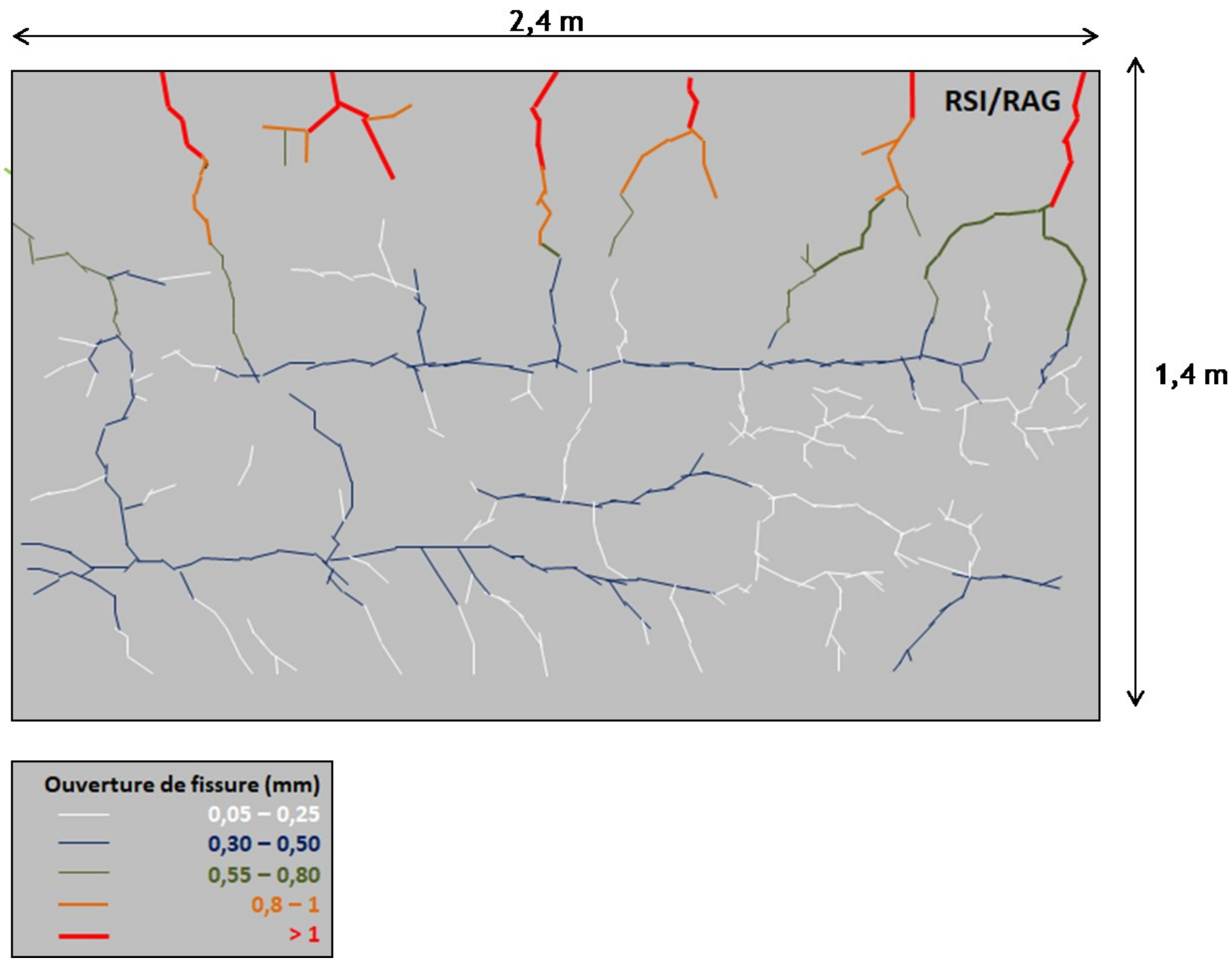


ASR-DEF mock-up strain evolution

Structural Scale: mock-ups

Photo of the ASR-DEF mock-up at t = 1150 days

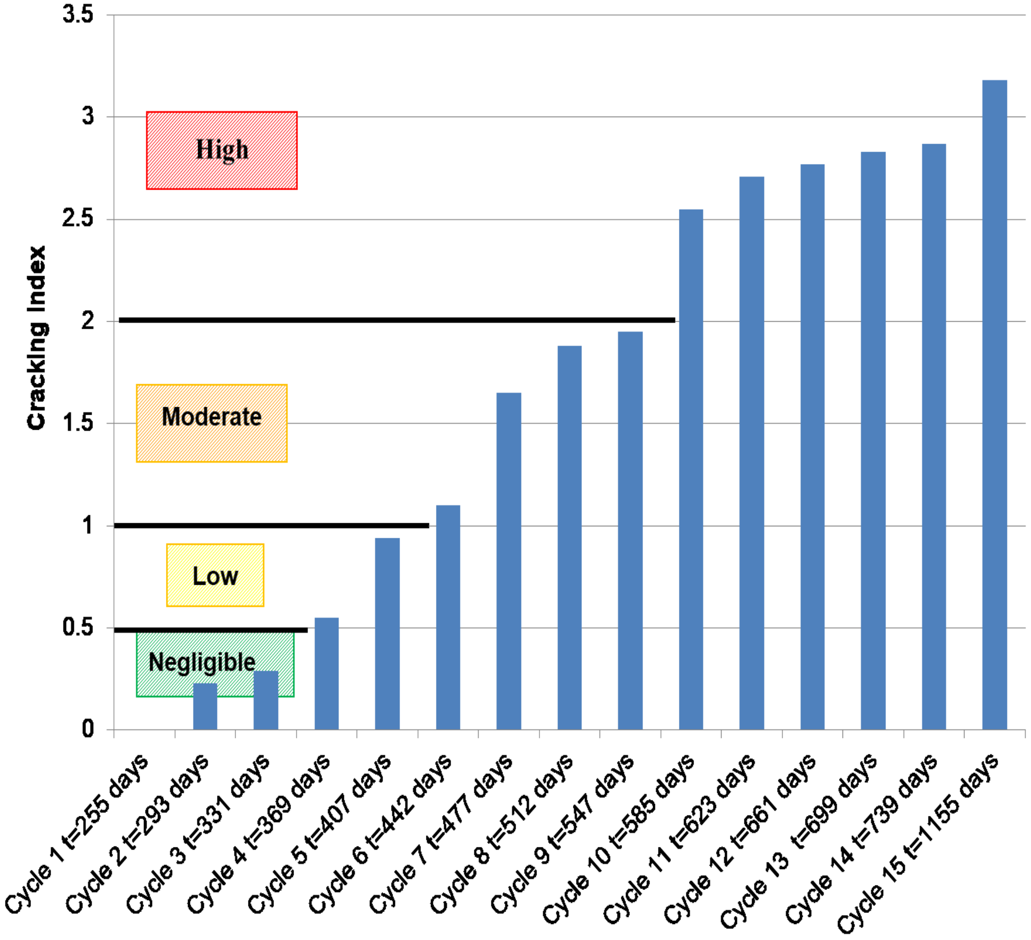
Structural Scale: mock-ups



rt (Jensen, 2012;

Structural Scale: mock-ups

- Evolution of the cracking index in the mock-ups

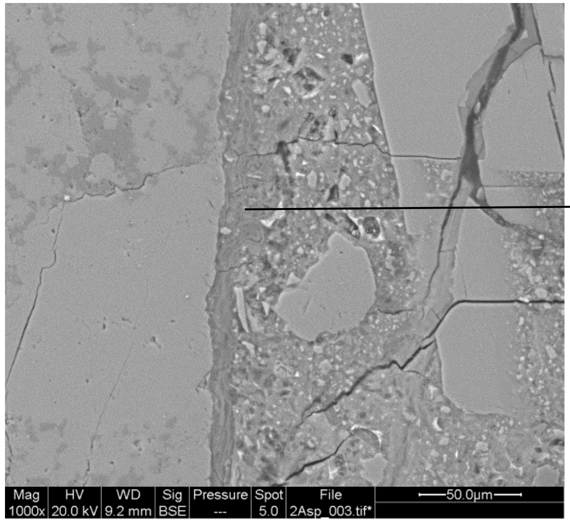


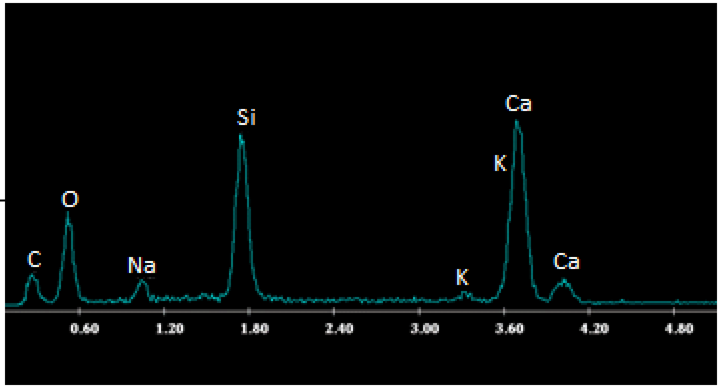
Cycle 6 (t =442 days) *Moderate Cracking*

Cycle 12 (t=661 days) *High Cracking*

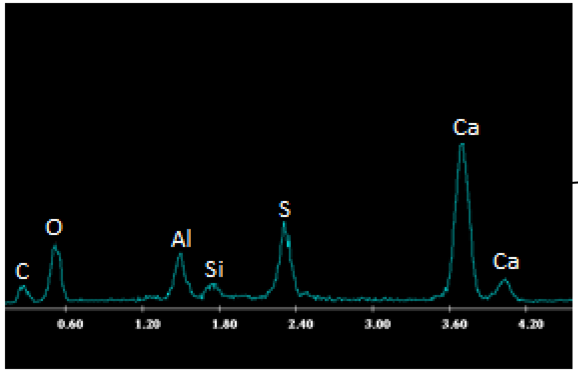
Échelle microscopique

- Échantillons prélevés de la maquette RAG-RSI à t = 303 jours

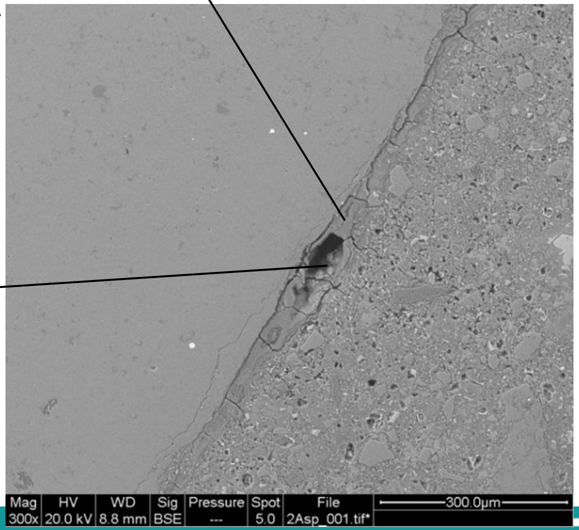




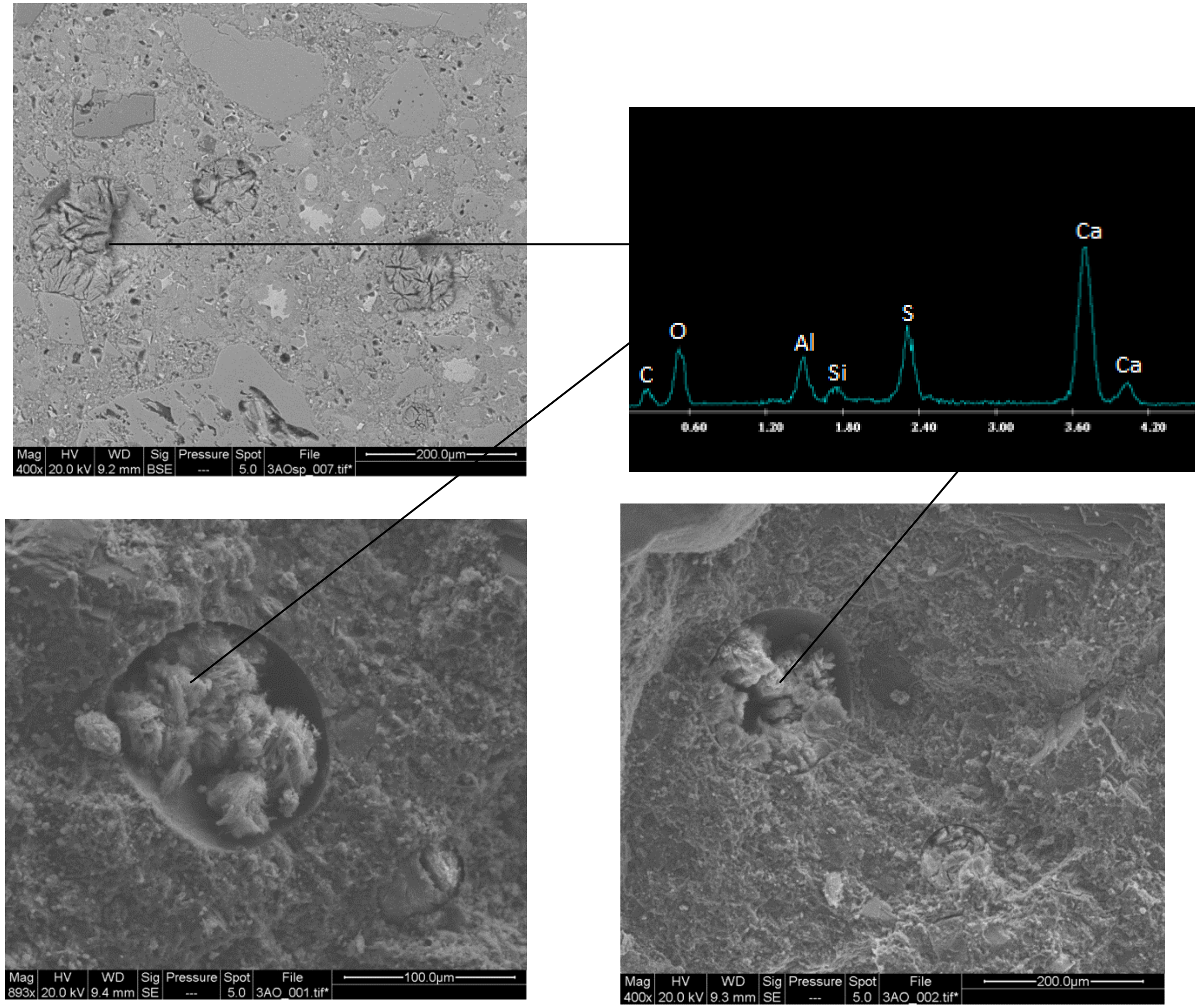
Spectre élémentaire associé au gel de RAG



Spectre élémentaire associé à l'ettringite



Échelle microscopique

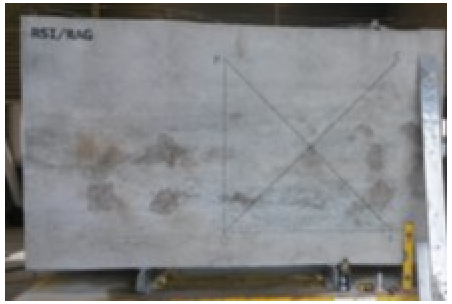


VALIDATION DE L'ORIGINE DU GONFLEMENT

Multi-scale Experimental campaign

Structural Scale: mock-ups

- Monitoring swelling
- Monitoring cracks (Damage Index)

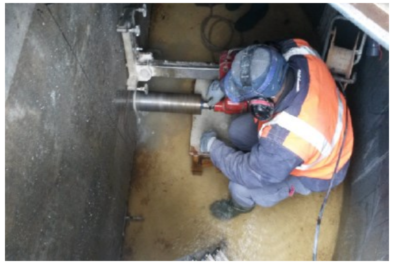


Specimen Scale: reconstituted concrete

- Early age thermal profil: *identical as the mockups*
- Conservation environement: *equivalent to the pools*

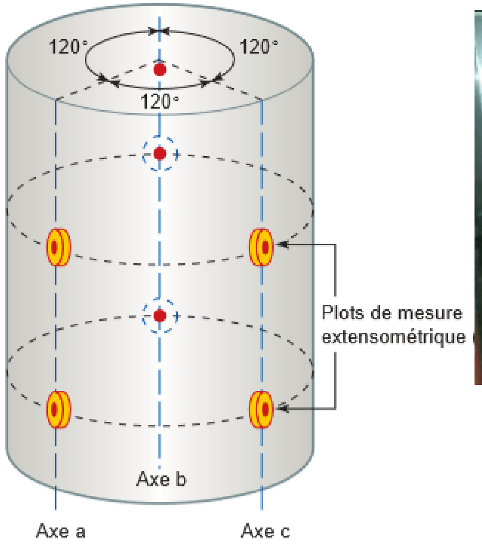
Specimen Scale: Coring

- 3 corings per mockup
- *Méthode d'essais LCPC 67*
- *Méthode d'essais LCPC 44*
- Résidual Swelling



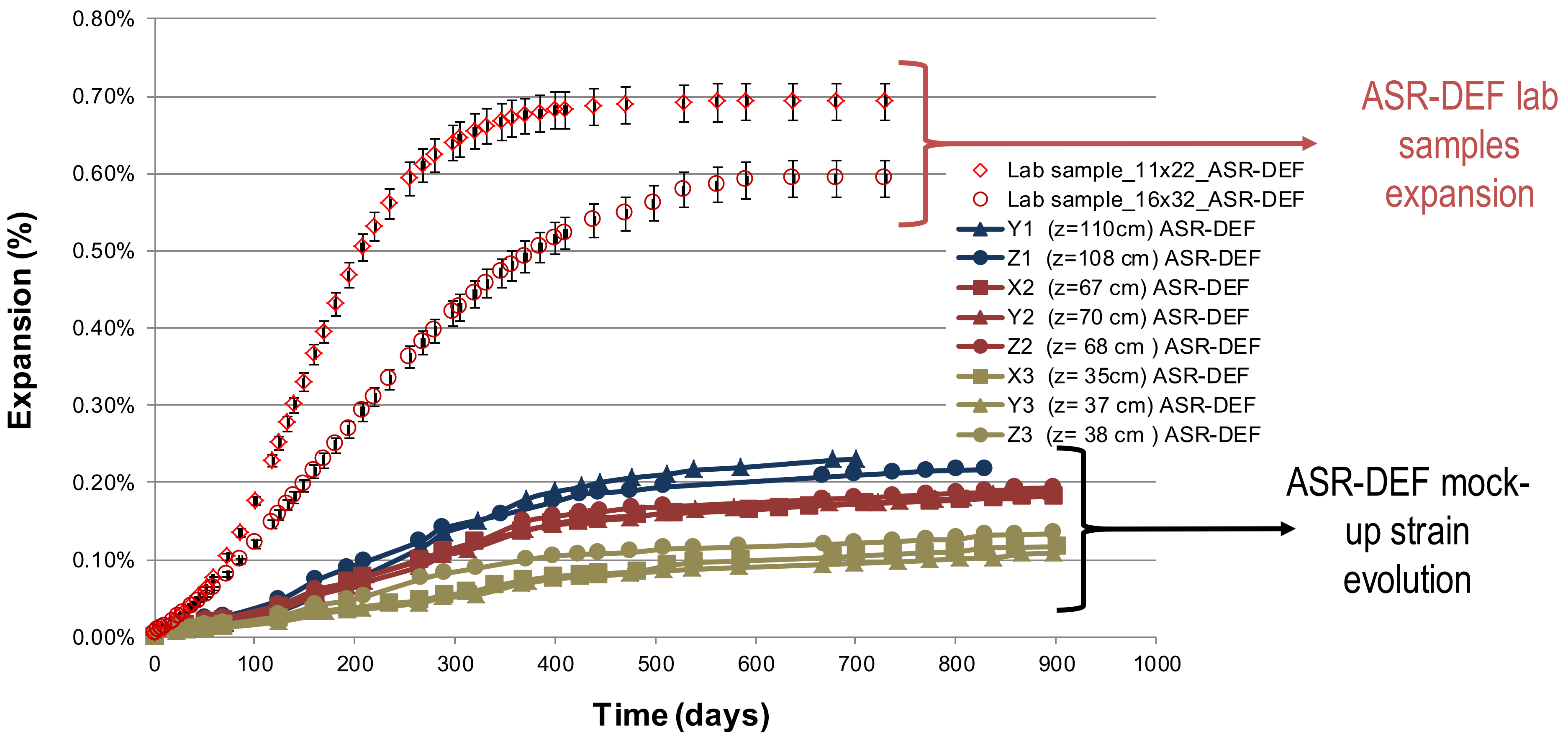
Speciman scale – lab sample (reconstituted concrete)

- 2 specimens size
- Same concrete mix
- Same heat treatement
- Conservation environment
  - Same ratio $\frac{V_{water}}{S_{exposed}}$
  - Same water renewal frequency
  - Same conservation temperature

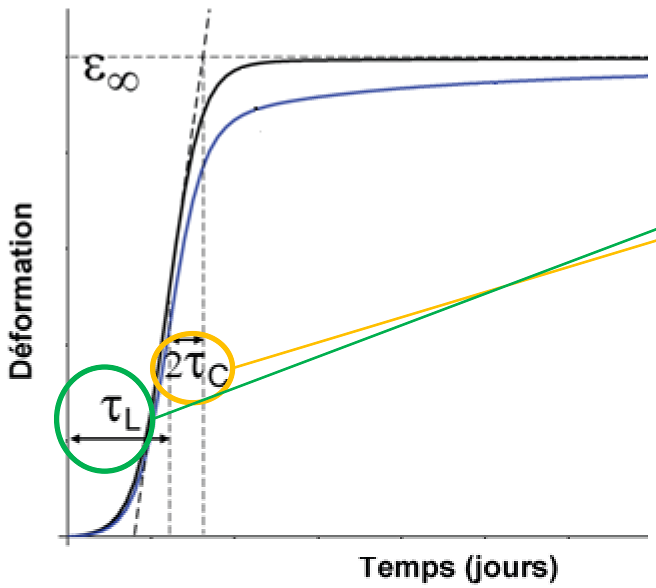


Speciman scale – lab sample (reconstituted concrete)

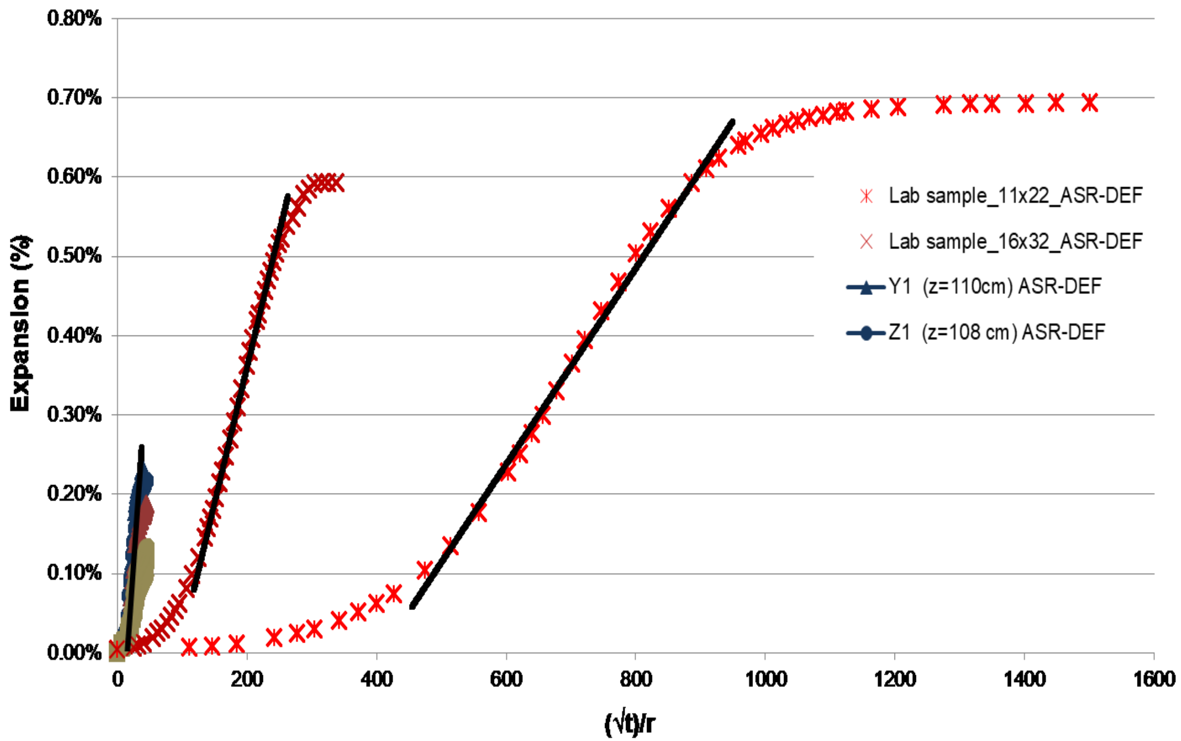
- Reconstituted concrete specimen strain evolution (equivalent conservation environment)



Discussion



	LabSample Ø11H22	LabSample Ø16H32	Mock-up – sensor Y1 (z= 110 cm)	Mock-up – sensor Z1 (z= 108 cm)
ε^{∞}	0.69%	0.61%	0.2225%	0.2050%
τ_L	135	150	290	250
τ_C	56	125	90	90



Discussion

	Ø11H22	Ø16H32	Mock-up
Concrete Volume (L) - V_c	2,091	6,43	3360
Exposed Surface (m^2) - S_e	0,095	0,20	11,92
Average radius r_{avg} (V_c/S_e) (m)	0,022	0,032	0,282
$r_{avg}/r_{Ø11H22}$	**1**	**1,45**	**12,82**

Different $\frac{V_{Concrete}}{S_{exposed}}$ ratios and cracking patterns

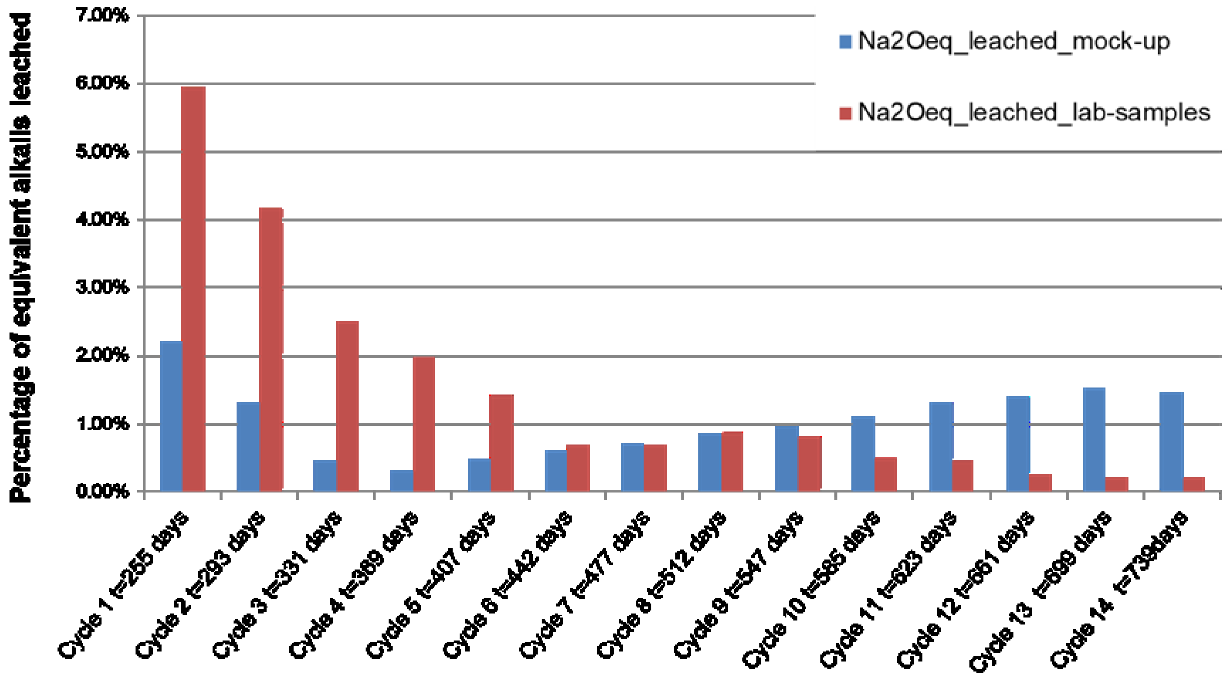
↓

Different leaching kinetics

↓

Different swelling behavior

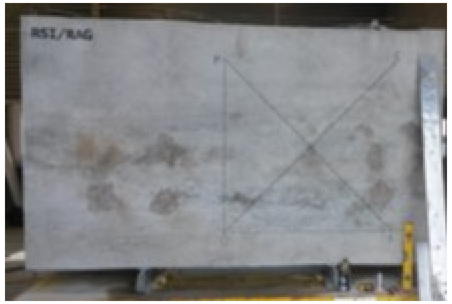
Quantities of alkalis leached at each cycle



Multi-scale Experimental campaign

Structural Scale: mock-ups

- Monitoring swelling
- Monitoring cracks (Damage Index)

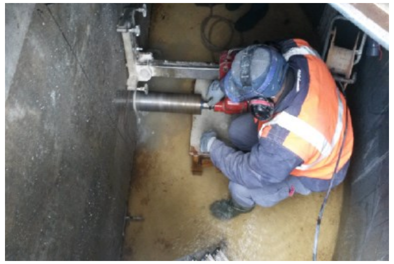


Specimen Scale: reconstituted concrete

- Early age thermal profil: *identical as the mockups*
- Conservation environement: *equivalent to the pools*

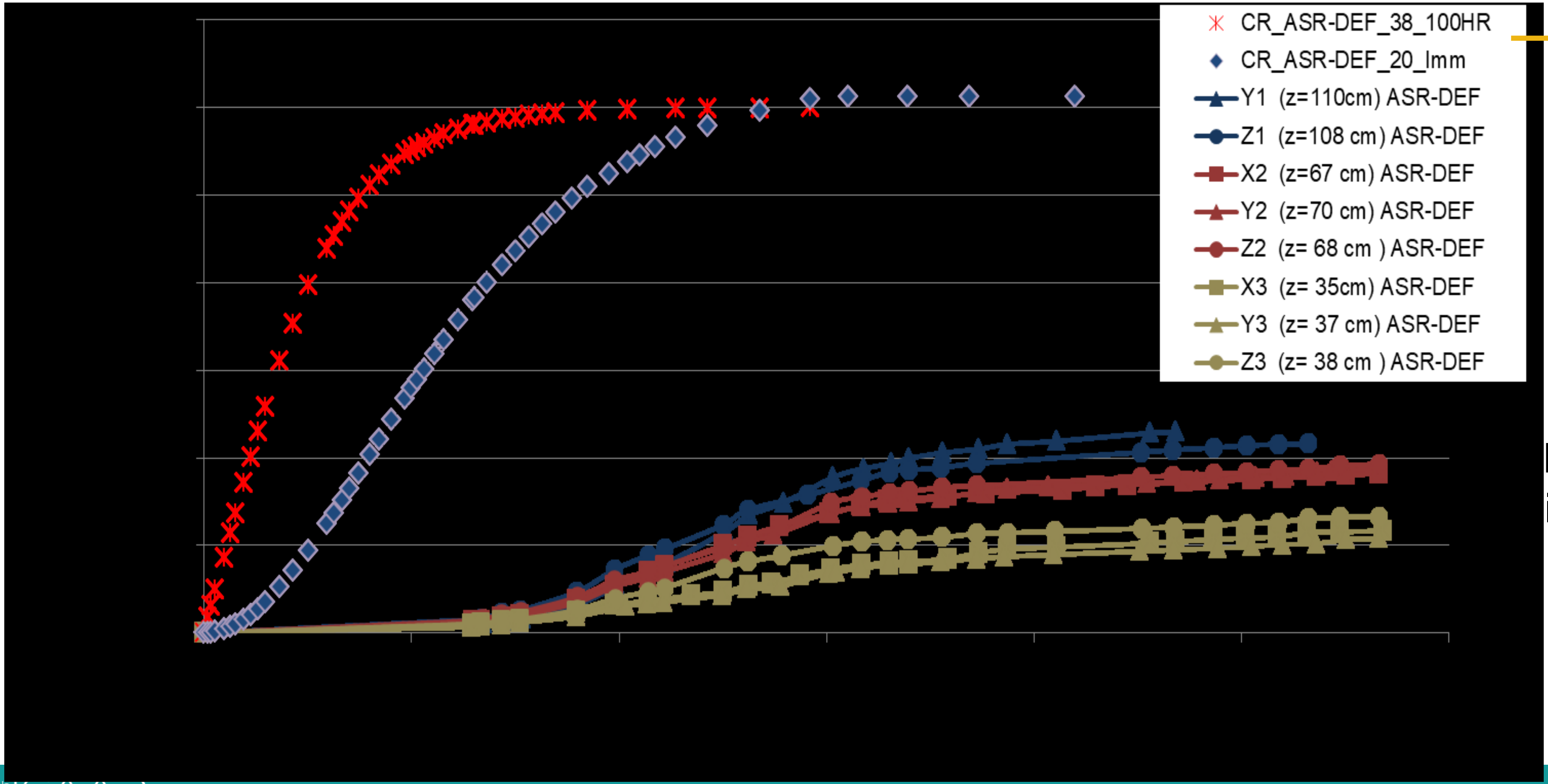
Specimen Scale: Coring

- 3 corings per mockup
- *Méthode d'essais LCPC 67*
- *Méthode d'essais LCPC 44*
- Résidual Swelling



Speciman scale – Corings (residual expansion test)

- Results of the residual expansion tests



mock-up residual expansion (coring)

F mock-up
in evolution

Conclusions

- Expansion in massive structures varies greatly from analogous laboratory samples.
  - Boundary conditions could hinder expansion along certain directions thus compensated by a higher expansion along unstressed directions which leads to an anisotropic behaviour in the material.

- We identified the existence of a scale effect on internal swelling reactions.
  - By comparing the strain evolution in different samples sizes subject to analogous concrete composition, thermal history and conservation environment, we found that the final swelling amplitude and the swelling kinetics are reduced by increasing the specimen's size.

- The conservation environment and in particular the storage temperature and the moisture exposure have a huge effect on the concomitant development of ASR and DEF.

- It ought to be mentioned that similar results were obtained in a parallel study investigating the Delayed Ettringite Formation (DEF) and ASR separately.

Thank you for your attention

email : jacques.jabbour@irsn.fr