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Alkali-Silica Reaction in concrete structures actual knowledge

Cour Master EPFL

L. SOFIA

December 2, 2025

École polytechnique fédérale de Lausanne

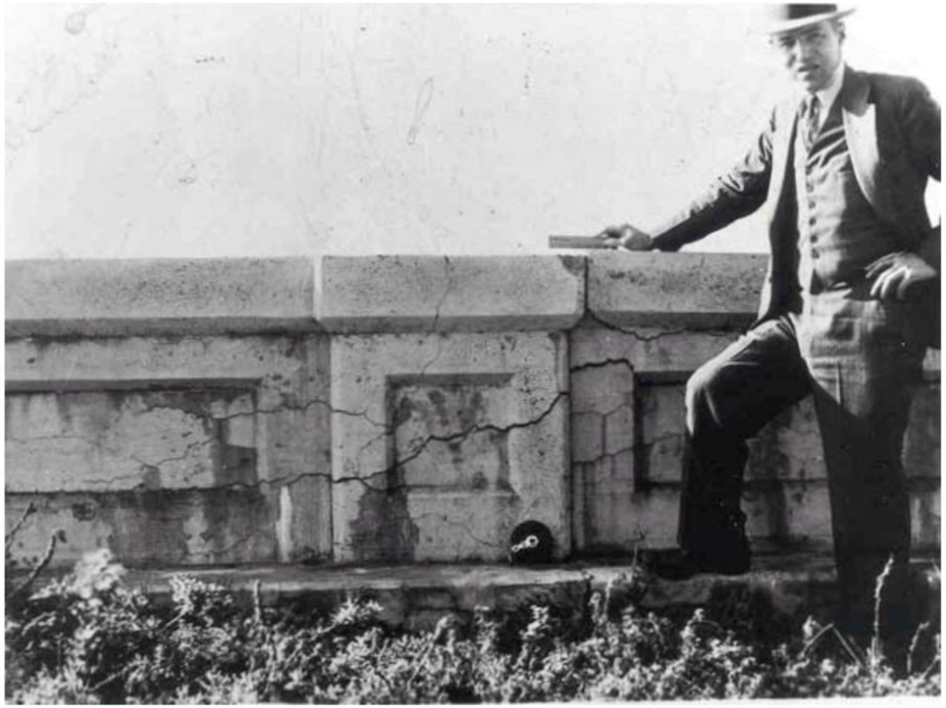


Figure 1.1. Thomas Stanton of the California State Division of Highways and a Bridge Parapet Wall that is Showing Signs of Damage due to Alkali-Silica Reaction

Alkali-silca reaction in concrete structures actual knowledge

Laboratoire des Matériaux de Construction (LMC – EPFL) - Professeure Karen Scrivener

- Reasearch works : 7 theses
- Scientific articles : > 20
- Collaboration with Rilem, EMPA, TFB, etc…
- Contributions with the OFEN, local entreprise and design offices

***Rilem**: **R**éunion **I**nternationale des **L**aboratoires et **E**xperts des **M**atériaux, systèmes de construction et ouvrages)*

Summary

- What is Akali-Silica Reaction (ASR or AAR)?
- What can be done to mitigate the phenomenon
- What to do with an damaged structure
- Monitoring the structure
- Laboratory testings
- Work on a damaged structure: Chambon Dam
- Conclusion

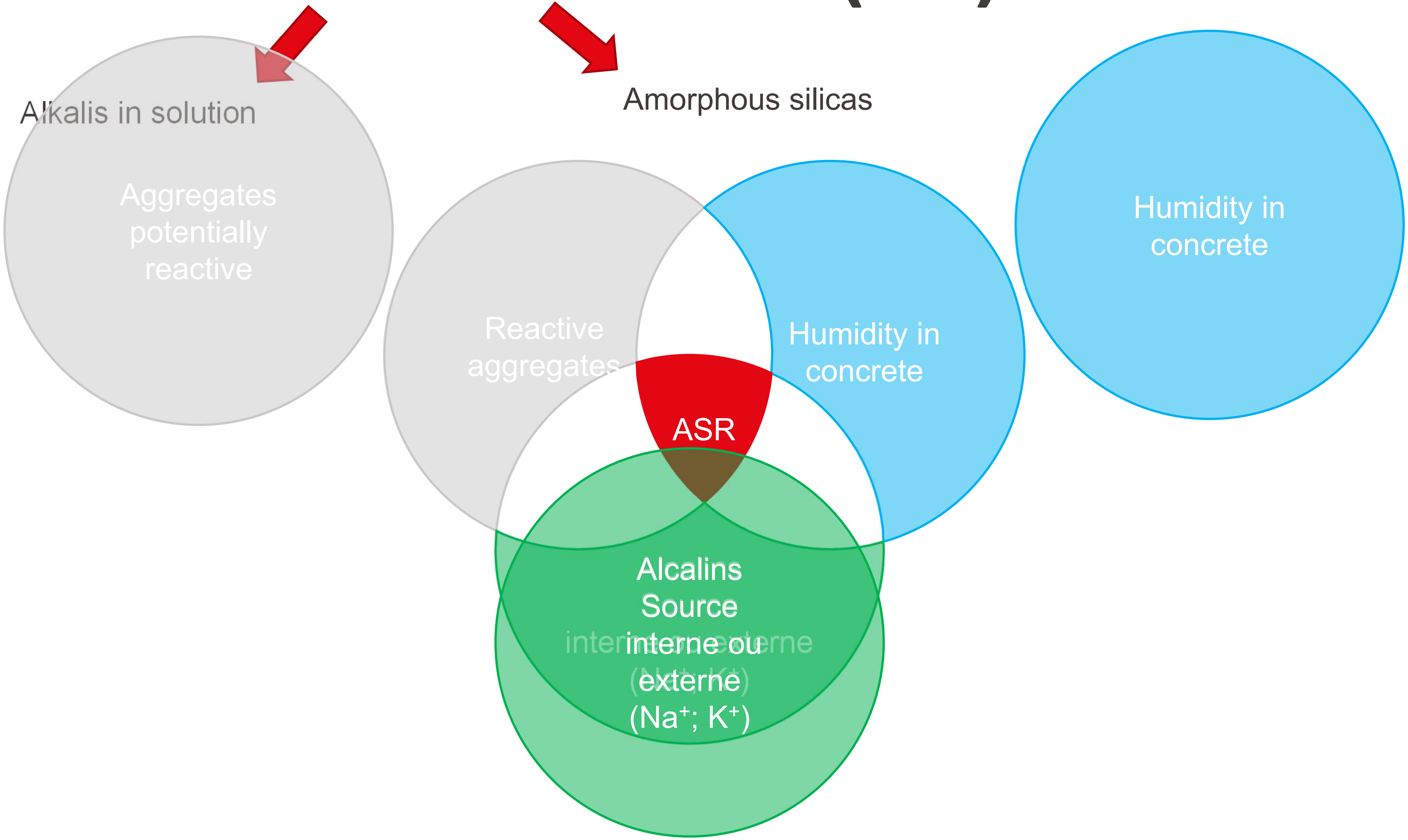
AAR?

- Alkali–Aggregate Reaction
  - ASR (Alkali – Silica Reaction)
  - ACR (Alkali - Carbonate Reaction)
    - Stone composed with Dolomite & Calcite & Clay
      - Dolomitic limestones with clay matrix
      - Microcrystalline clayey dolomitic limestones

Alkaline attack Dolomite → Formation of Calcite + Brucite → Swelling of the Clay matrix → Cracks.

Map cracking similar to ASR but different origin

Alkali-Silica Reaction (ASR)?



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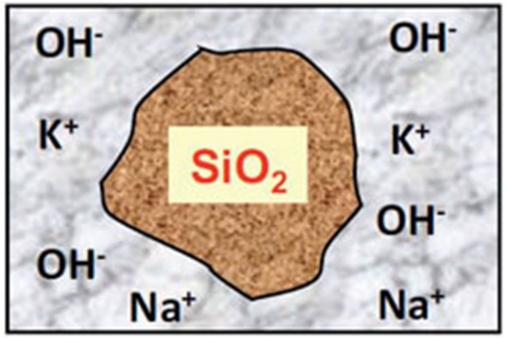
Alkali-Silica Reaction (ASR)?

Chemical reactions :

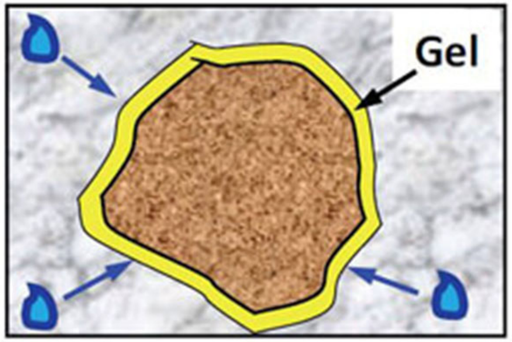
Silica dissolution

$$SiO_2 + 2OH^- \rightarrow SiO_3^{2-} + H_2O$$



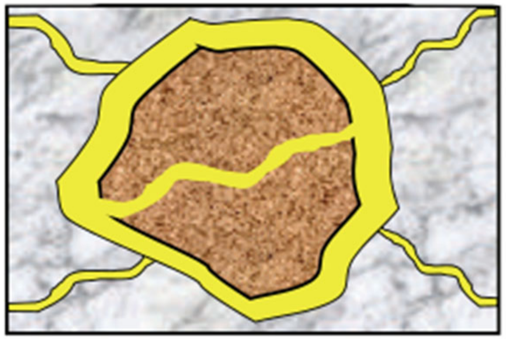
Gel formation

$$SiO_3^{2-} + 2Na^+ + H_2O \rightarrow Na_2SiO_3 \cdot H_2O \text{ (ASR Gel)}$$



Gel Expansion (hydration)

$$Na_2SiO_3 \cdot H_2O + nH_2O \rightarrow \text{Swollen Gel}$$



Sources : https://www.fhwa.dot.gov/pavement/concrete/asr/pubs/hif12022.pdf

What's going on?

Dissolution of alkalis in water

$Na_2O + H_2O \rightarrow 2\ Na^+ + 2\ OH^-$

$K_2O + H_2O \rightarrow 2K^+ + 2OH^-$

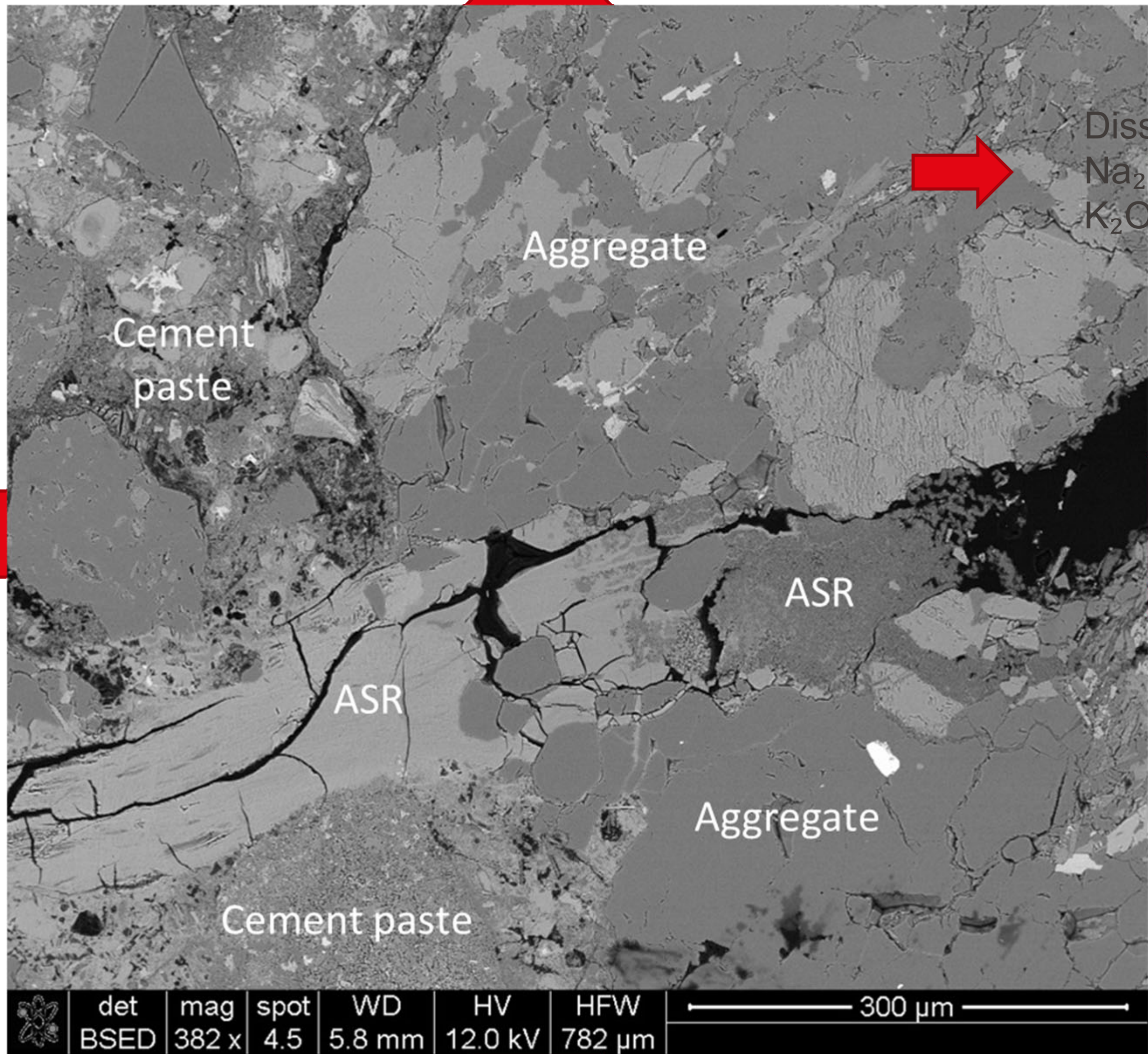
Gel formation

$Na_2SiO_3 \cdot H_2O$ (ASR Gel)

Silica dissolution

$$SiO_2 + 2OH^- \rightarrow SiO_3^{2-} + H_2O$$

Cracks formations



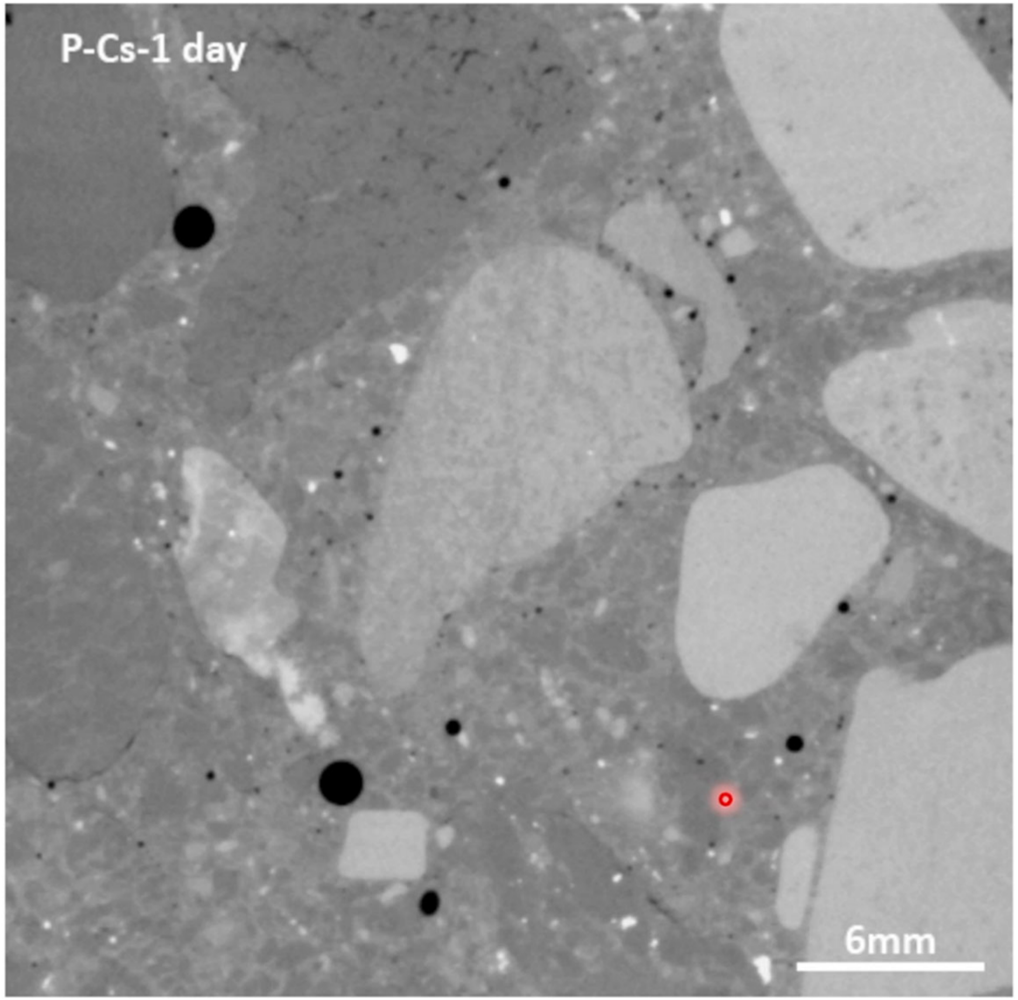
...sion (hydration)

$\ldots + nH_2O \rightarrow$ Swollen Gel

Source: LMC

What's going on?

ASR expansion between 1 to 250 days in laboratory



Source: Mahdieh Shakoorioskooie – EMPA – Concrete and Asphalt Laboratory

Consequences on field

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Source : AAR Facts Book, Mickael D, A. Thomas, B. Fournier, 2013

Consequences on field

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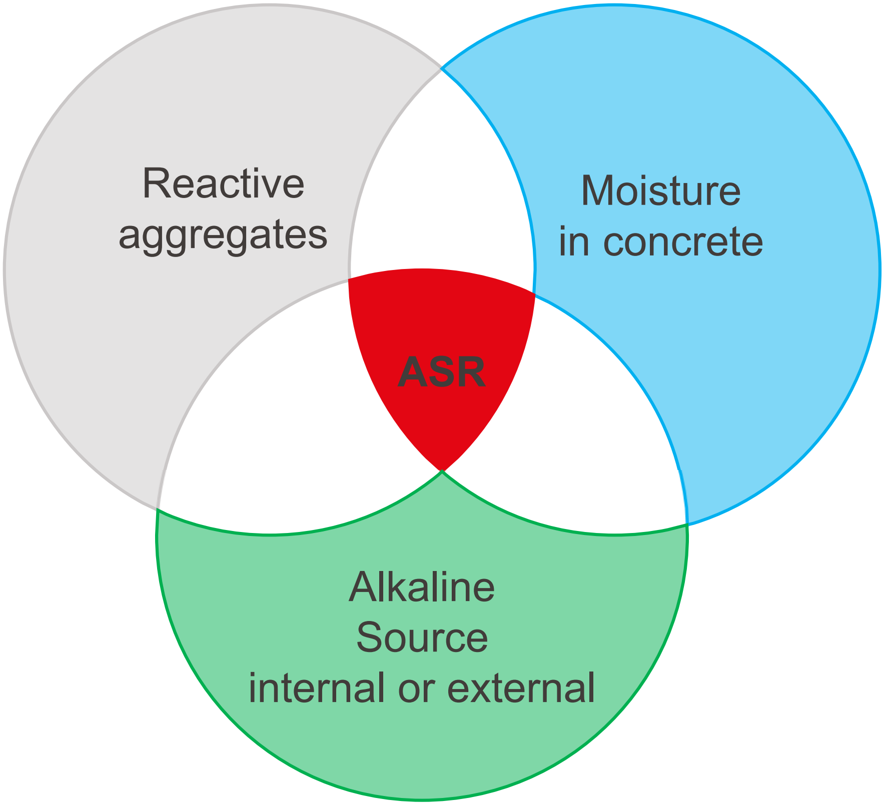
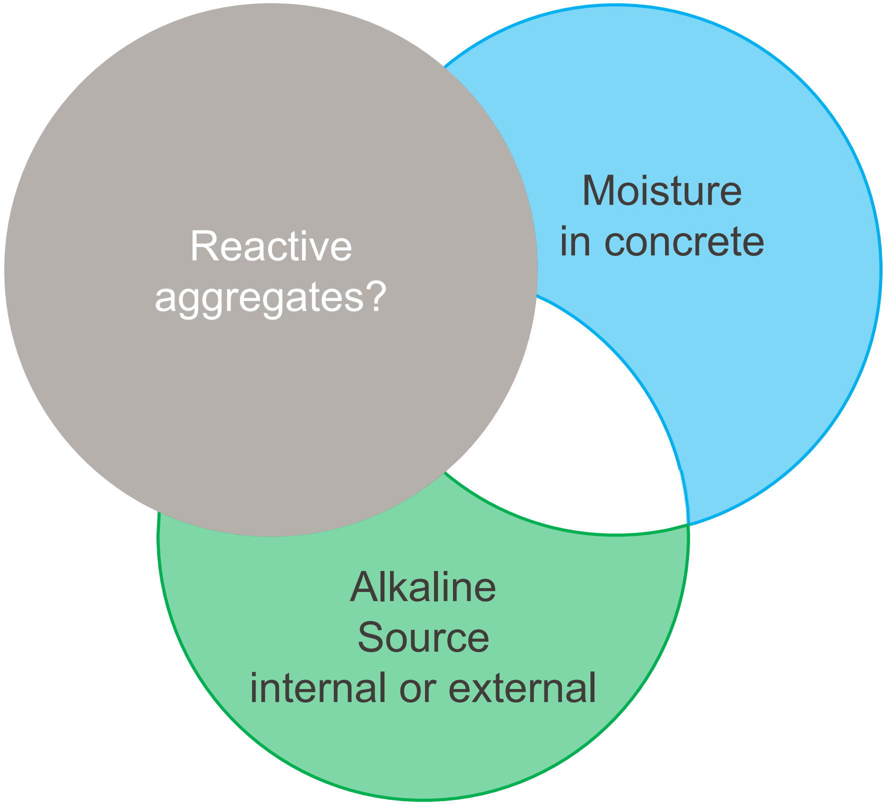
How to mitigate this phenomenon?



How to mitigate this phenomenon?



Aggregates analysis

- Petrography

https://austone.au/wp-content/uploads/2023/07/Petrographic_Report_July-2023.pdf

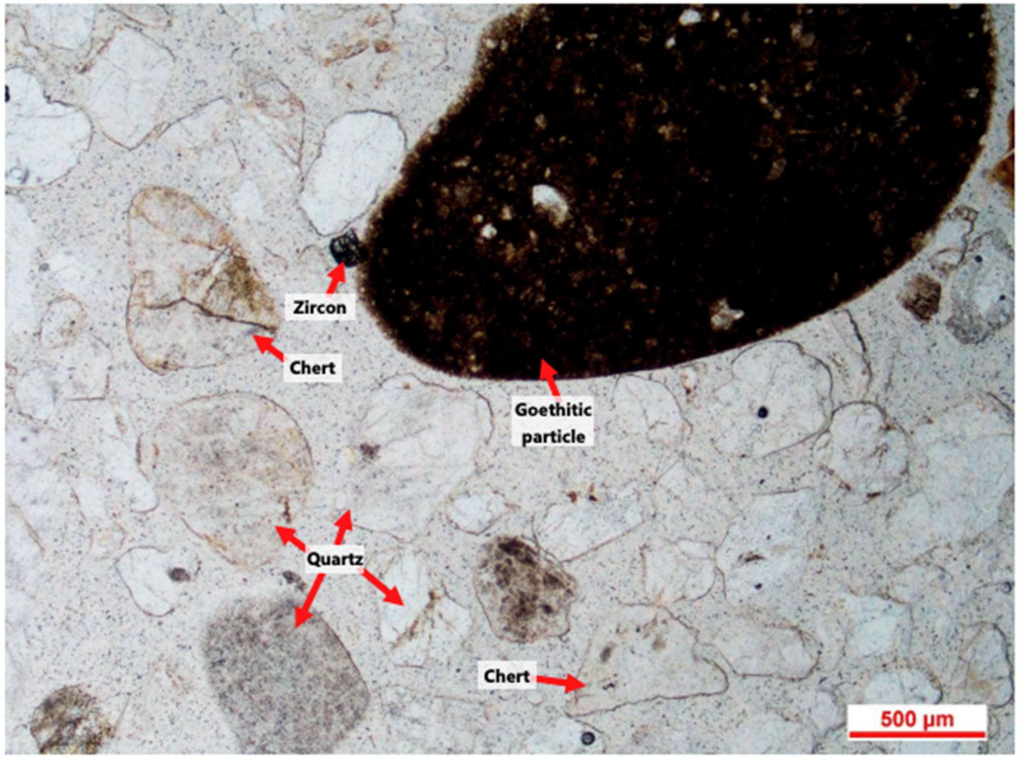


Plate 6: Microphotograph of the sample, showing abundant variably sized grains of quartz, zircon, chert and goethite. Image shown in plane polarised light. Scale = 500µm x 40 magnification. F.O.V. 3.7mm.

Aggregates analysis

- Petrography
- Microbar test according SIA MB 2042

Mélange	1	2	3
Rapport C/G	2	5	10
Ciment	(80 ± 0,1) g	(80 ± 0,1) g	(100 ± 0,1) g
Solution NaOH	(24 ± 0,05) g	(24 ± 0,05) g	(30 ± 0,05) g
Granulat	(40 ± 0,05) g	(16 ± 0,05) g	(10 ± 0,05) g

- Casting, unmolde after 24 h and measurement of lenght
- Steam curing 240 min
- Keep the sample at 20 °C until its temperature reaches 20 °C (approximately 4 to 24 hours)
- Store in a 10% KOH solution in a stainless steel container for 360 minutes at 150°C.
- Store the samples for 1 hour before measuring their length.

3 criteria are used to classify the reactivity :

- "NR" (Non-Reactive) when the average of the swelling of 3 samples is below 0.11%,
- "PR" (Potentially Peactive) when at least one average value (usually that corresponding to the C/G ratio = 2) is higher than 0.11%.
- "PRP" (Potentially Reactive with Pessimum effect) when the average value corresponding to the C/G ratio = 5 is more than 10% > the C/G ratio = 2.

Aggregates analysis

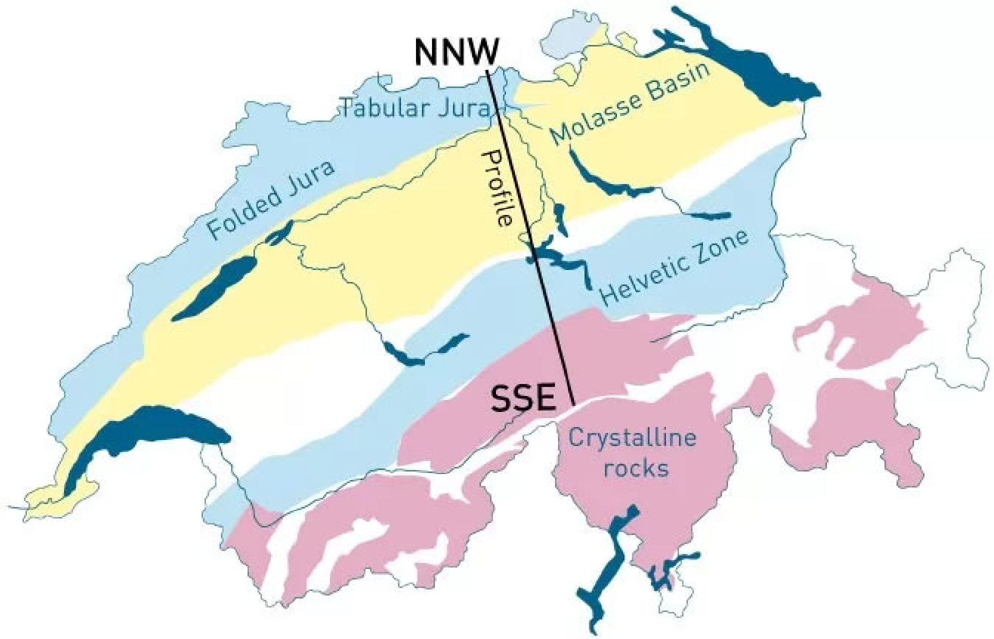
- Petrography
- Microbar test according SIA MB 2042

The majority, i.e. ≈ 90% of Swiss aggregates, exhibit reactivity to ASR!

- **Apline geology** mainly stressed rocks rich in reactive forms of silica
- **Glacial depositis** responsible of the heterogeneity of the aggregates
- **Metamorphic rocks** dominance, gneiss, schist containing quartz under deformation
- **Siliceous impurities in limestones** present chert or siliceous layers making them reactive

Aggregates analysis

- More than 400 structures are affected (Merz et al. 2006).
- 20-30% of Swiss dams are affected.
- 90% of the aggregates were classified as potentially reactive to ASR (Merz & Leemann, 2012).



Swiss geology map from Nagra portal

How to mitigate this phenomenon?

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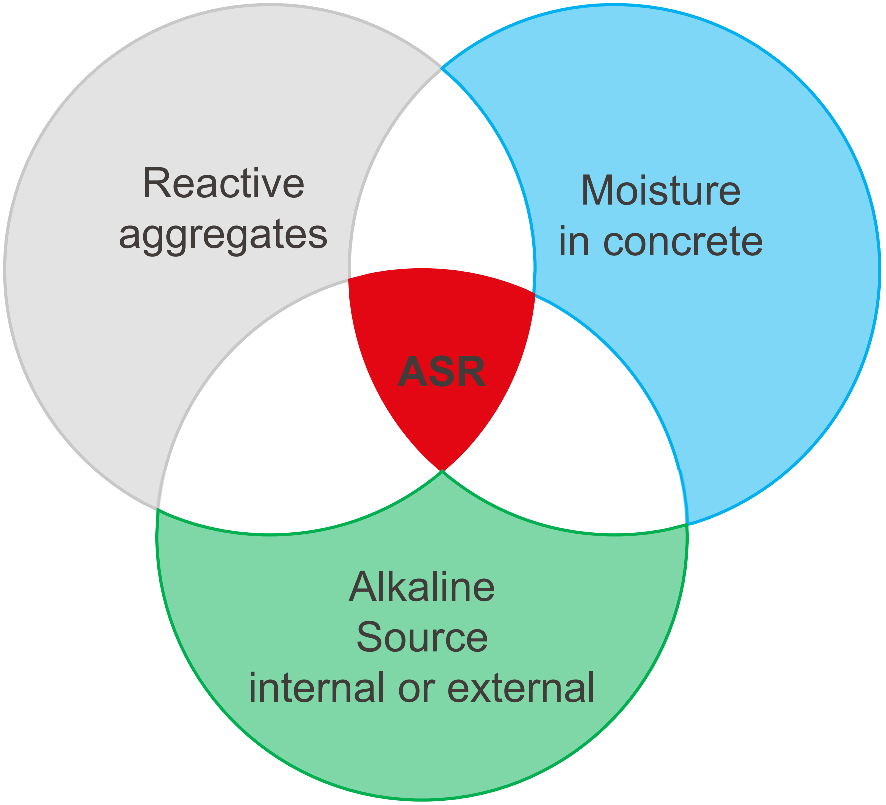
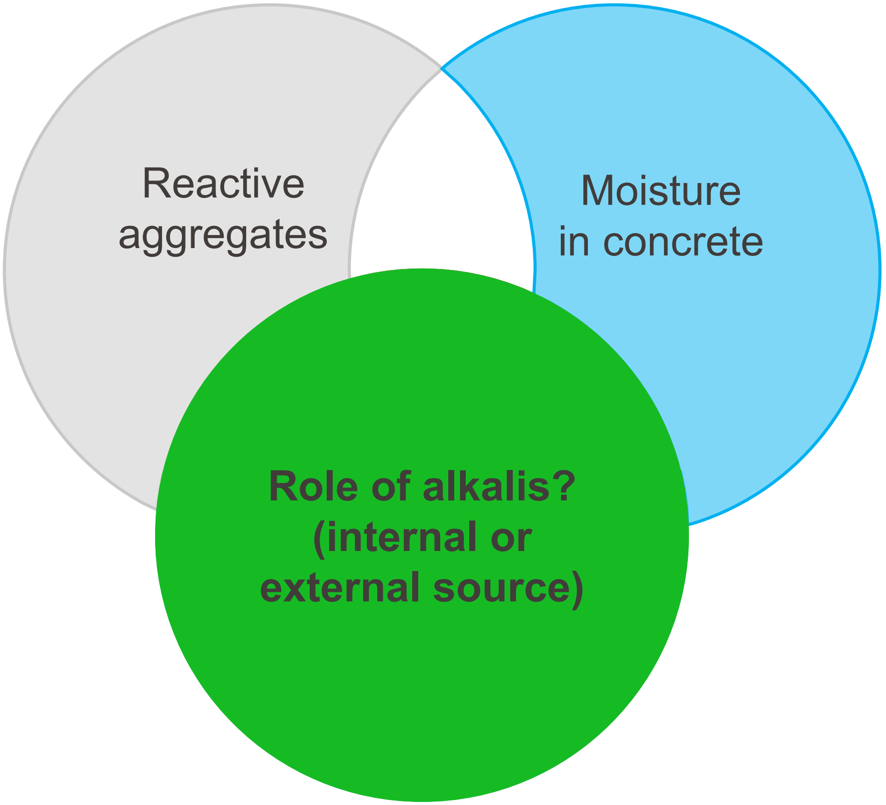


How to mitigate this phenomenon?



Alkali content

- Reducing the alkali content silica reaction damage.
- Use of mineral additives (SC
    - Silica fume
    - Metakaolin
    - Fly ash
    - Slag
    - Calcined shists
    - etc…
- Use only cement type CEM

Nevertheless, cements coı

con

Tableau 1 – Les 27 produits de la famille des ciments courants

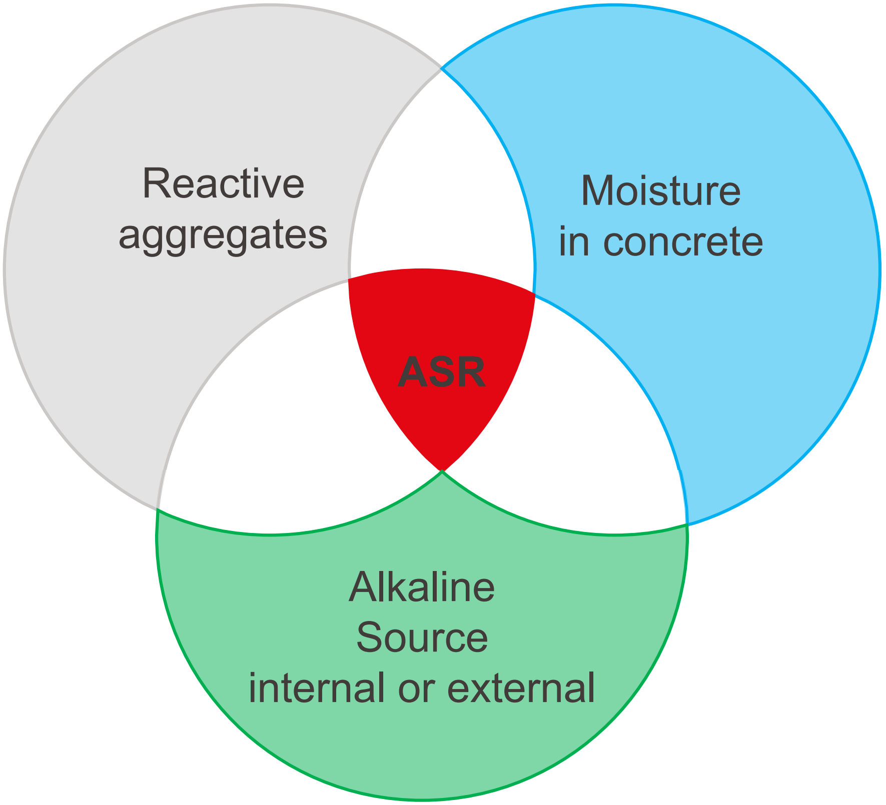
Princi-paux types	Notation des 27 produits (types de ciment courant)		Composition (pourcentage en masse [a]										
			Constituants principaux										
			Clin-ker	Laitier de haut four-neau	Fumée de silice	Pouzzolanes		Cendres volantes		Schist e calcin é	Calcaire		Cons-tituant s secon-daires
						Natu-relle	Natu-relle calci-née	Sili-cieuse	Cal-cique				
			K	S	D[b]	P	Q	V	W	T	L	LL	
CEM I	Ciment Portland	CEM I	95-100	-	-	-	-	-	-	-	-	-	0-5
CEM II	Ciment Portland Au laitier	CEM II/A-S	80-94	6-20	-	-	-	-	-	-	-	-	0-5
		CEM II/B-S	65-79	21-35	-	-	-	-	-	-	-	-	0-5
	Ciment Portland à la fumée de silice	CEM II/A-D	90-94	-	6-10	-	-	-	-	-	-	-	0-5
	Ciment Portland à la pouzzolane	CEM II/A-P	80-94	-	-	6-20	-	-	-	-	-	-	0-5
		CEM II/B-P	65-79	-	-	21-35	-	-	-	-	-	-	0-5
		CEM II/A-Q	80-94	-	-	-	6-20	-	-	-	-	-	0-5
		CEM II/B-Q	65-79	-	-	-	21-35	-	-	-	-	-	0-5
	Ciment Portland aux cendres volantes	CEM II/A-V	80-94	-	-	-	-	6-20	-	-	-	-	0-5
		CEM II/B-V	65-79	-	-	-	-	21-35	-	-	-	-	0-5
		CEM II/A-W	80-94	-	-	-	-	-	6-20	-	-	-	0-5
		CEM II/B-W	65-79	-	-	-	-	-	21-35	-	-	-	0-5
	Ciment Portland au schiste calciné	CEM II/A-T	80-94	-	-	-	-	-	-	6-20	-	-	0-5
		CEM II/B-T	65-79	-	-	-	-	-	-	21-35	-	-	0-5
	Ciment Portland au calcaire	CEM II/A-L	80-94	-	-	-	-	-	-	-	6-20	-	0-5
		CEM II/B-L	65-79	-	-	-	-	-	-	-	21-35	-	0-5
		CEM II/A-LL	80-94	-	-	-	-	-	-	-	-	6-20	0-5
		CEM II/B-LL	65-79	-	-	-	-	-	-	-	-	21-35	0-5
	Ciment Portland composé [c]	CEM II/A-M	80-94	←------------				6-20				------------→	0-5
		CEM II/B-M	65-79	←------------				21-35				------------→	0-5
CEM III	Ciment de haut fourneau	CEM III/A	35-64	36-65	-	-	-	-	-	-	-	-	0-5
		CEM III/B	20-34	66-80	-	-	-	-	-	-	-	-	0-5
		CEM III/C	5-19	81-95	-	-	-	-	-	-	-	-	0-5
CEM IV	Ciment pouzzolani-que[c]	CEM IV/A	65-89	-	←------------→		11-35	←------------→		-	-	-	0-5
		CEM IV/B	45-64	-	←------------→		36-55	←------------→		-	-	-	0-5
CEM V	Ciment composé[c]	CEM V/A	40-64	18-30	-		<--------18-30--------→			-	-	-	0-5
		CEM V/B	20-38	31-50	-		←---------31-50------→			-	-	-	0-5

a Les valeurs indiquées se réfèrent à la somme des constituants principaux et secondaires.

b La proportion de fumées de silice est limitée à 10 %.

c Dans le cas des ciments Portland composés CEM II/A-M et CEM II/B-M, des ciments pouzzolaniques CEM IV/A et CEM IV/B et des ciments composés CEM V/A et CEM V/B, les constituants principaux, autres que le clinker, doivent être déclarés dans la désignation du ciment (voir un exemple à l'article 8).

How to mitigate this phenomenon?



Example of deterioration linked to an exposure change

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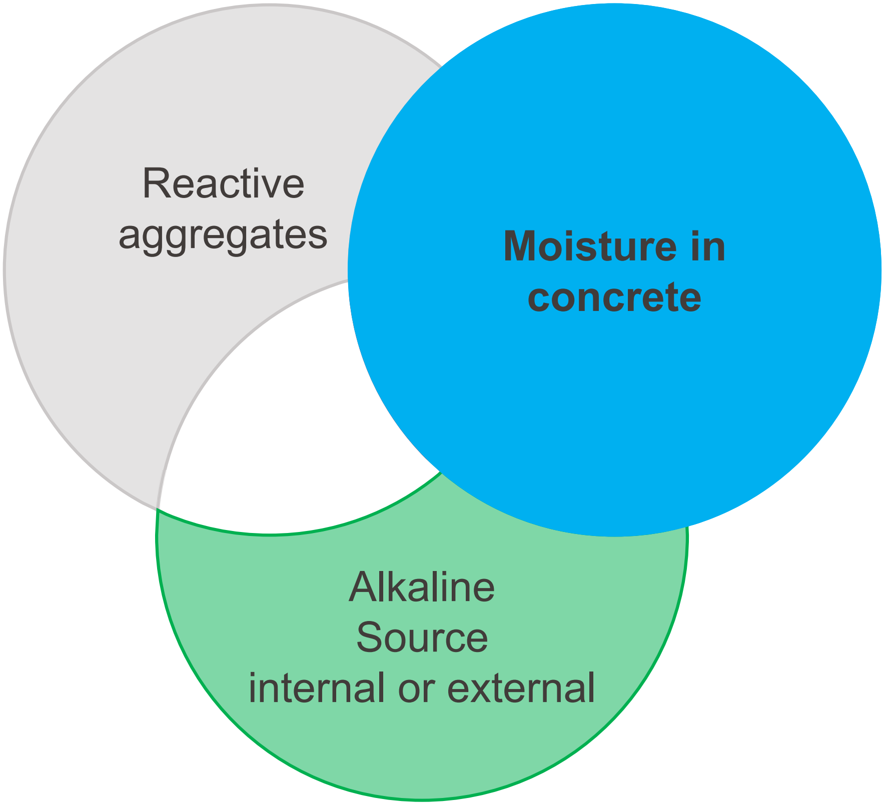

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Example of deterioration linked to an exposure change

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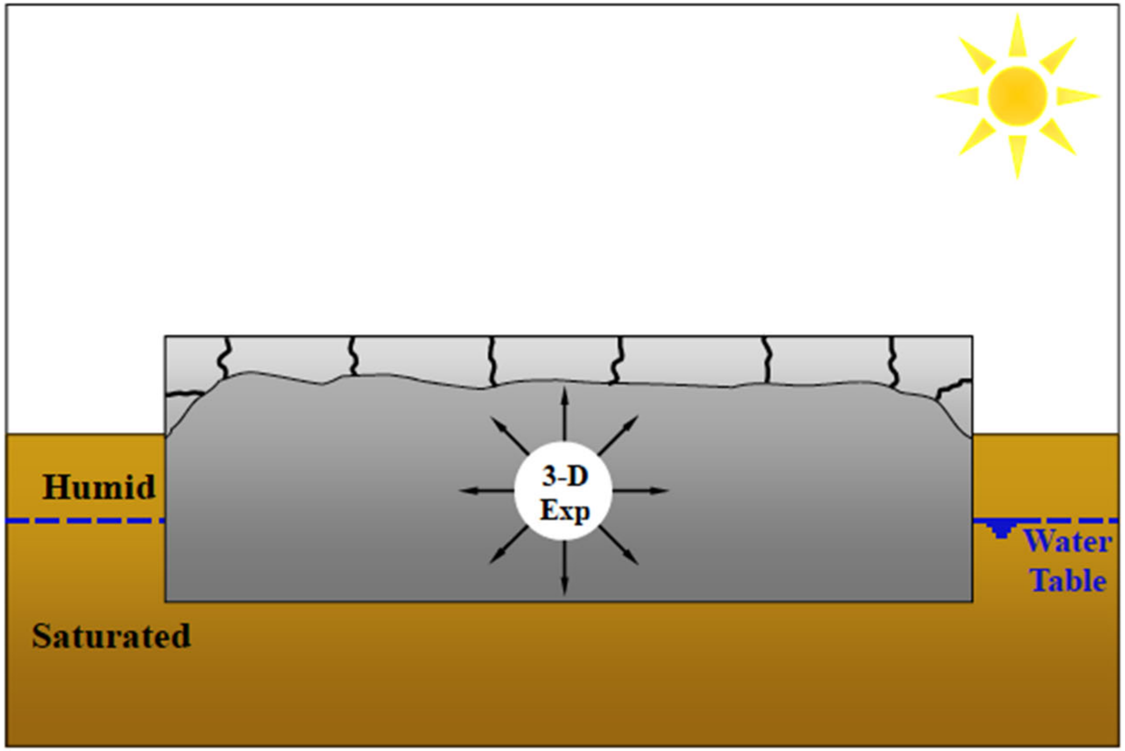
Example of deterioration linked to an exposure change



Source : *ASR American study*

How to mitigate this phenomenon?

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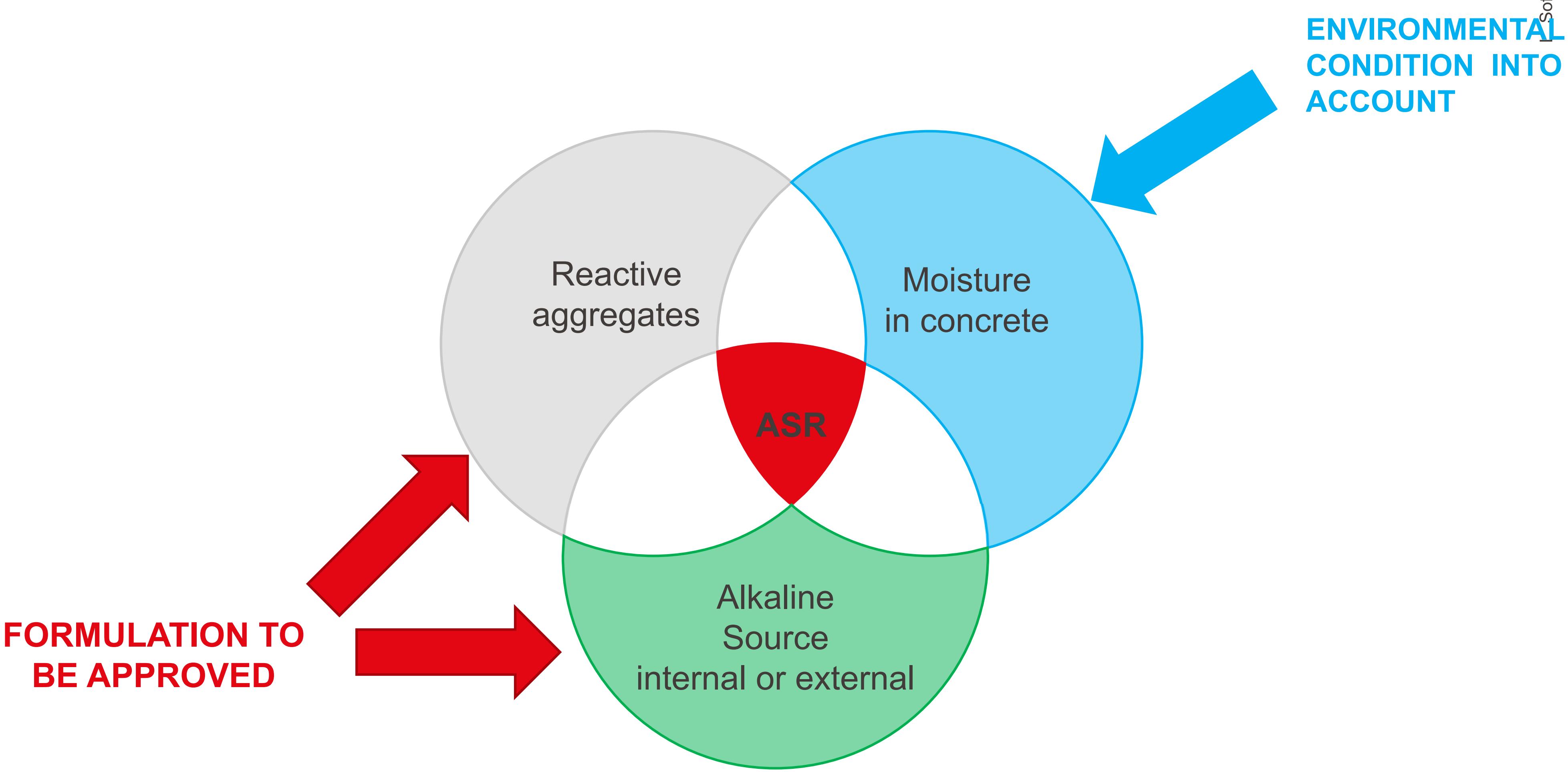
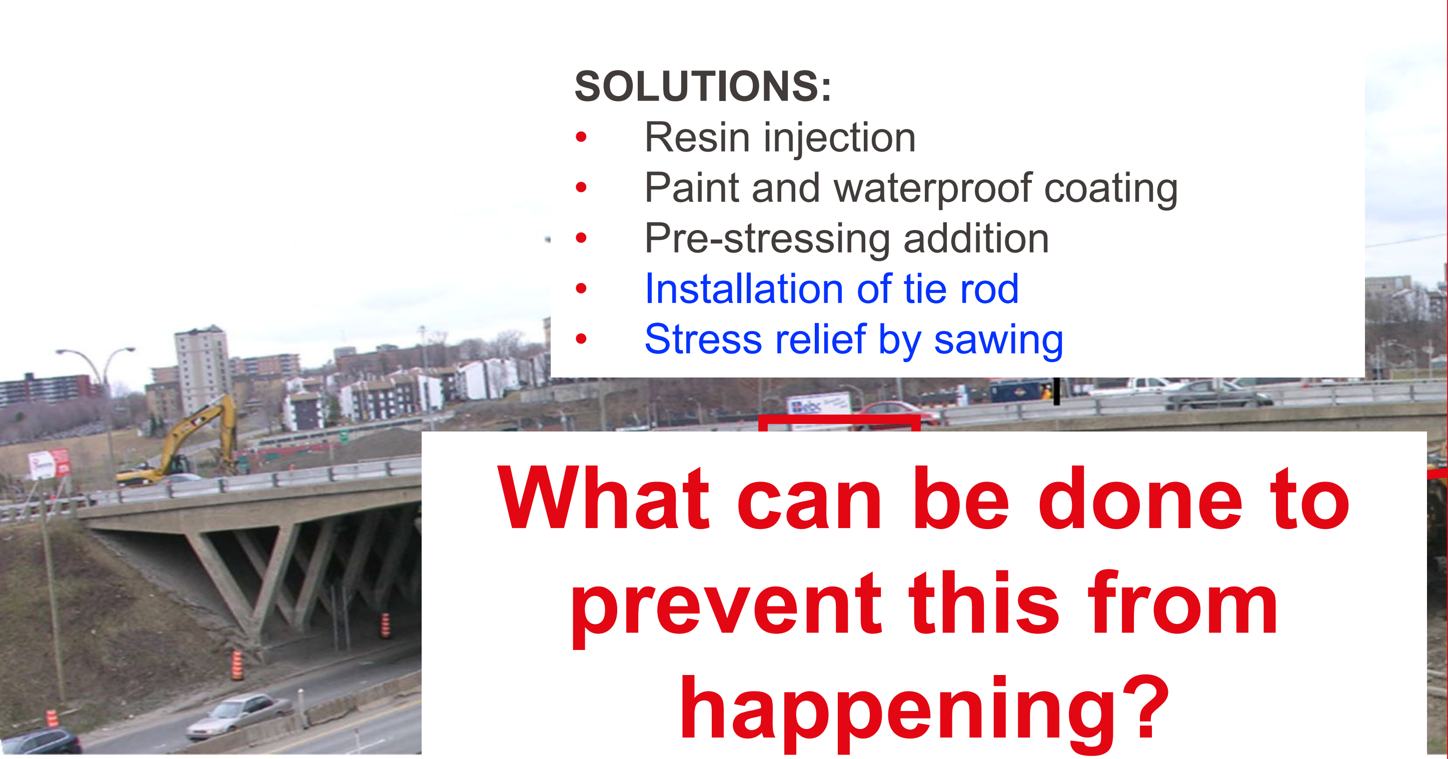


Structure maintenance



SOLUTIONS:
- Resin injection
- Paint and waterproof coating
- Pre-stressing addition
- Installation of tie rod
- Stress relief by sawing

What can be done to prevent this from happening?

Overview of the interchange Robert Bourassa - Charest

Outils d'investigation de la réactivité alcalis-granulats dans les infrastructures en béton
B. Fournier, L. Sanchez, S. Beauchemin: 08.2015

Monitoring of existing structures

- Structure monitoring
- Observation of the evolution of the reaction
- Sample collection
  - Microscopic analysis
  - SDT testing
  - Residual expansion measurements

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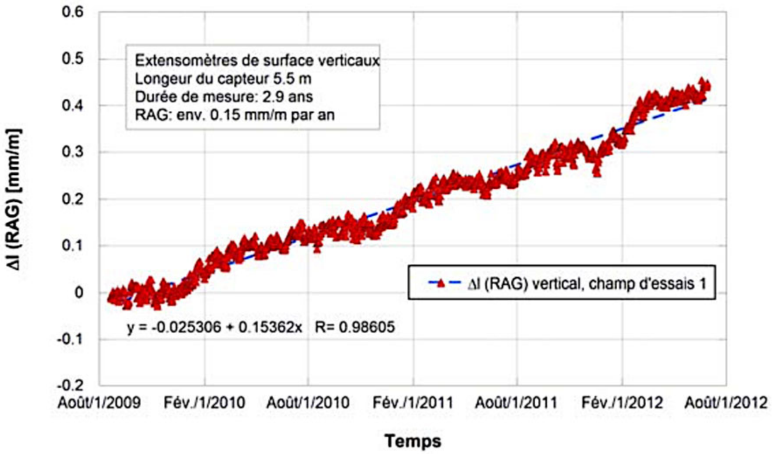
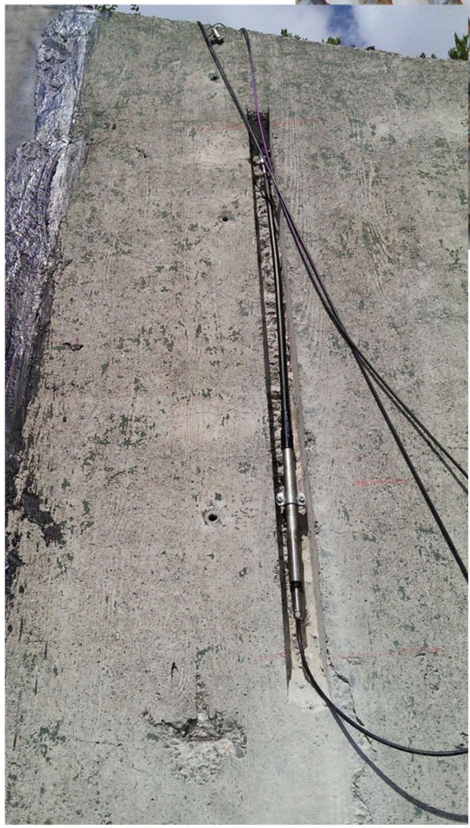
Structure monitoring

- Concrete expansion
- Temperature
- Moisture





Observation on field and sampling

Must be performed by a properly trained person:

- Establish a diagnosis for any suspected ASR or swelling phenomenon.
- Establish a crack index on site
- In order to collect samples representative of the pathology

Observation on field and sampling

In-situ measurements of expansion and deformation in ASR-affected concrete elements. A-E.

Observation on field and sampling

A. Wooden-stick method. B-C. Portable humidity probes. D. Automatic in-situ monitoring of temperature, humidity and expansion (vibrating wire) in a bridge deck affected by ASR (Siemes and Gulikers 2000).

Observation on field and sampling

A

B

A. Impact-echo B. Non-Linear acoustic technique

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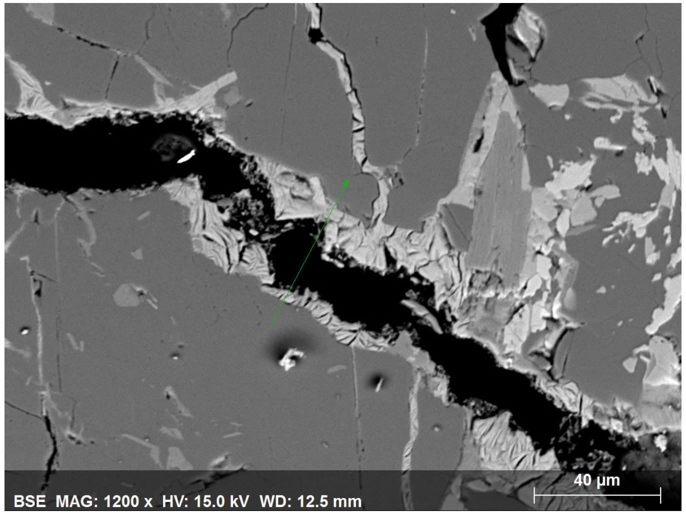
Sampling

Microstructure analysis:

Optical microscopy or SEM on thin sections

These results will determine the need to investigate further!

Properties of the microstructure

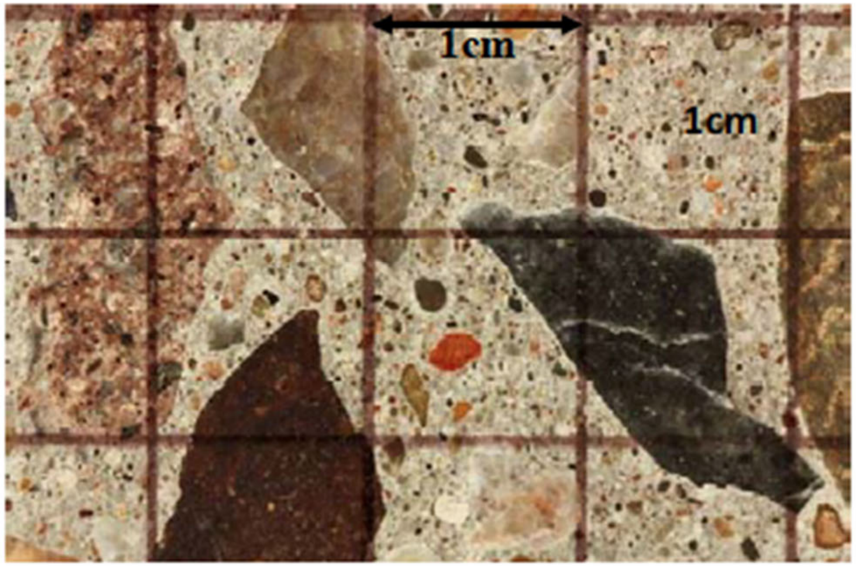


the pathology observed on site

Laboratory observations

A

B



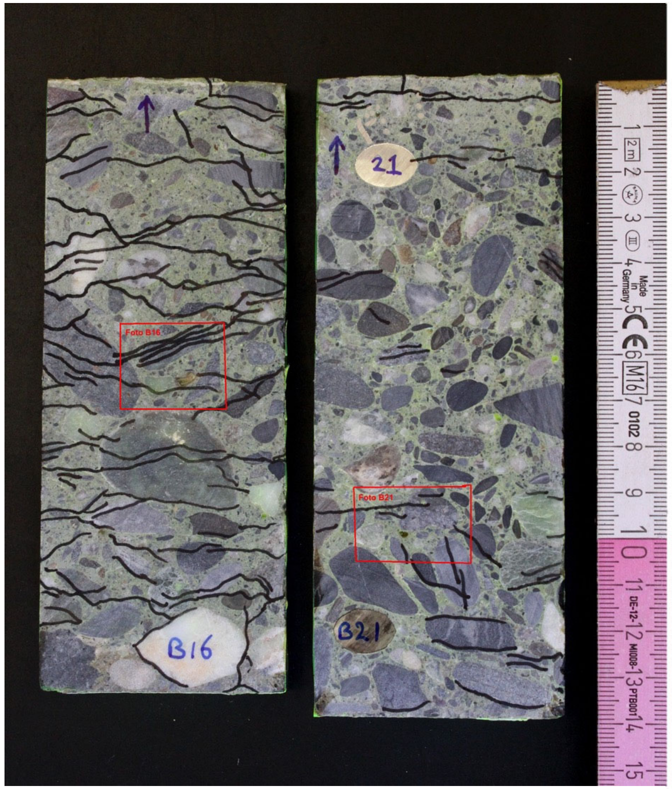
Examination of the polished concrete section under the stereomicroscope for the determination of the Damage Rating Index. Petrographic features of deterioration are counted in a one cm x one cm grid system drawn at the surface of the polished concrete section.

Laboratory observations

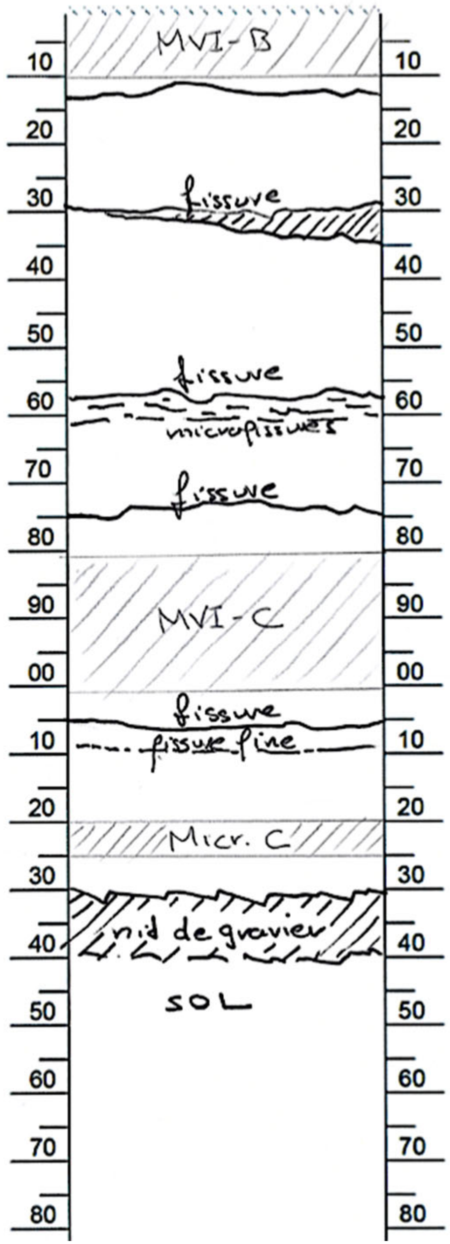
Detailed log of core samples:

To obtain information on:

- Type of cracks
- Amount of cracks
- Orientation of cracks
- Other pathology or characteristics



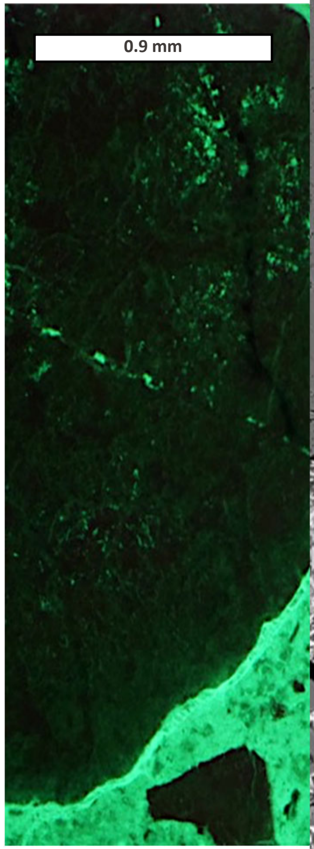
Source : laboratoire TFB

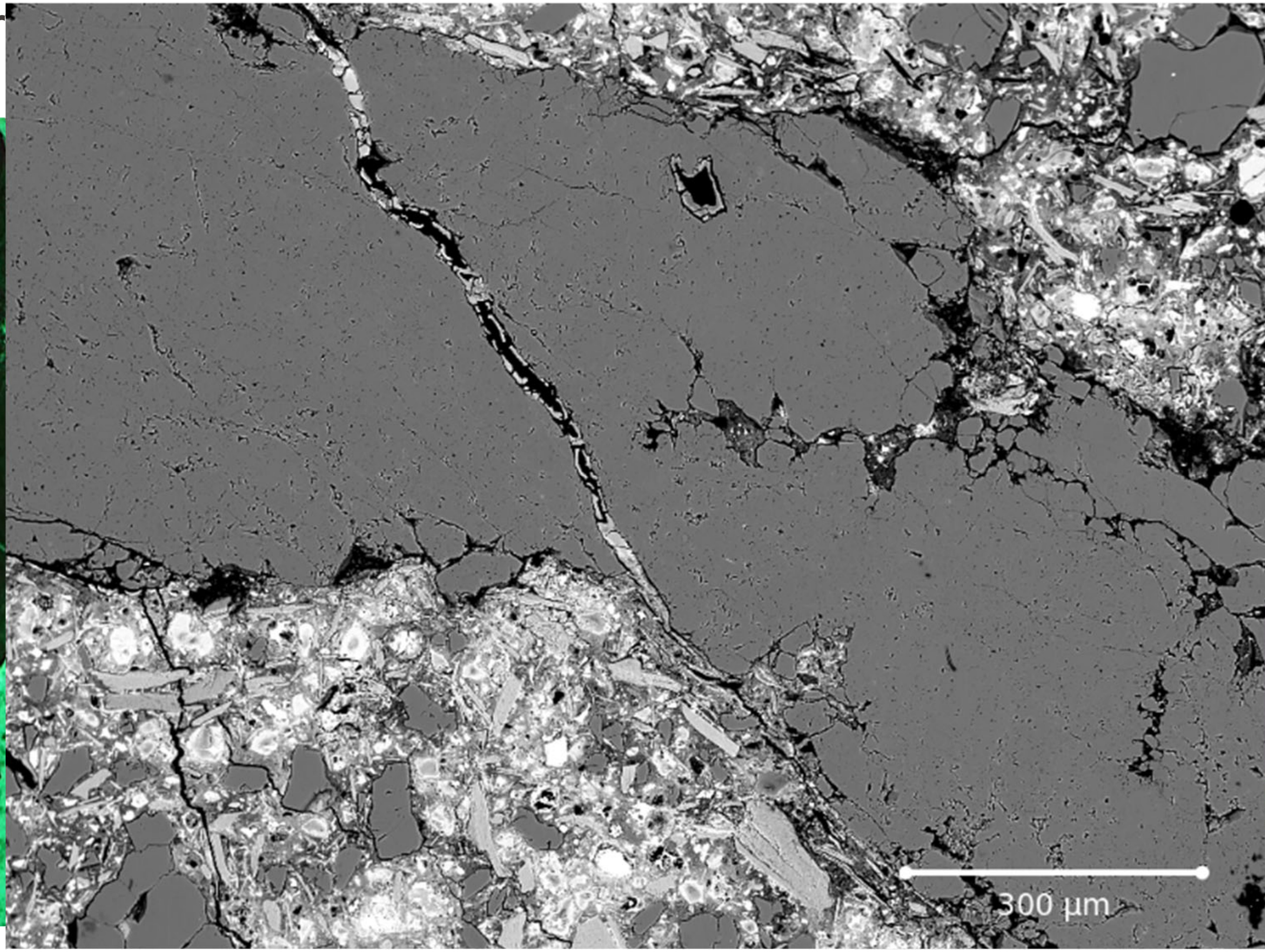


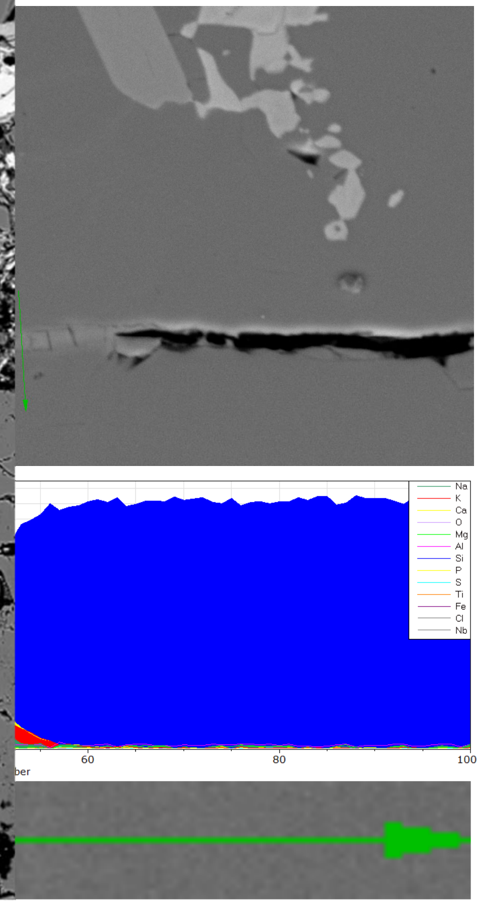
Laboratory observations

Microstructure analysis :

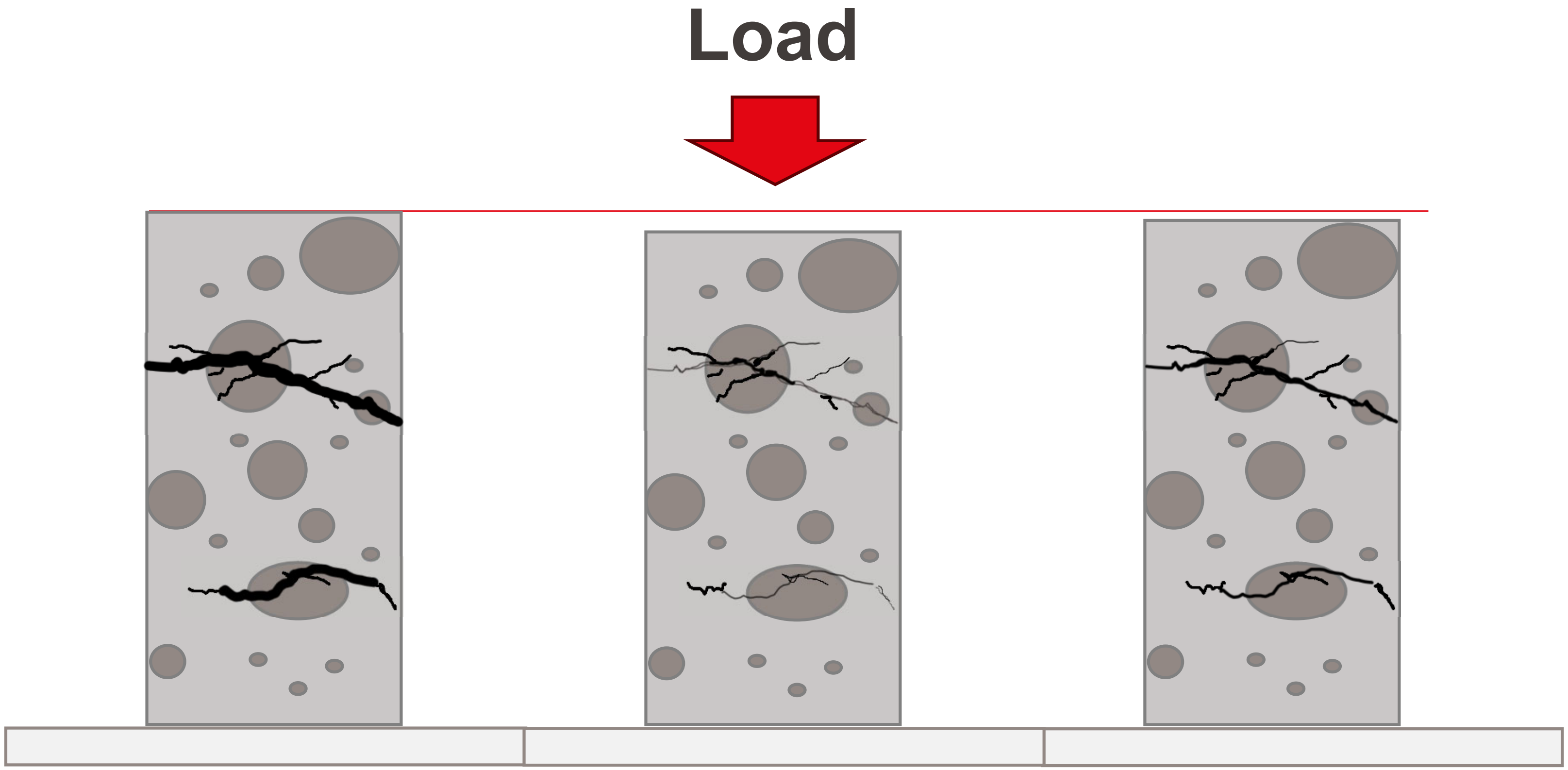
Optical micr ... icroscope (SEM)







Mechanical tests in laboratory
SDT (Stiffness Damage Test)



Mechanical tests in laboratory
SDT (Stiffness Damage Test)

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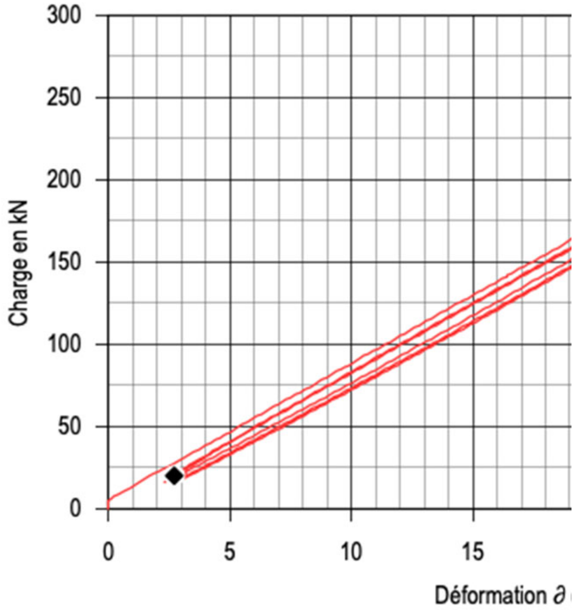


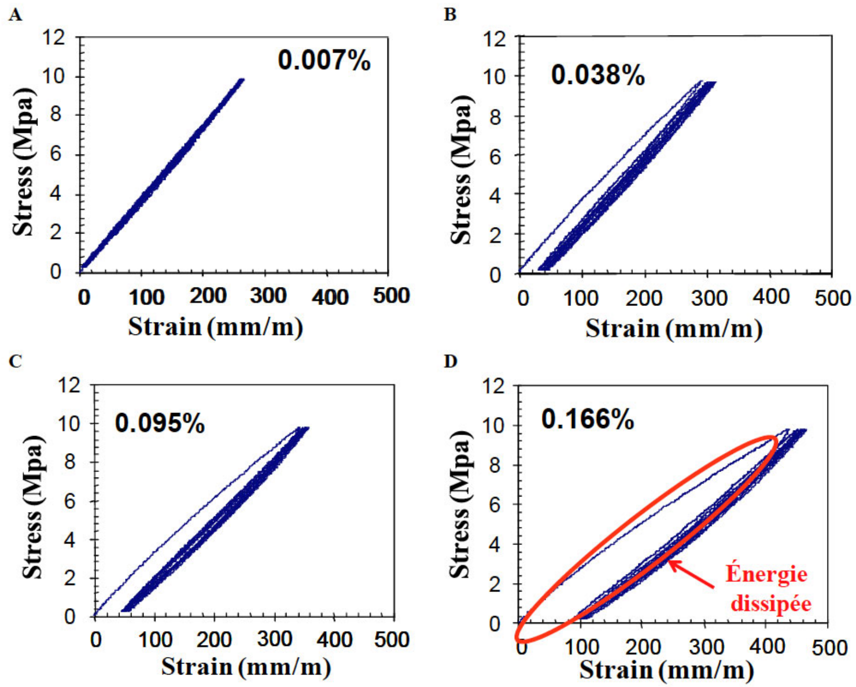
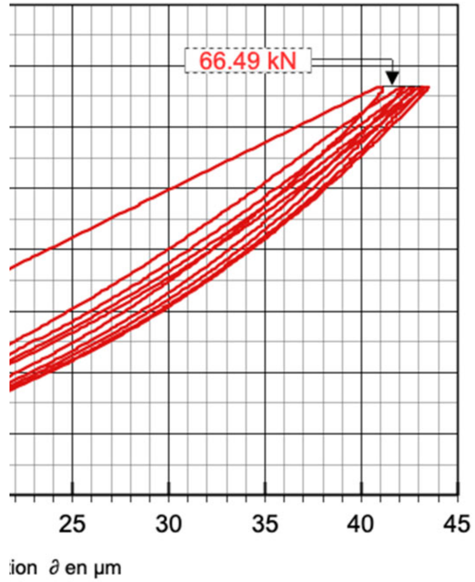


Figure 2.2 : Courbes typiques *contrainte-déformation* pour des échantillons de béton affectés par la RAS et soumis à 5 cycles de chargement / déchargement lors de l'essai SDT (charge de 10MPa). Les échantillons de béton avaient atteint différents niveaux d'expansion variant entre 0,007% (A) et 0,166% (B) (Smaoui et al. 2004a).



Without dan

maged

Source : LMC

Figure 2.1 : Résultats typiques de courbes *contrainte – déformation* obtenues au cours des cycles de l'essai SDT pour un béton endommagé (A) et un béton sain (B) (Crisp et al. 1993).

Correlation between SDT and microscopy

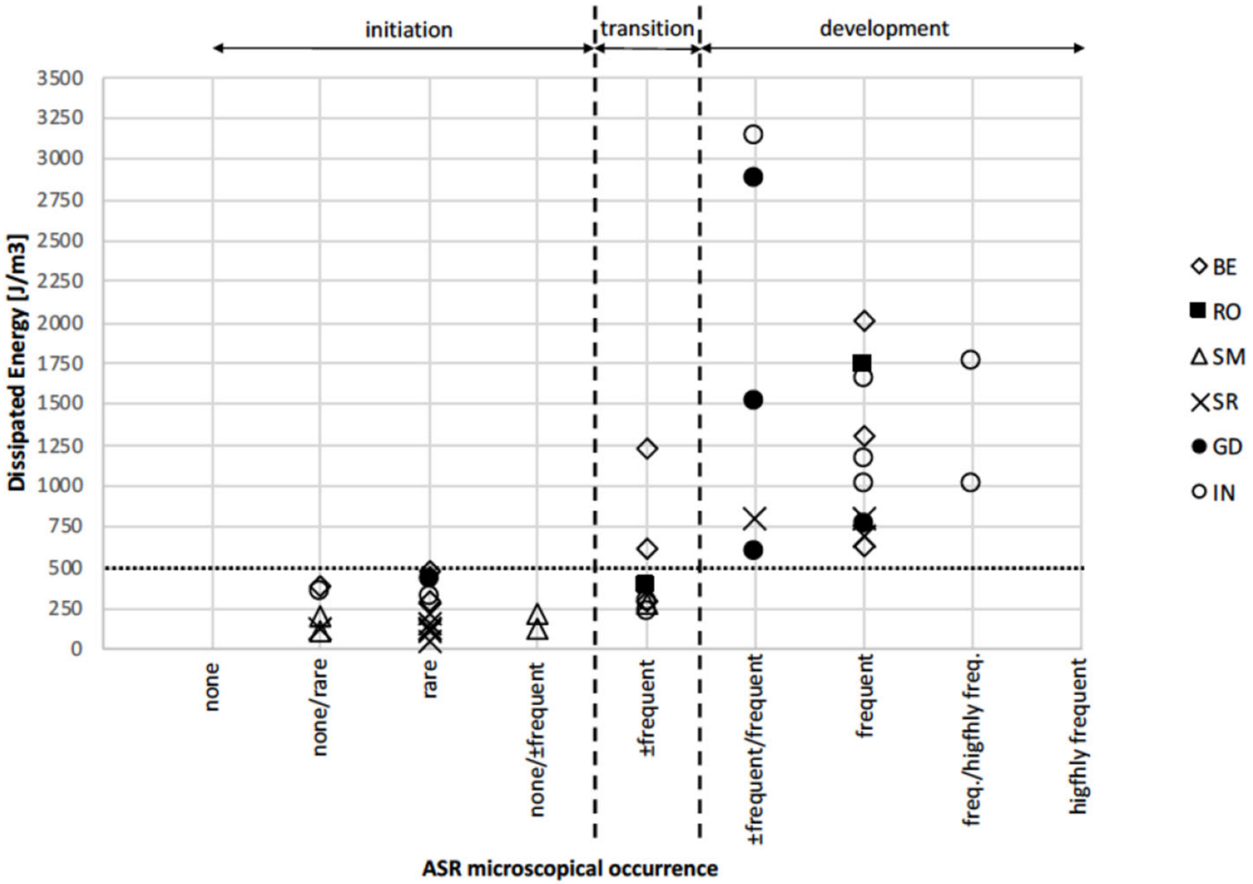
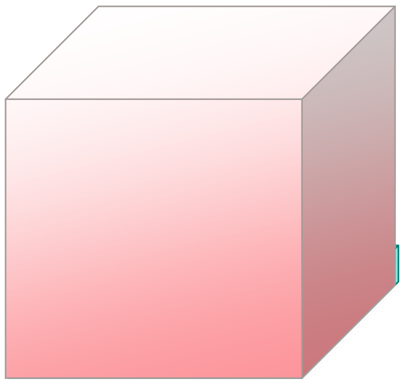


Figure 3.3: Dissipated energy after the first load cycle of SDT compared to the microscopical ASR occurrence

Source : TFB, T. Chappex, Extrait de Correlation of mechanical fatigue testing and semi-quantitative optical microscopy analysis for the robust diagnosis of field ASR damaged structures

Residual expansion

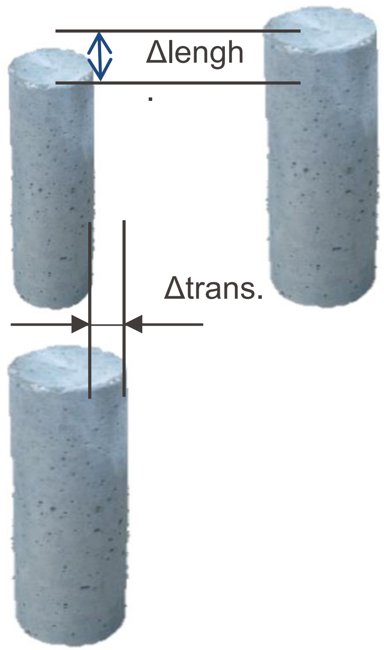
Concrete core



Steam condition
at 38°C

Expansion

Δlengh = longitudinal variation



Δtrans. = transverse variation

How to vali a concrete mix design?

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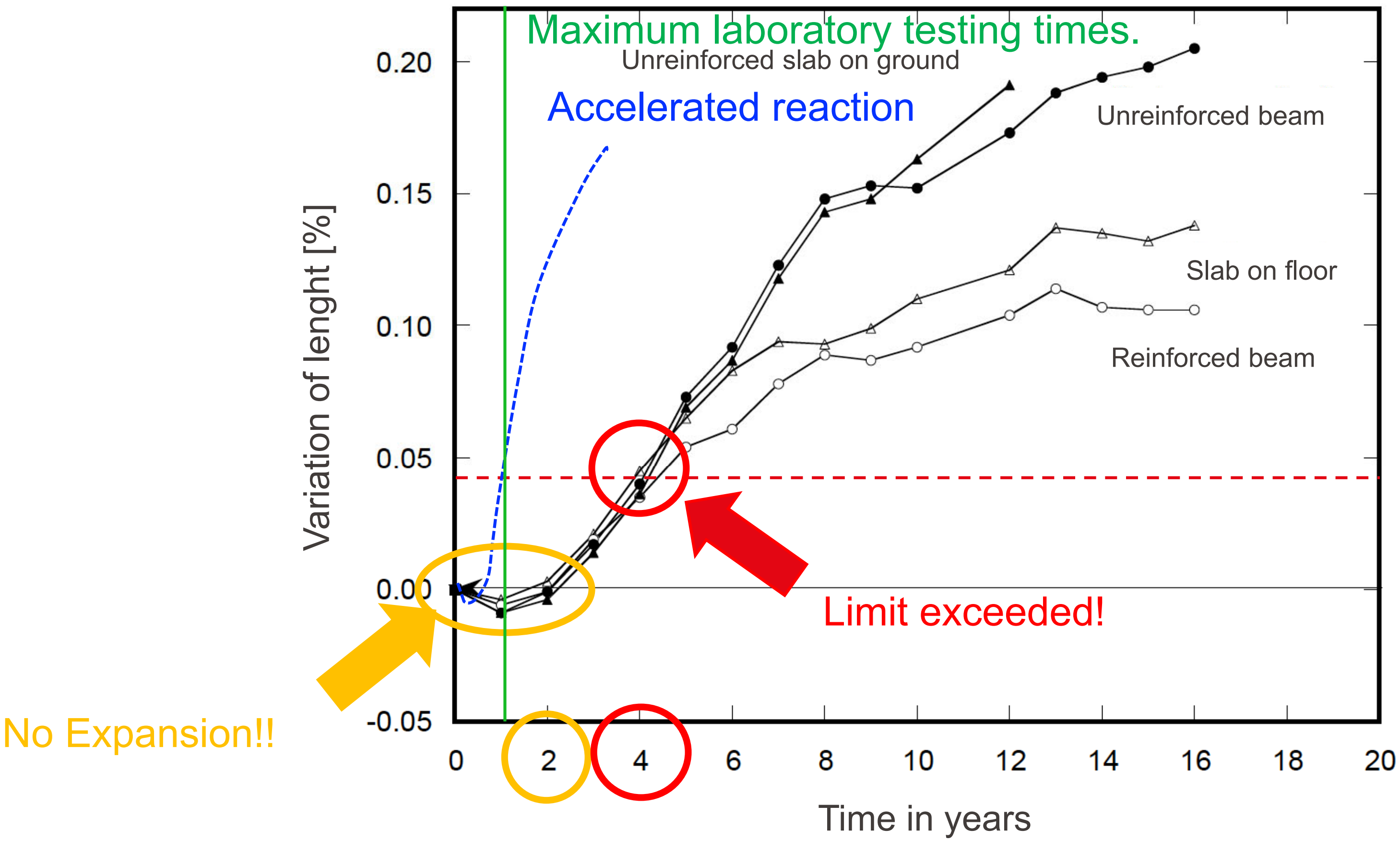
How to vali a concrete mix design?



Expansion of mix number 6 (high content of alkalis) in various elements

Speed up the reaction:
By modifying:
- alkaline content
- the temperature
- Storage conditions

Expansion limit
0.04 [%]

Source: Preventative Measures for Alkali-Silica Reaction: The Kingston Outdoor Exposure Site for ASR - After 16 Years, MERO-031; ISBN 978-1-4249-6748-3

Example

30 Days

30 °C

3 minutes

100 °C

Source: Presentation A. Leeman, EMPA

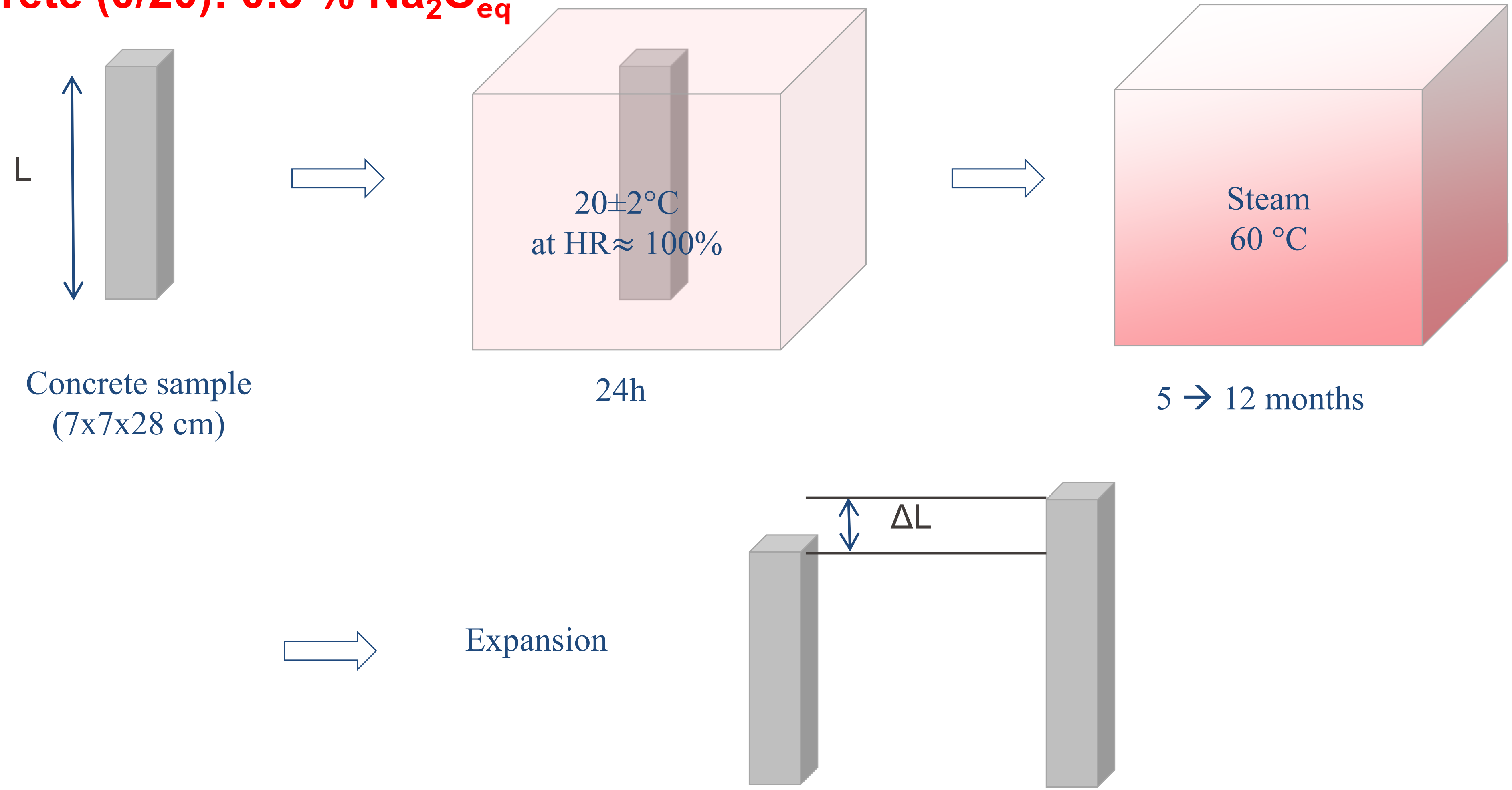
What do Swiss standards offer?

- Technical specifications **SIA 2042**
- SIA 262-1: 2019 : Annexe G

Performance test

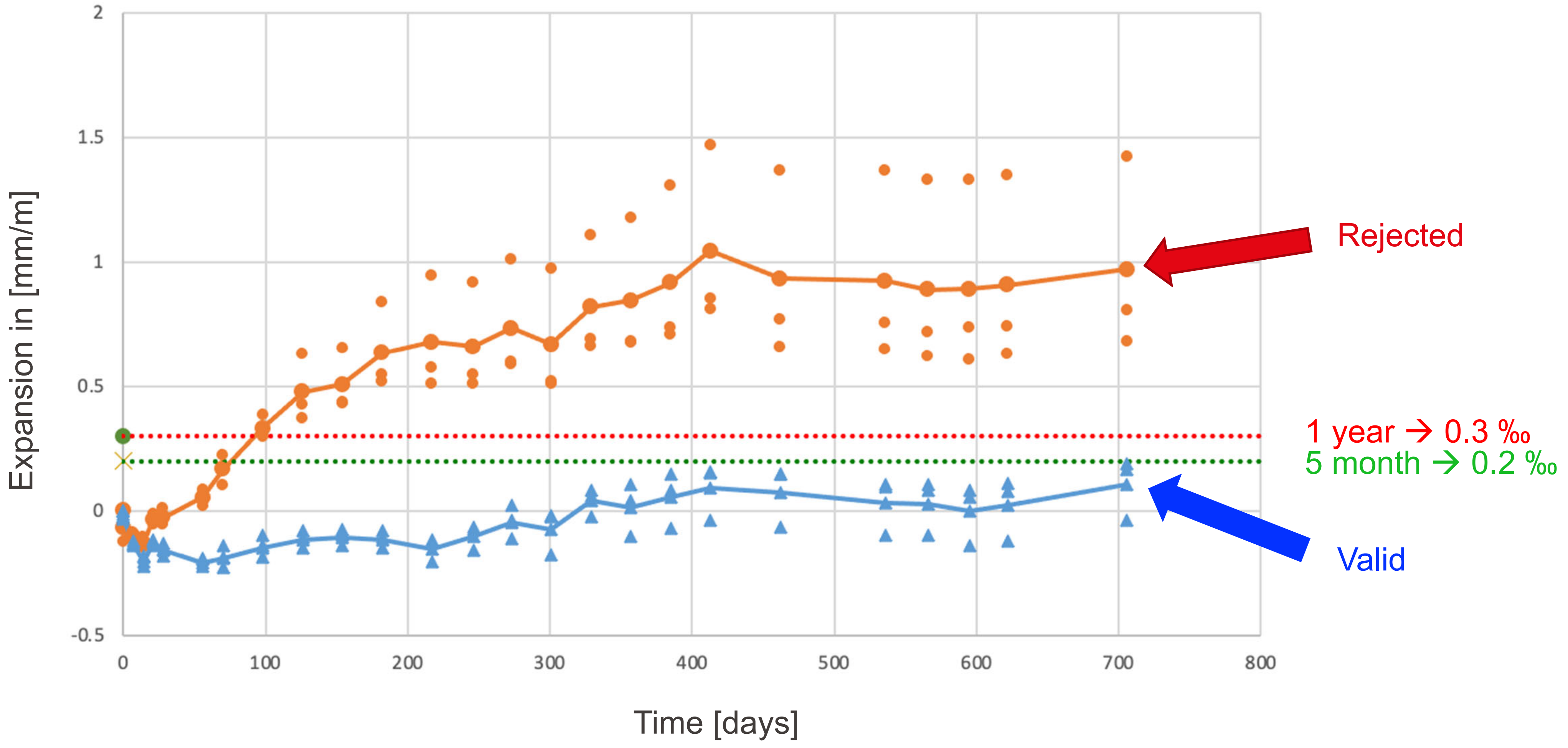
SIA 262-1 – Performance test?

Concrete (0/20): 0.8 % Na_2O_{eq}



EPFL

SIA 262-1 – Performance test?



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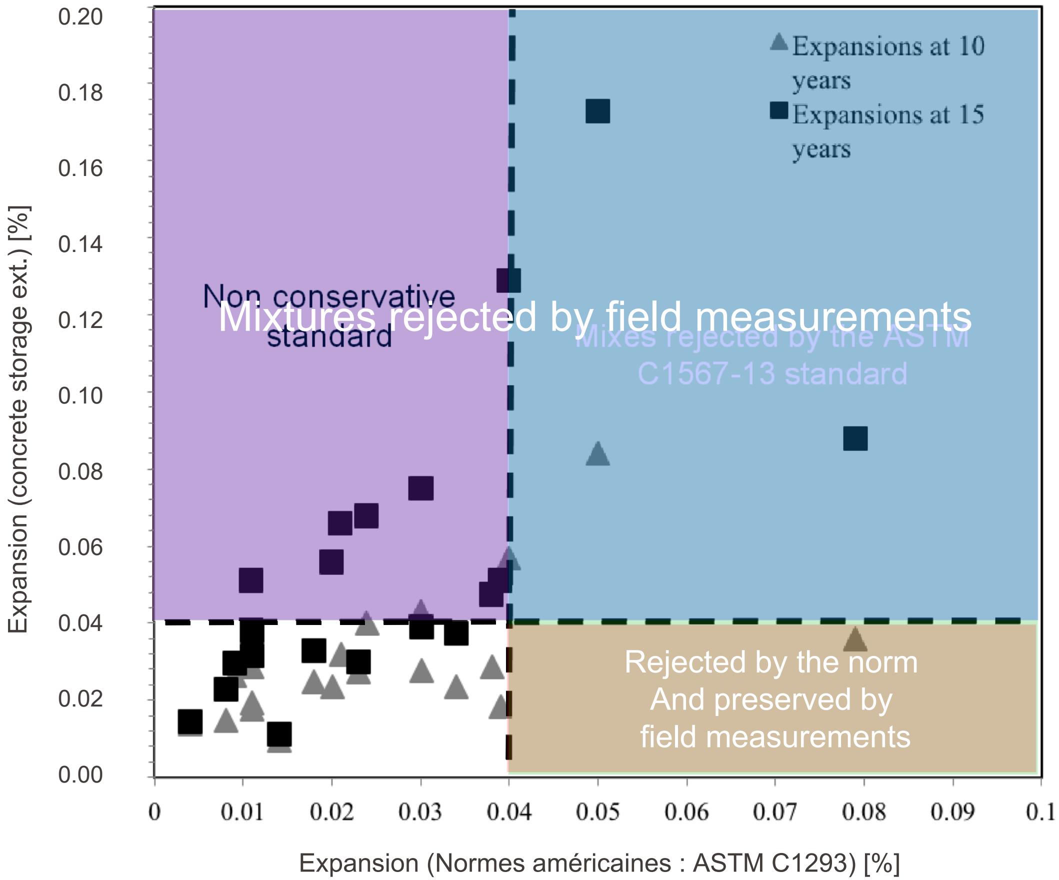
Limitations of standards



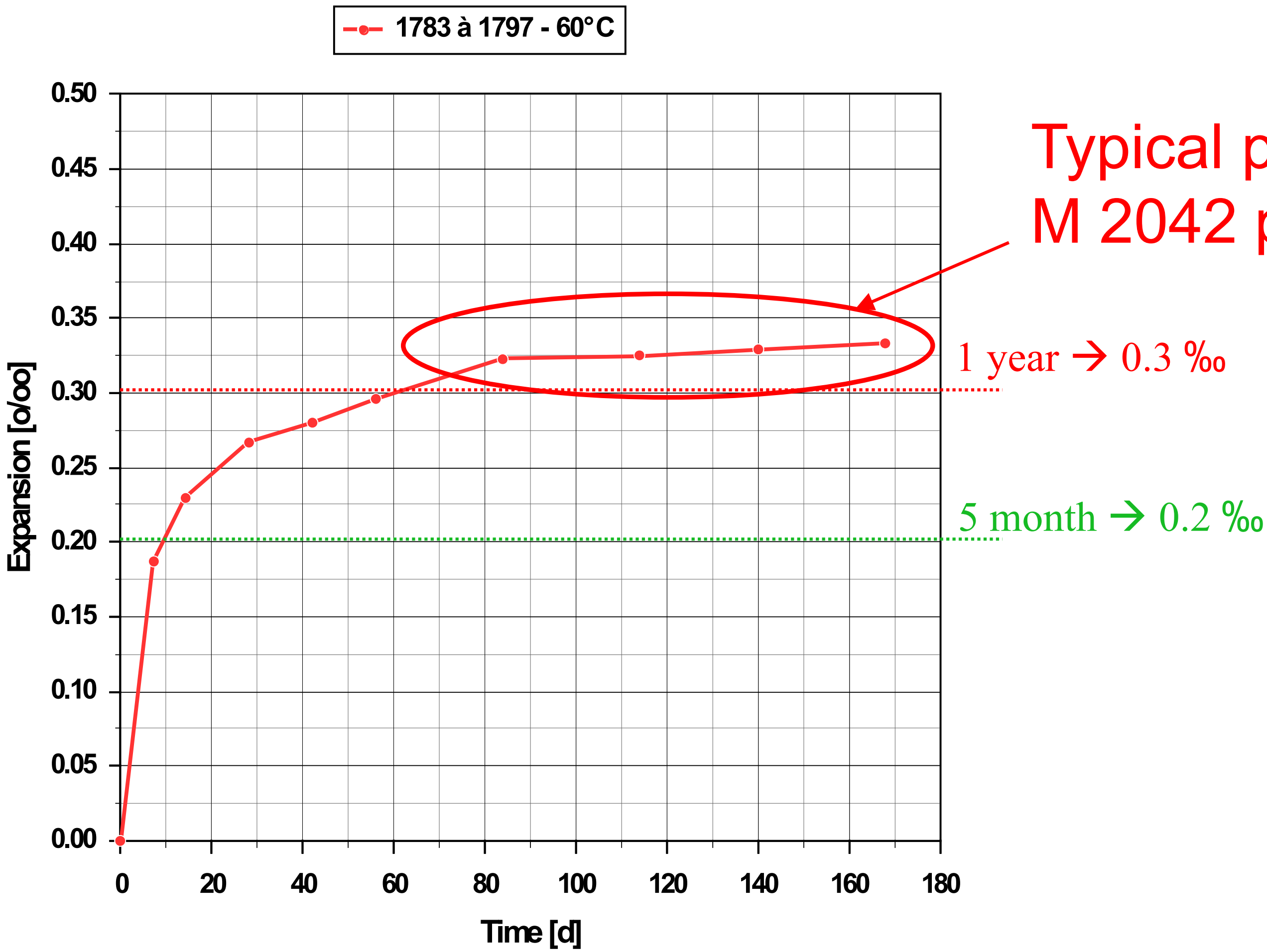
Ref: The University of Texas at Austin Exposure Site

Exposure blocks conditions:
Storage on field
0.95% Na_2O_{equ}

ASTM tests conditions:
100% relative humidity at 38°C
1.25% Na_2O_{equ} (0.45 mol/l)

Current standard are not always able to predict ASR reactivity of concrete

Limitations of standards



3 options:

- **No water**
- **No alkali**
- **No amorphous silica**

- *Typical results of swelling-time curve according the M 2042* [3]

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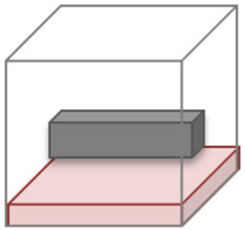
Limitations of standards

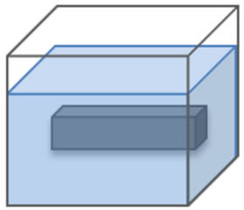
Standard (MB2042)



1 or 28 days

(9000-8000)

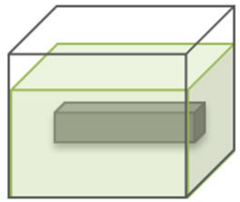
Alkaline solution



1 or 28 days

(7000-6000)

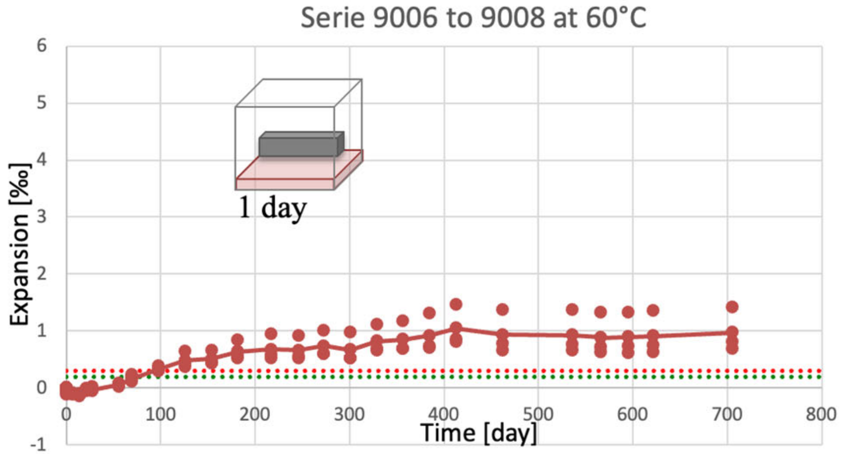
Pore solution

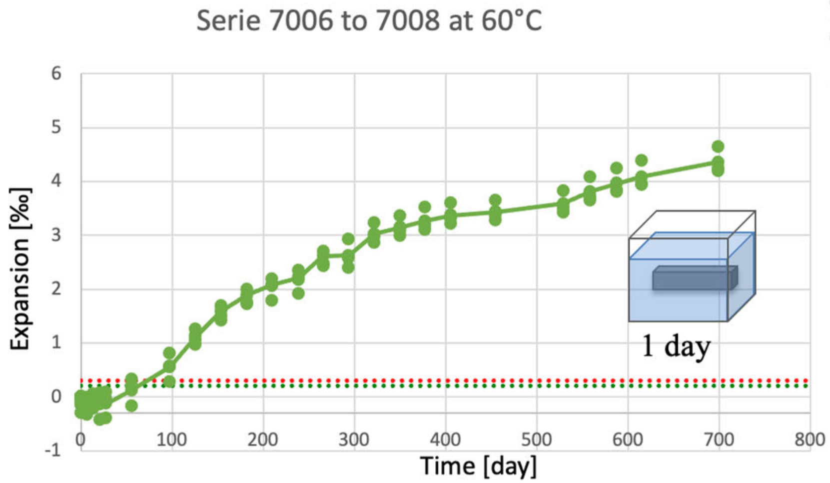


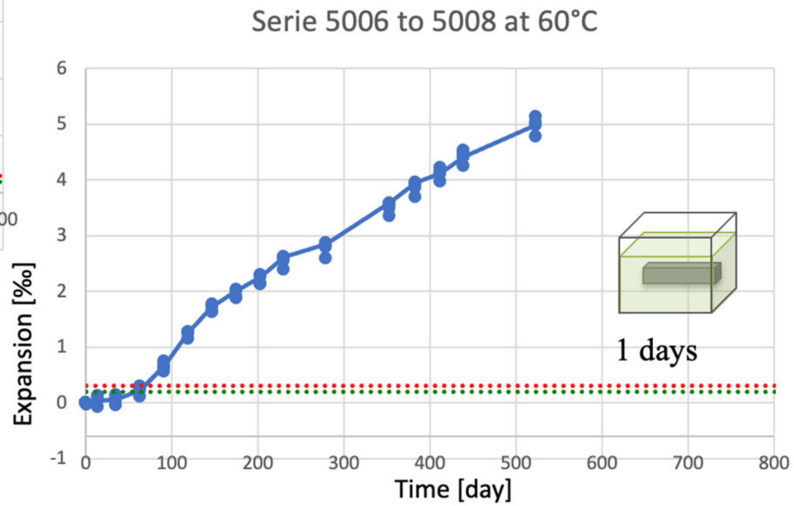
1 or 28 days

(5000-4000)

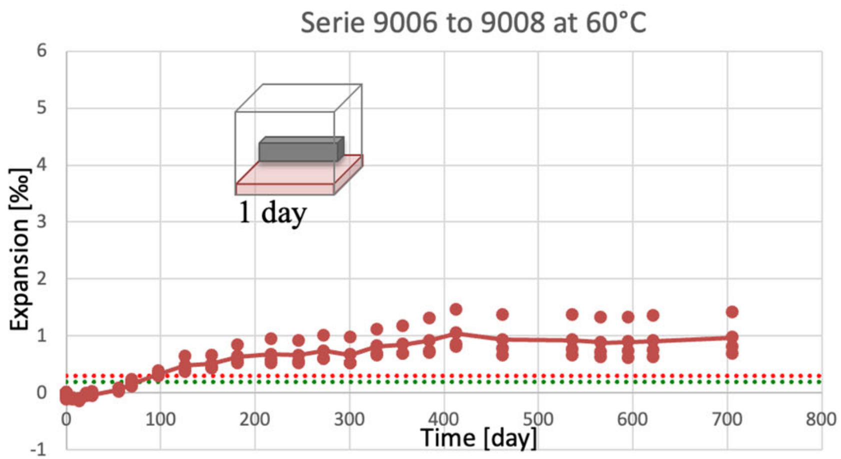
Limitations of standards

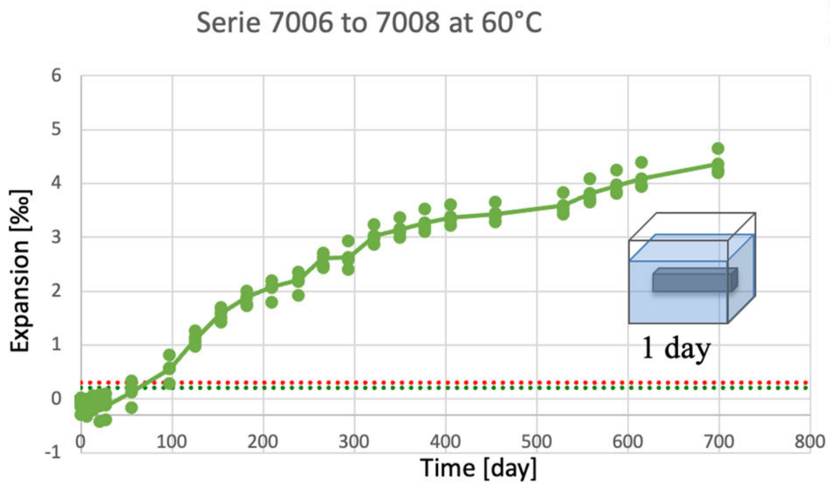


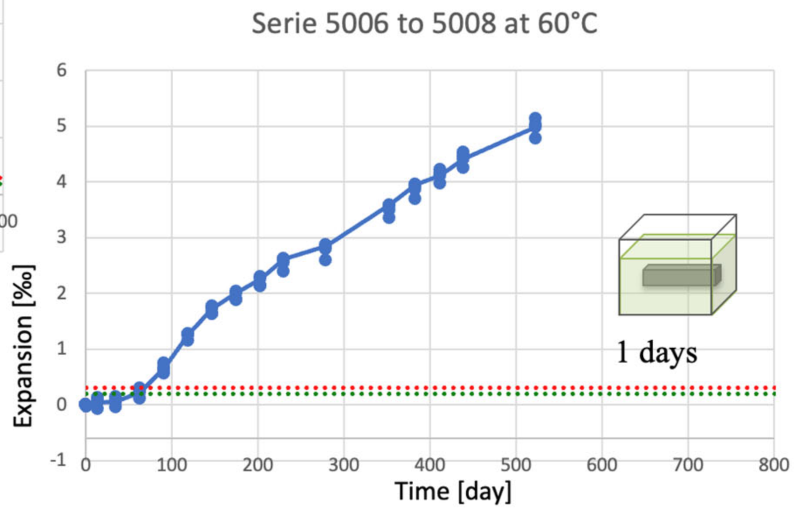




Limitations of standards



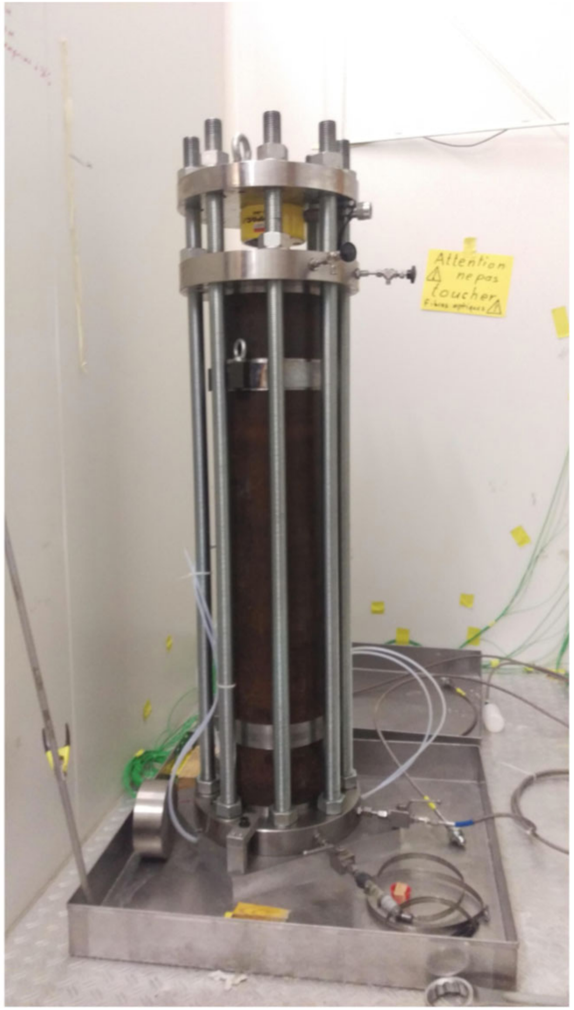


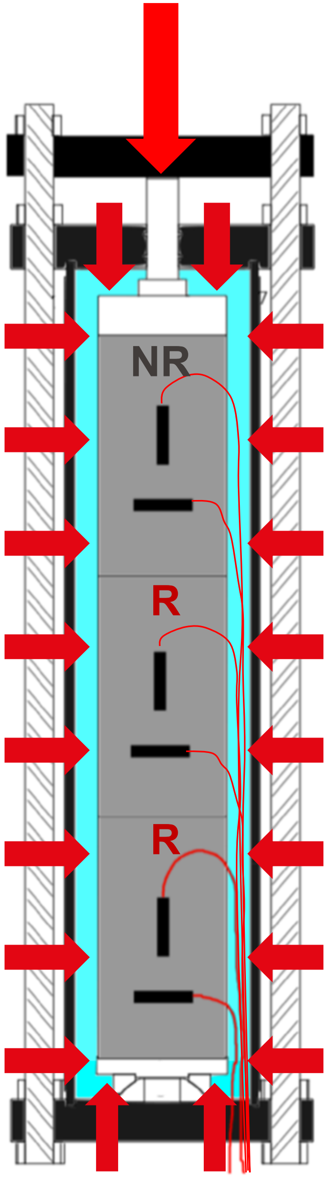


Limitations of standards

Final test in progress

- Design based on tri-axial cells used for rock mechanics
- Independent axial/lateral load
  - Axial load applied via a hydraulic jack
  - Radial load applied via a pressurised alkali solution
- Alkali solution
  - Promote the reaction
  - Avoid leaching
- Constant temperature (38°C)





What to do with a construction affected by ASR

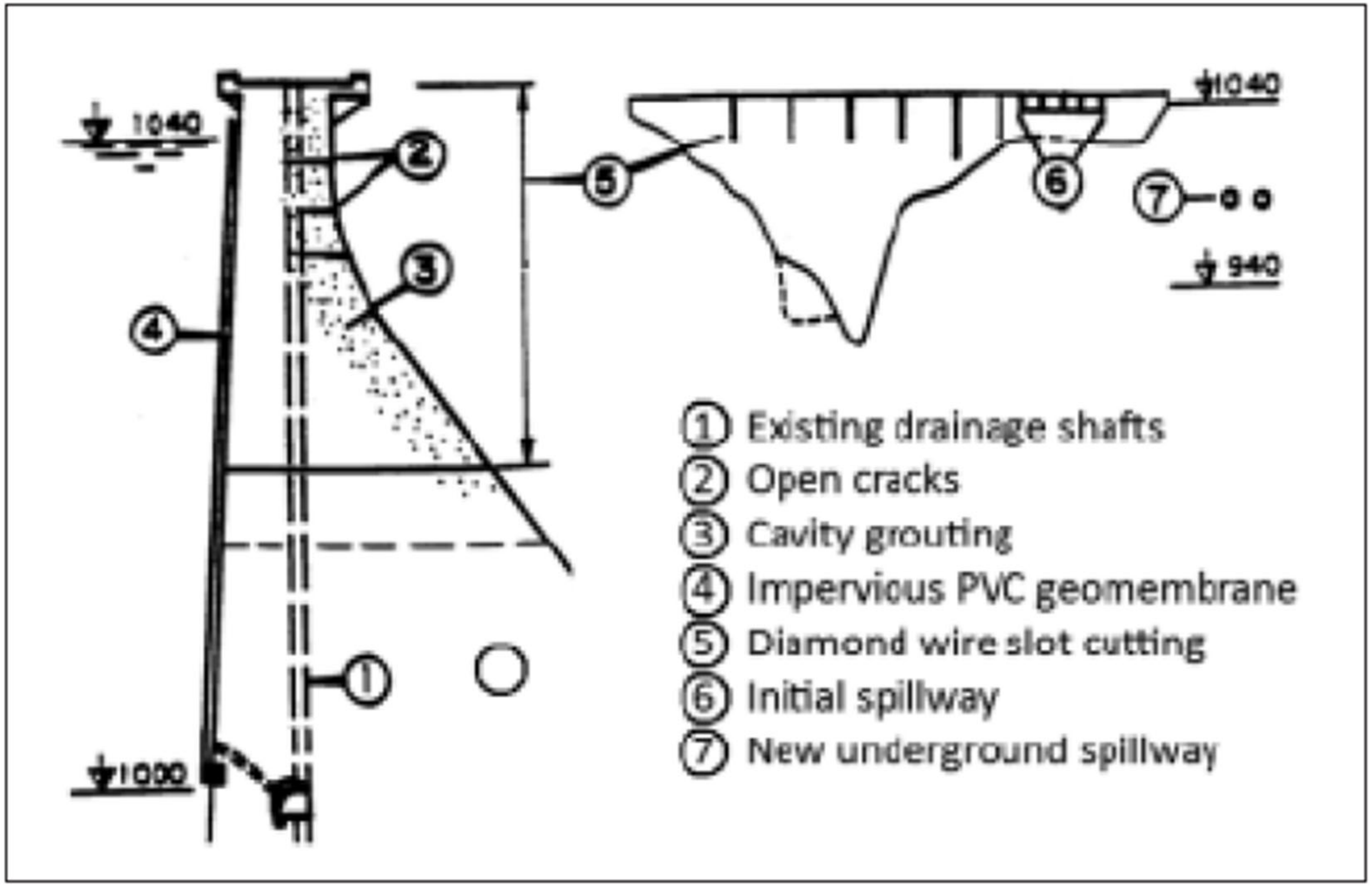


Figure 2: The 1992-1993 campaign of reinforcement works at Chambon dam (Source: Fry)

What to do with a construction affected by ASR

Chambon - Gravity dam

- 88 m height above natural ground
- 137 m above the
- Crest length of 294 m
- built between 1929 and 1935.
- cement dosage varies from 150 to 250 kg/m^3

First ASR damage observed around 1958

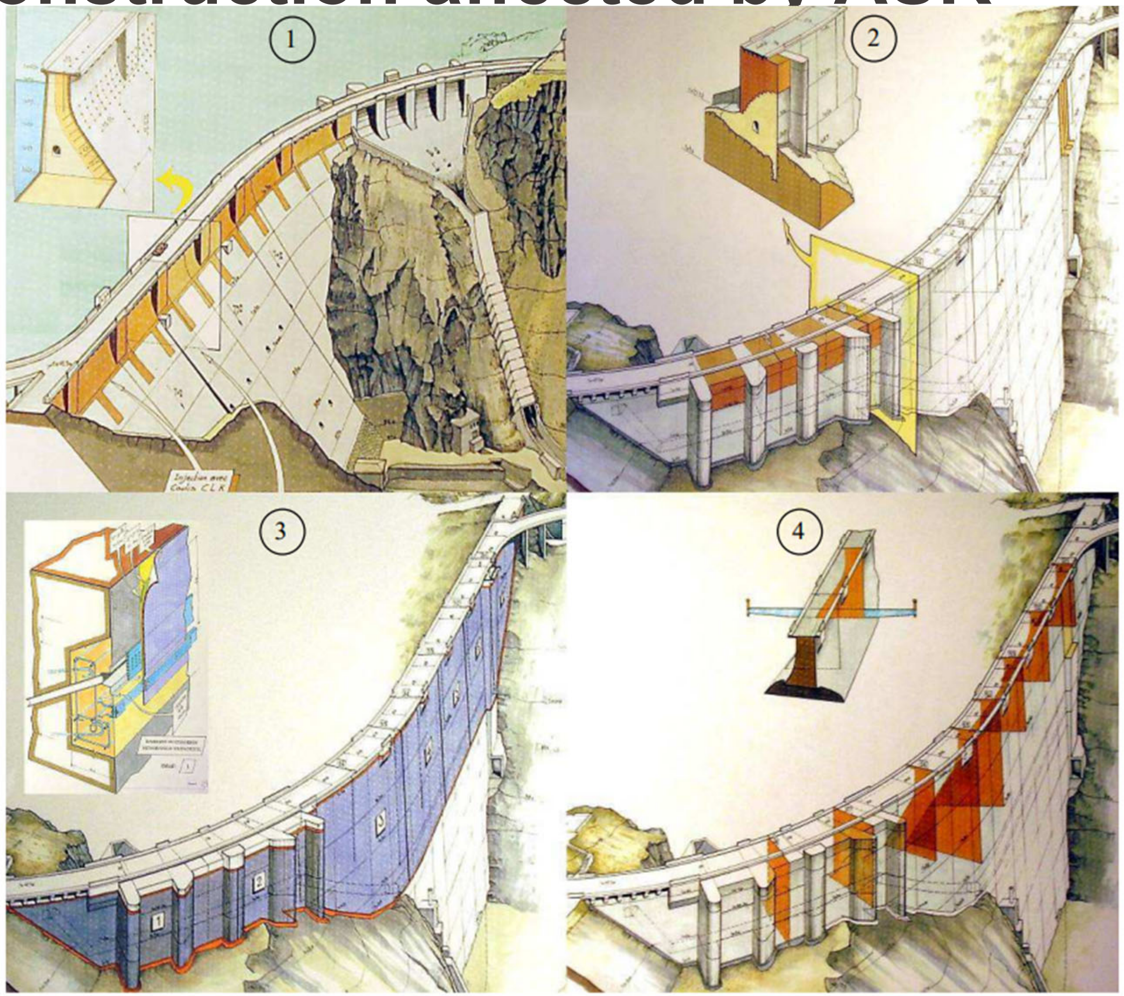


Figure 1 : *Travaux réalisés dans les années 1990 en lien avec l'alcali-réaction*

What to do with a construction affected by ASR

Chambon - Gravity dam

1. Crack injection
2. Sealing of the old spillway passages
3. Upstream protection: a waterproofing membrane was installed on the upper 40 metres of the upstream facing between 1991 and 1995.
4. Sawing: Between 1995 and 1997, eight vertical saw cuts were made using an 11 mm diamond wire in the upper part of the dam.

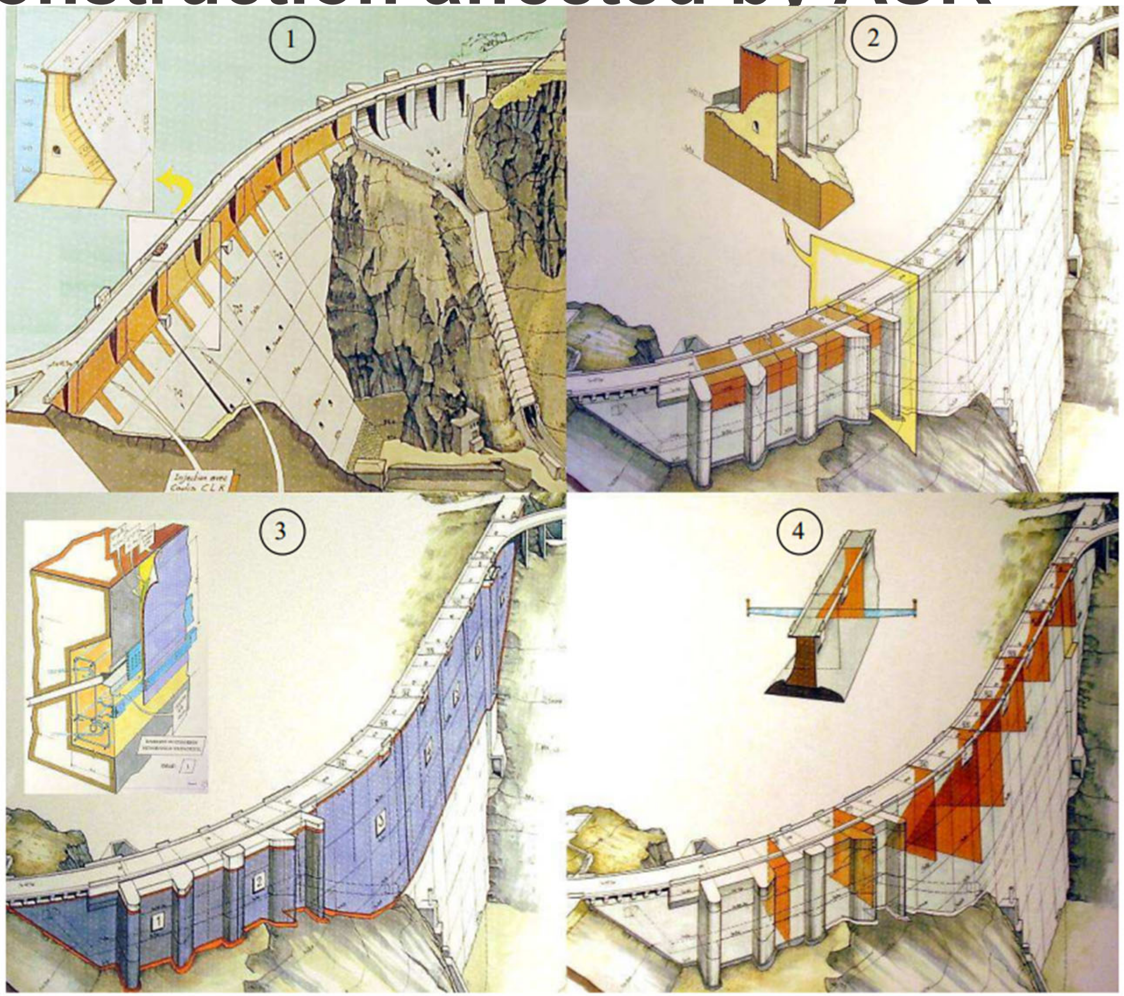


Figure 1 *: Travaux réalisés dans les années 1990 en lien avec l'alcali-réaction*

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What to do with a construction affected by ASR

From Janvier 2013 to December 2014

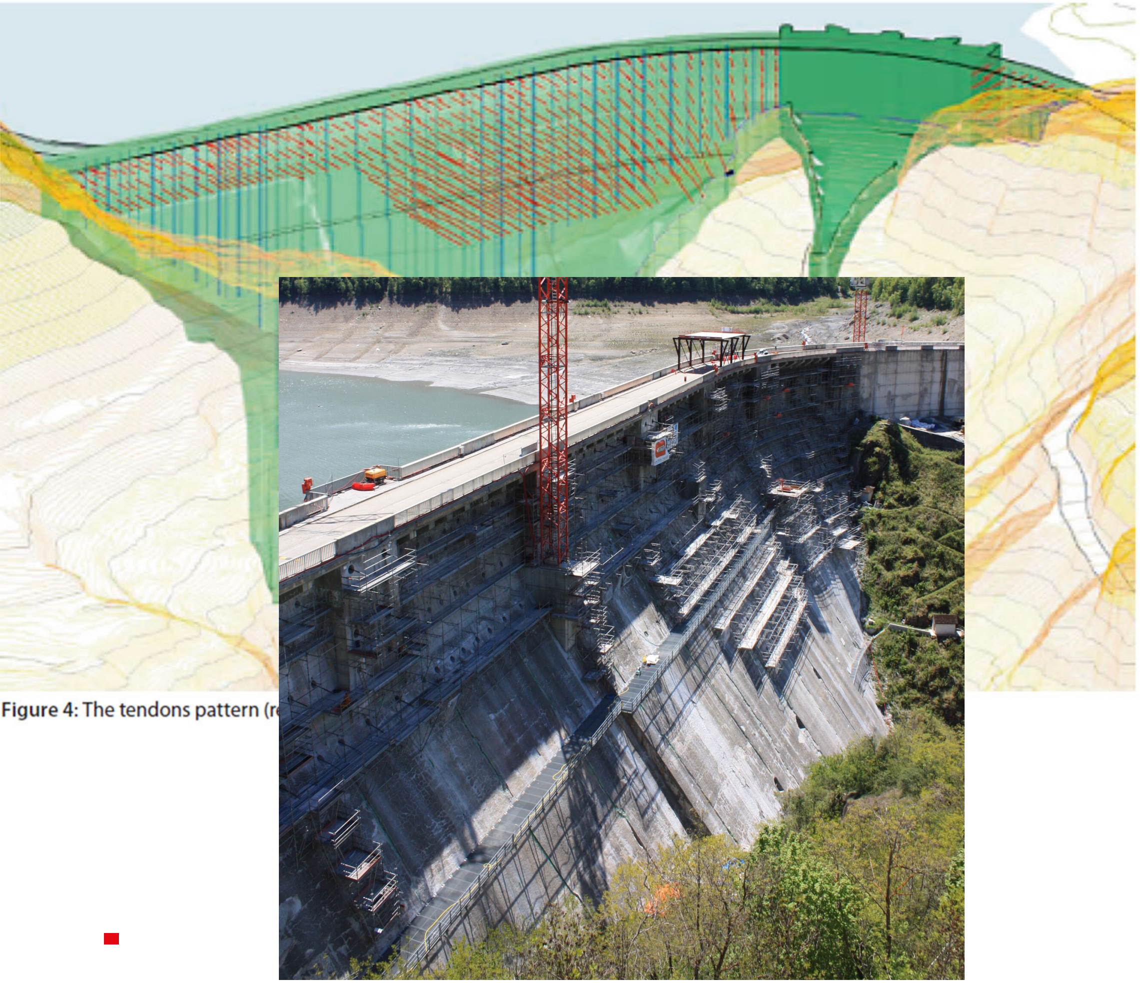
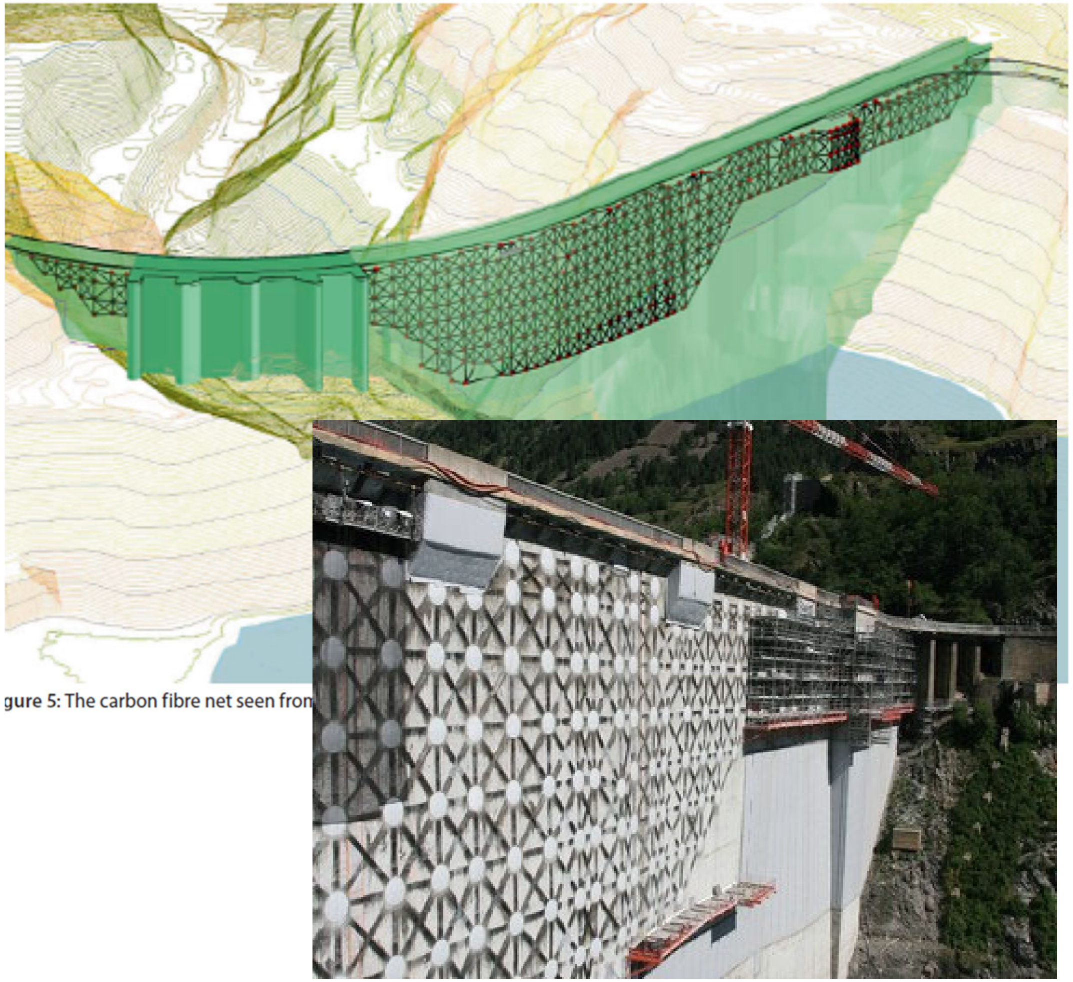
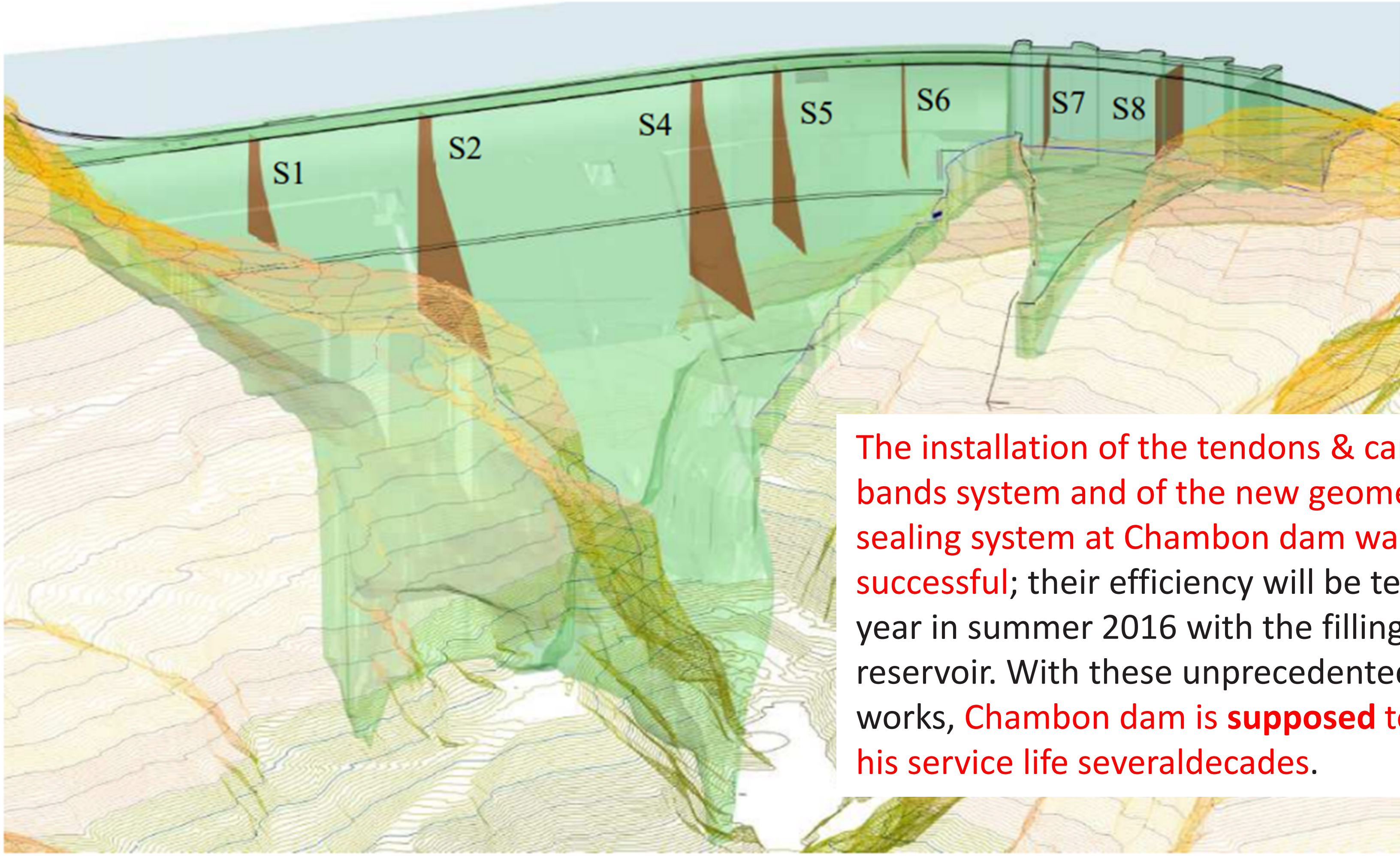


Figure 4: The tendons pattern (r



gure 5: The carbon fibre net seen fron

What to do with a construction affected by ASR



The installation of the tendons & carbon bands system and of the new geomembrane sealing system at Chambon dam was successful; their efficiency will be tested this year in summer 2016 with the filling of the reservoir. With these unprecedented repair works, Chambon dam is **supposed** to extend his service life severaldecades.

Sources : https://www.barrages-cfbr.eu/IMG/pdf/4.01.confortement_barrage_chambon.pdf

Conclusion

Alkali Granulate reaction is a very slow chemical reaction.

- A complex reaction that requires in-depth knowledge in order to warn of or identify potential defects related to ASR.
- Prevention through concrete formulation is not sufficient, but necessary to eradicate the problem.
- Need to regularly inspect old and new structures.
- Catalyst for other pathologies and effects may accumulate (freezing/thawing, sulphate attack, chloride penetration, etc...)

Improvement?

- Establishment of a long-term exposure site to vali performance tests on standard Swiss concrete.
- Continue research to minimise the gap between laboratory measurements and field measurements..


Thank you for your attention!
Questions?