

Interaction between the swelling due to ISR and creep due to bi-axial compression constraints

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T3.1.2 of WP3: Interaction between the swelling due to ISR and creep shrinkage due to bi axial compression constraints

T4.2.4 of WP4: Assessment and improvement of Fib code model 2010 formulas

- **PhD Title:** Experimental study and modeling of the effect of biaxial prestressing on the internal swelling reactions of concrete

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- **Context and literature**
- **Experimental program**
- **Results and discussions**
- **Conclusions and perspectives**

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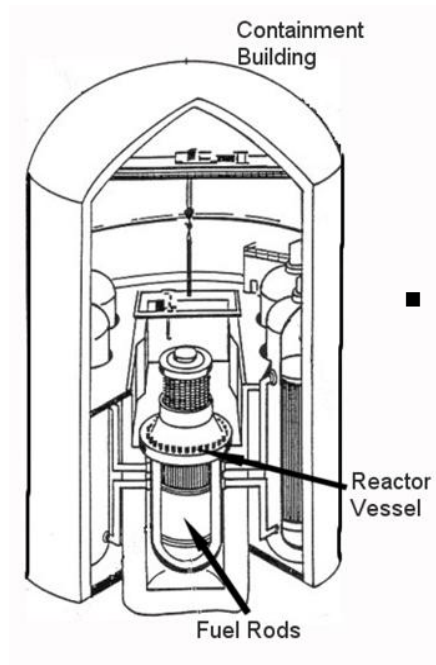
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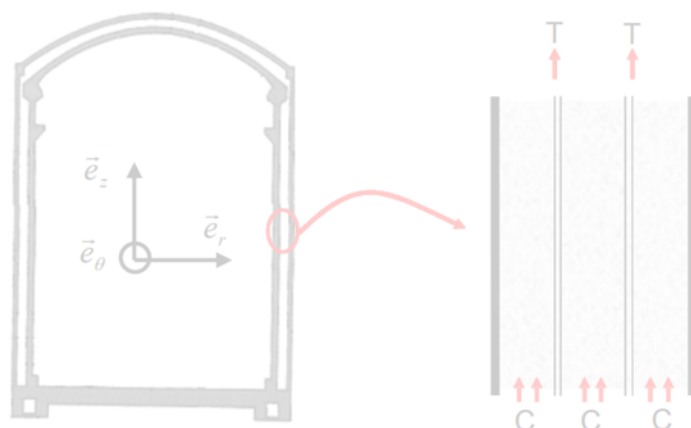
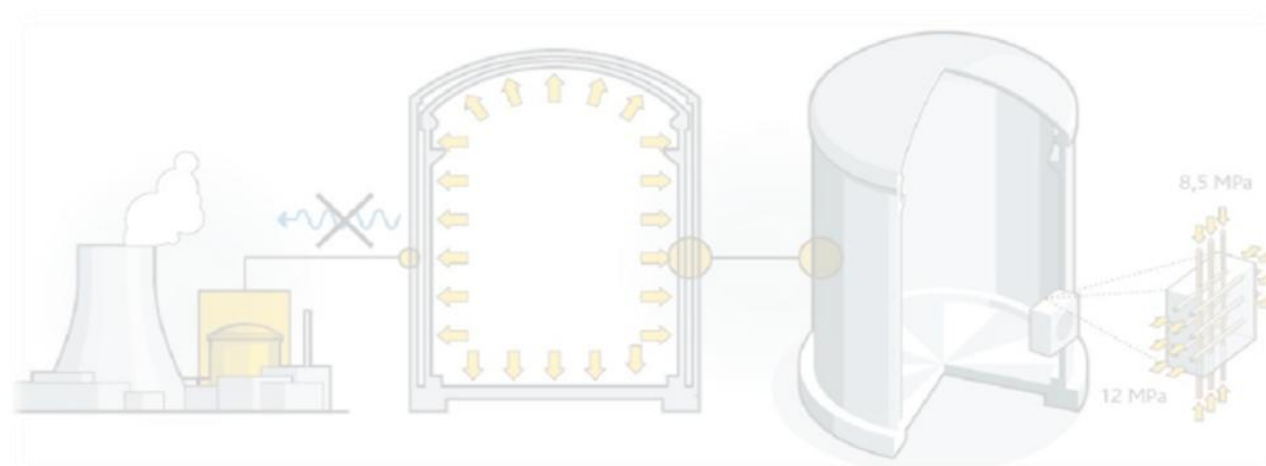
Results and Discussions

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Conclusion, Perspectives



- **Containment structure : Containment building around nuclear reactor**



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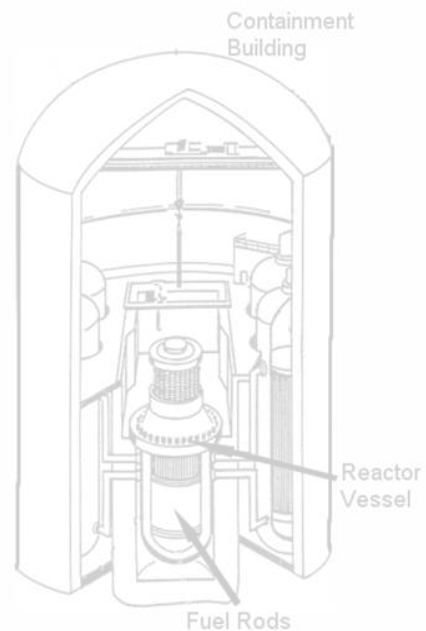
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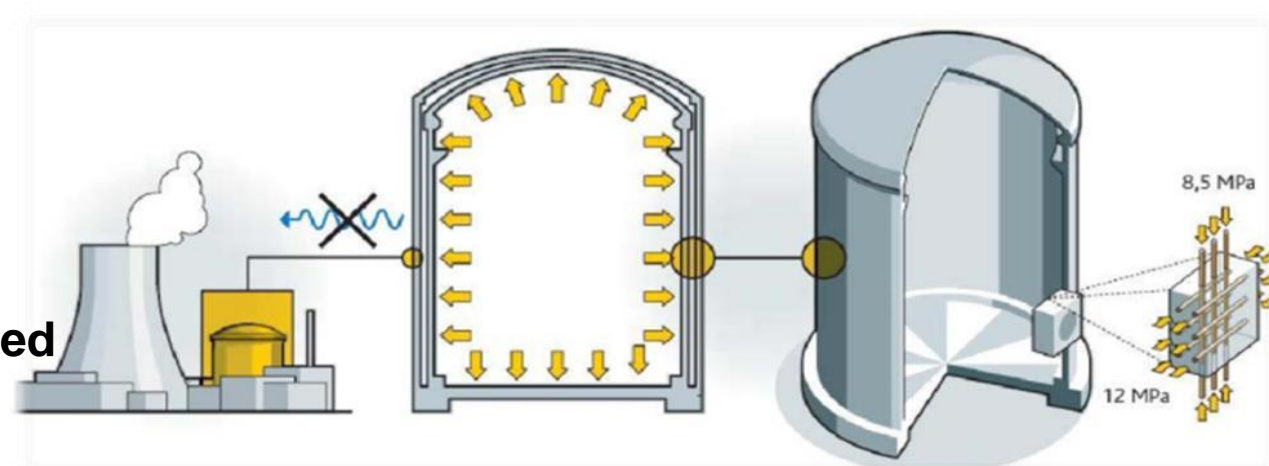
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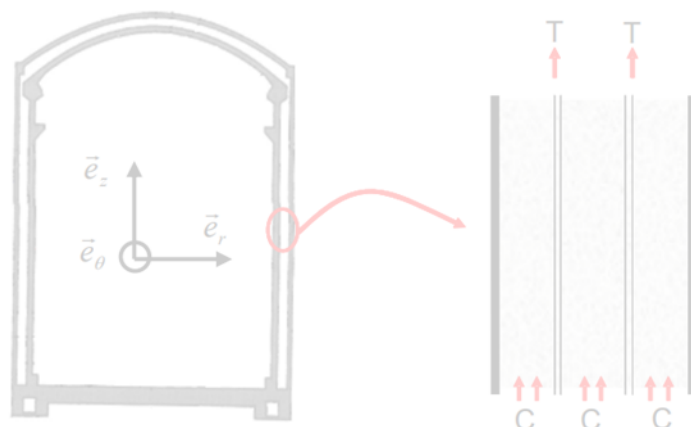
Conclusion, Perspectives



- Internal wall: biaxially prestressed



[Granger 1996, Le Pape et al 2003]



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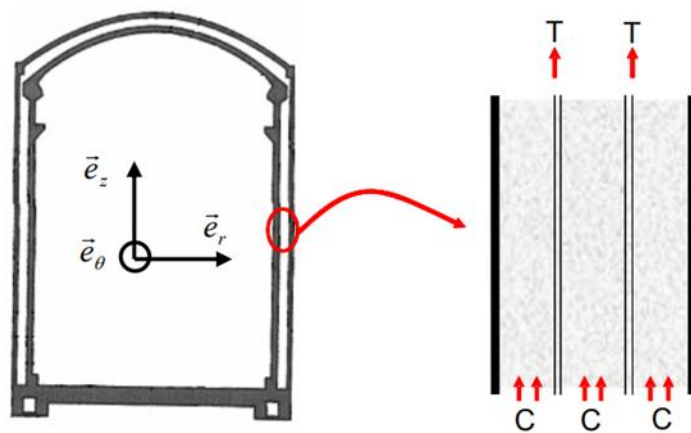
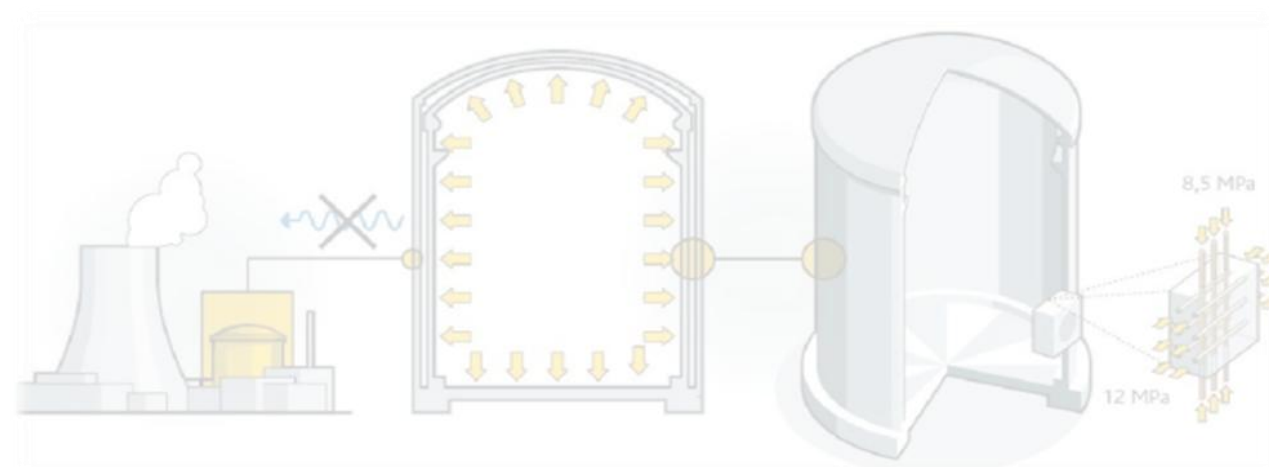
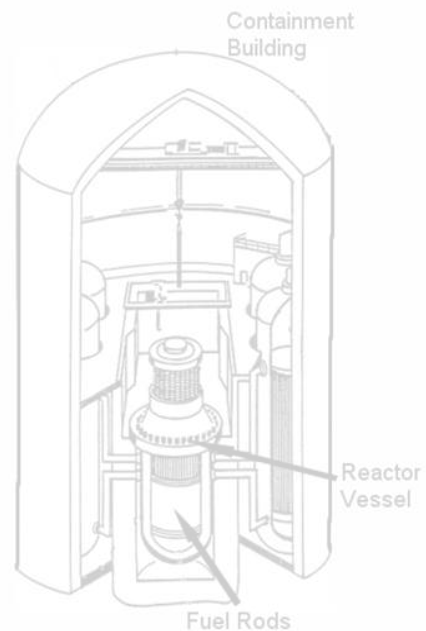
Experimental Program

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Reviron [2007]

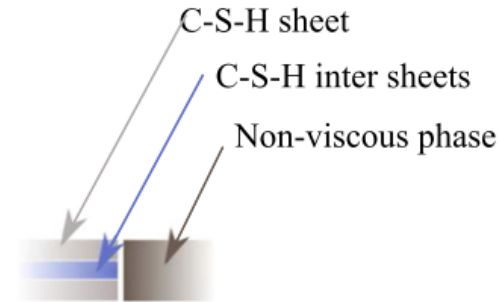
- Loss of prestress

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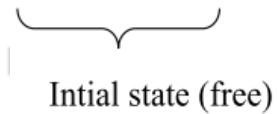
Context and Literature

Concrete creep

■ C-S-H sheets



■ Instantaneous elastic



[Sellier et al., 2016]

$$\varepsilon_{elastic} = \frac{\sigma}{E}$$

■ Viscous sliding of C-S-H sheets

$$\frac{\partial \varepsilon_{ij}^K}{\partial t} = \frac{1}{\tau^K} \left(\frac{\varepsilon_{ij}^E}{\varphi^K} - \varepsilon_{ij}^K \right)$$

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Concrete creep

- C-S-H sheets

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- Instantaneous elastic response

$$\varepsilon_{elastic} = \frac{\sigma}{E}$$

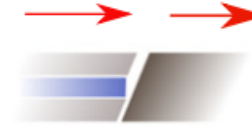
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- Viscous sliding of C-S-H sheets

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Instantaneous strain
(elastic response)

[Sellier et al., 2016]

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Concrete creep

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- C-S-H sheets

- Instantaneous elastic response

$$\varepsilon_{elastic} = \frac{\sigma}{E}$$

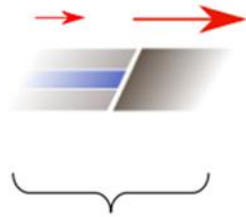
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Results and
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- **Viscous sliding of C-S-H sheets**

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Delayed strain induced by
intersheet sliding

[Sellier et al., 2016]

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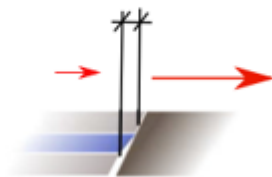
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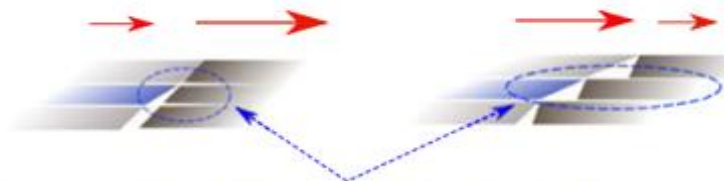
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Material rearrangement – non-linearity

Viscous sliding limited by
non-viscous phases



Stress concentration on non-viscous phases



Damage induced by stress redistribution between
viscous and non-viscous phases

[Sellier et al., 2016]

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Thermal effect

- **Thermal activation of creep (Arrhenius effect)**

Rapid and durable thermal expansion

- **Thermal transient strain**

Stress and temperature applied simultaneously

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Context and Literature

Internal swelling reaction – Delayed ettringite formation

Temperature > 65°C at early age

2

Experimental Program

Relative humidity > 95%

Cement composition

3

Results and Discussions

- **Destabilization** of the ettringite at an early age : $T > 65^{\circ}\text{C}$

- **Delayed** ettringite precipitation (ambient temperature + humidity)

- Generation of **internal pressures, expansions, cracks**

4

Conclusion, Perspectives

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Context and Literature

Internal swelling reaction – Delayed ettringite formation

Temperature > 65°C at early age

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Relative humidity > 95%

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Results and Discussions

- Destabilization of the ettringite at an early age : $T > 65^{\circ}\text{C}$
- **Delayed** ettringite precipitation (ambient temperature + humidity)
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Context and Literature

Internal swelling reaction – Delayed ettringite formation

Temperature > 65°C at early age

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Experimental Program

Relative humidity > 95%

Cement composition

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Results and Discussions

- Destabilization of the ettringite at an early age : $T > 65^{\circ}\text{C}$
- Delayed ettringite precipitation (ambient temperature + humidity)
- Generation of **internal pressures, expansions, cracks**

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Context and Literature

Coupling

▪ Coupling : creep / DEF

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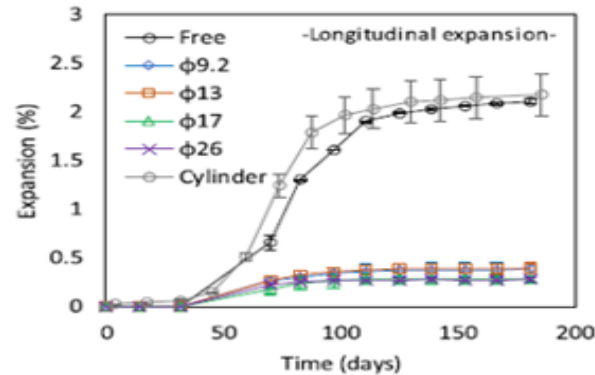
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Loaded direction

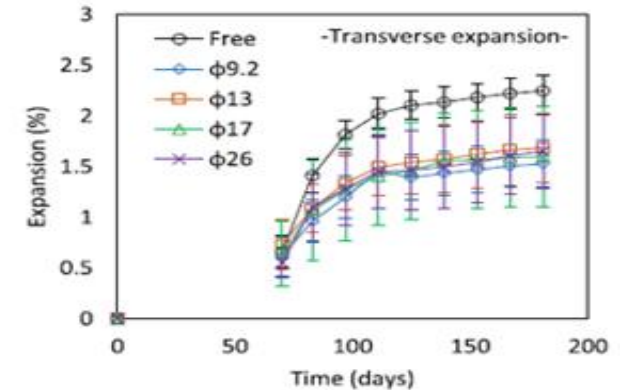
- Expansion decreases significantly
- Confinement degree has a small impact
- Equivalent expansion kinetics



[Kawabata et al., 2021]

Stress free direction

- Expansion was smaller than the free expansion
- Cracks observed parallel to the loaded direction



[Kawabata et al., 2021]

Context and Literature

Experimental Program

Results and Discussions

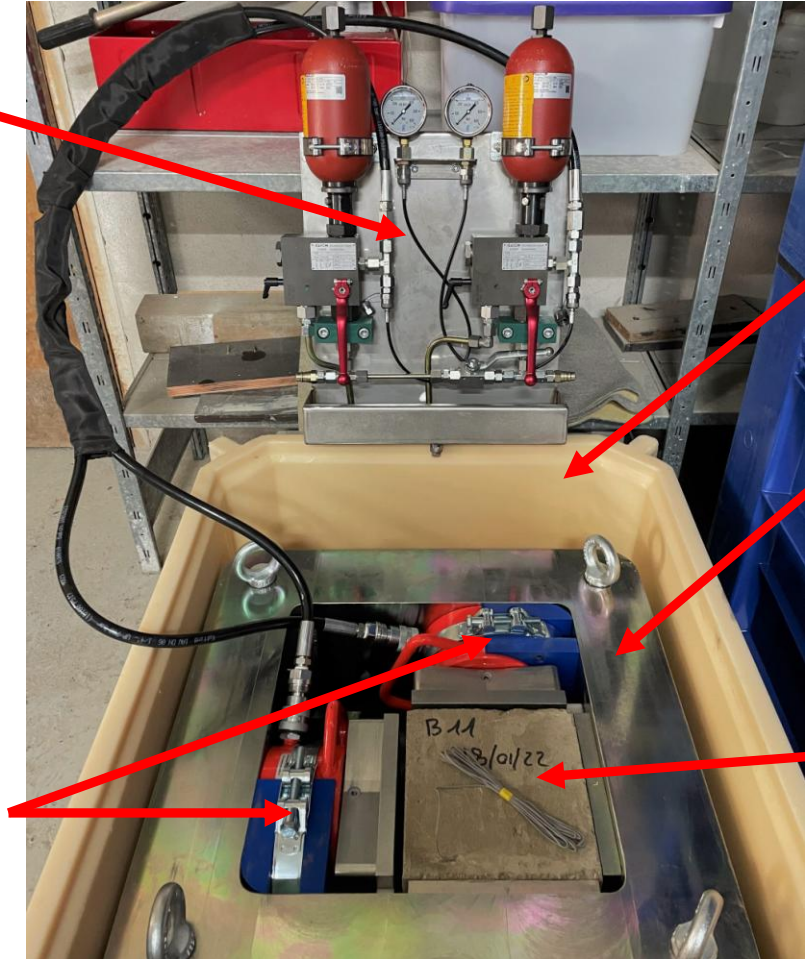
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B11-242
30-8-28
EP5

Load adjustment s

Hydrau

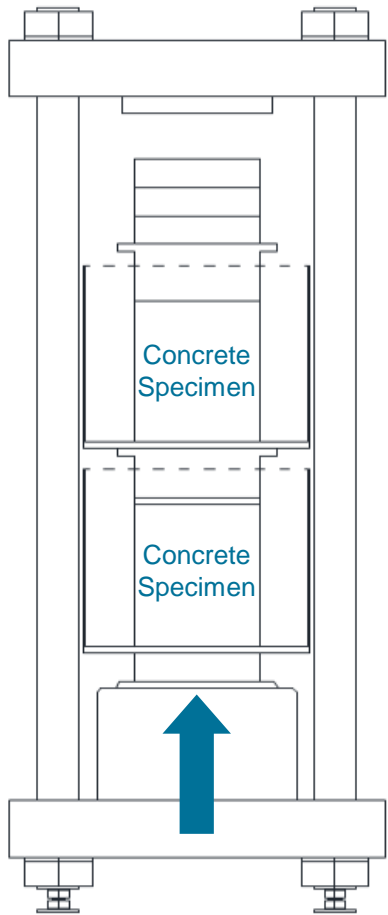
Hydraulic jacks



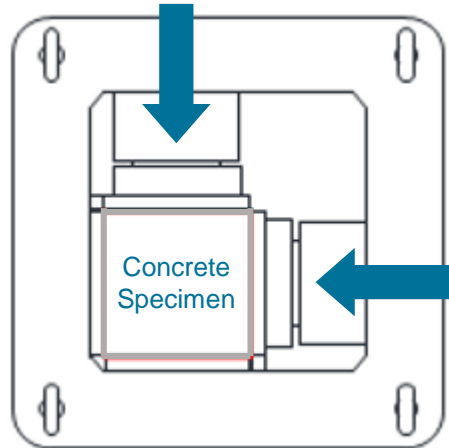
Concrete specimen

Configurations

Uni-axial Frame



Bi-axial Frame



3D stress state - mechanical conditions

- **[0 0 0]**: without prestressed
- **[12 0 0]**: uniaxial prestressed - model calibration
- **[12 12 0]**: symmetrical biaxial prestressed - 2D orthotropic loading
- **[12 8,5 0]**: asymmetrical biaxial prestressed - Representative loading

Development of ISRs - environmental conditions

- **DEF**: 20°C – 38°C, Heat treatment at 80°C for three days
- **ASR**: 38°C (operating temperature of the nuclear reactor), reactive aggregates

Storage conditions:

- Water immersion for developing ISR – basic creep

Number of tests expected:

- 32 (22 different configurations)

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Concrete biaxial casting

- 4 reactive specimens (heat treatment at 80°C) (20cm x 20cm x15cm)
- 4 non-reactive specimens (20cm x 20cm x15cm)

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Compressive strength

- Reactive specimens – 26 MPa (heat treatment effect)
- Non-reactive specimens – 40 MPa

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Thermal cycle DEF

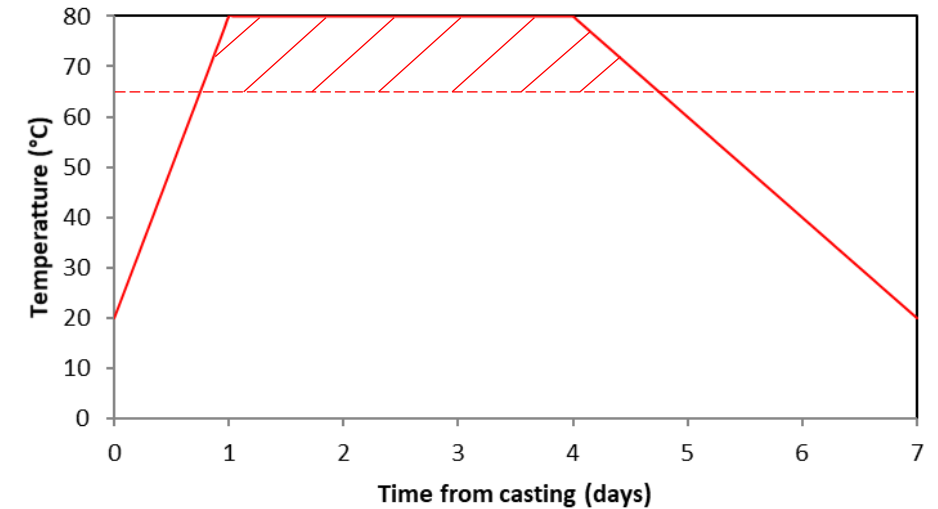
- Effective thermal energy : 1260 °C.h

$$\int_{t=7 \text{ days}}^{t=0} (T - 65^{\circ}\text{C}) \cdot dt$$

- Pessimism value of B11 concrete :
≈ 1800 °C.h

- Optical fiber thermal strain compensation :

$$\Delta_{\varepsilon}^{comp} = \Delta_{\varepsilon}^{mesu} - \Delta_T \times \frac{C_{TR}}{C_{\varepsilon R}}$$



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Context and Literature

Thermal cycle DEF

- Thermal energy : 1200 °C.h

$$\int_{t=7 \text{ days}}^{t=0} (T - 65^{\circ}\text{C}).dt$$

- Pessimism value of B11 concrete : 1800 °C.h

- Optical fiber thermal strain compensation :**

$$\Delta_{\varepsilon}^{comp} = \Delta_{\varepsilon}^{mesu} - \Delta_T \times \frac{C_{TR}}{C_{\varepsilon R}}$$

- Coefficient of thermal expansion : (CTE) 11.7 $\mu\text{m.m}^{-1}.\text{C}^{-1}$**

2

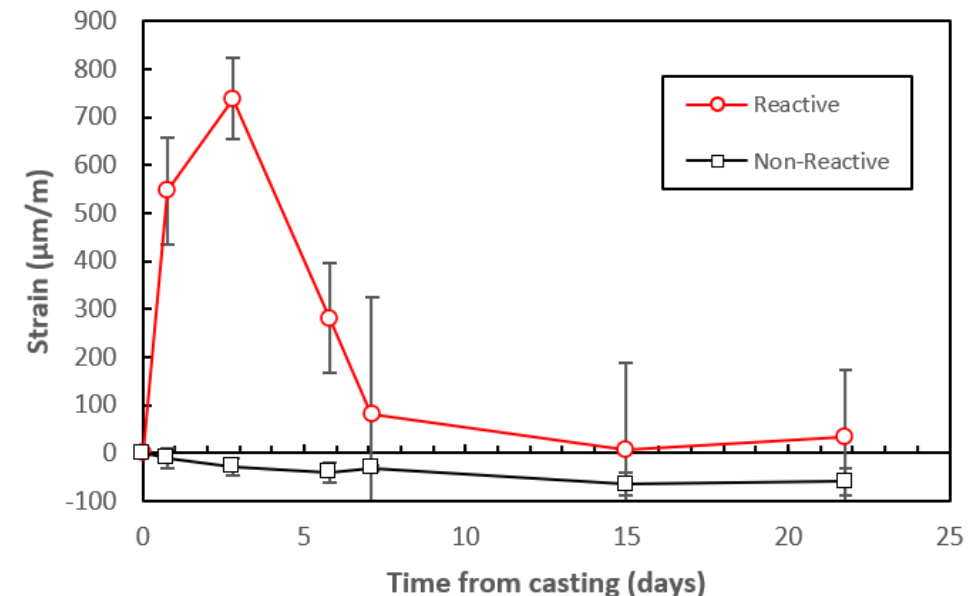
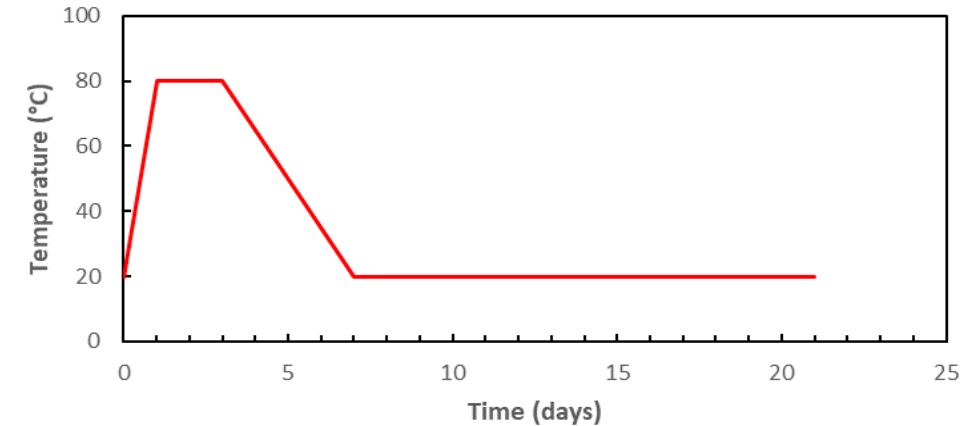
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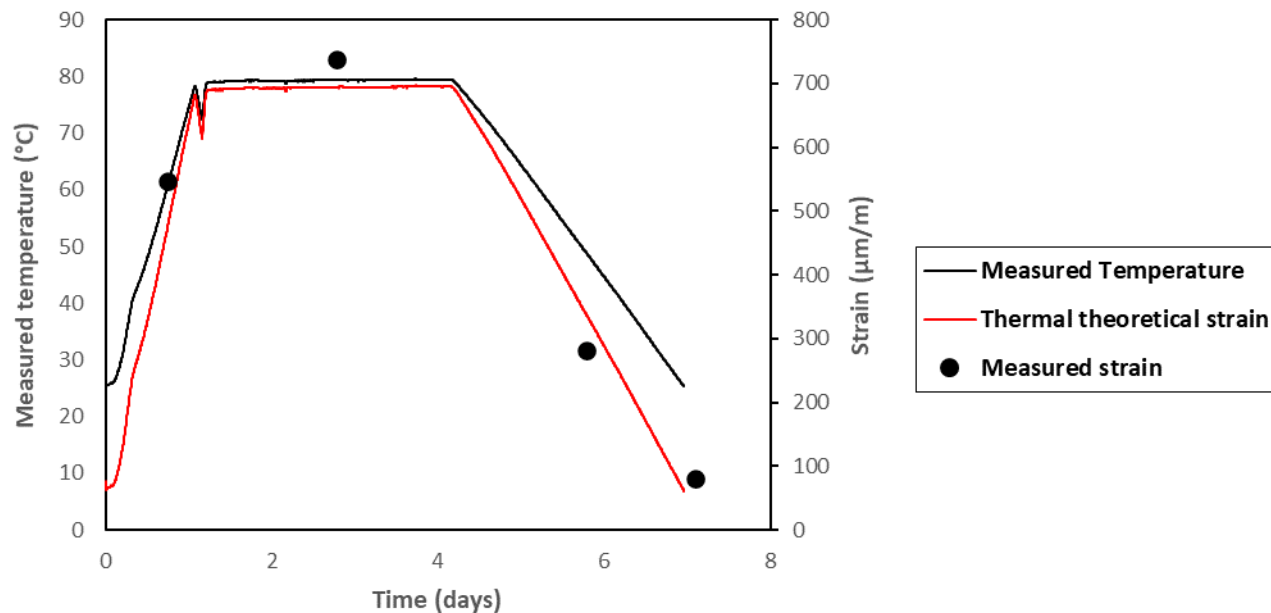
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Thermal cycle DEF



- Measured temperature with thermocouples inserted in a test tube in the climatic chamber
- Thermal theoretical strain = Measured temperature \times CTE

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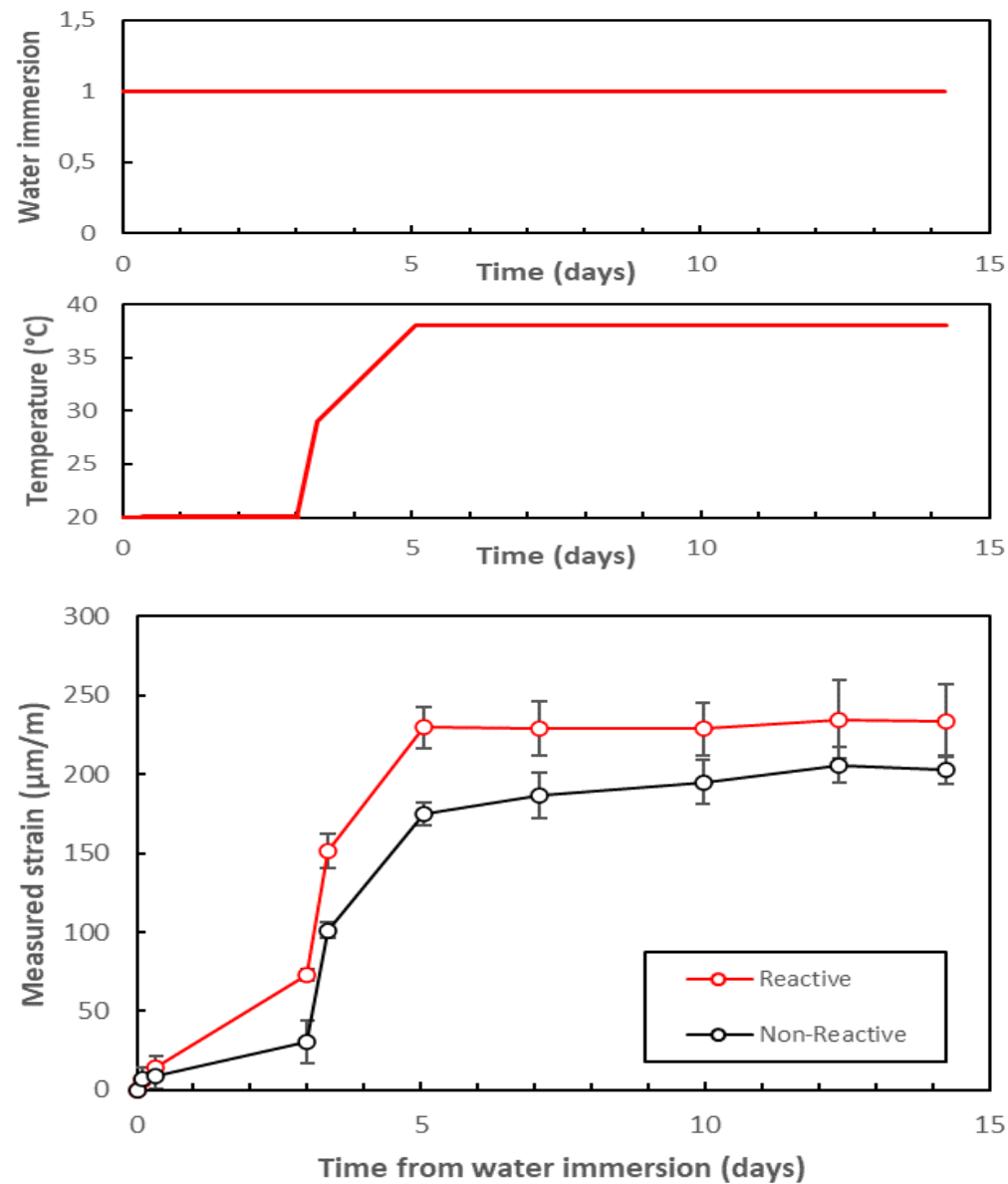
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Hydro-thermal conditions



- After 35 days of endogenous curing

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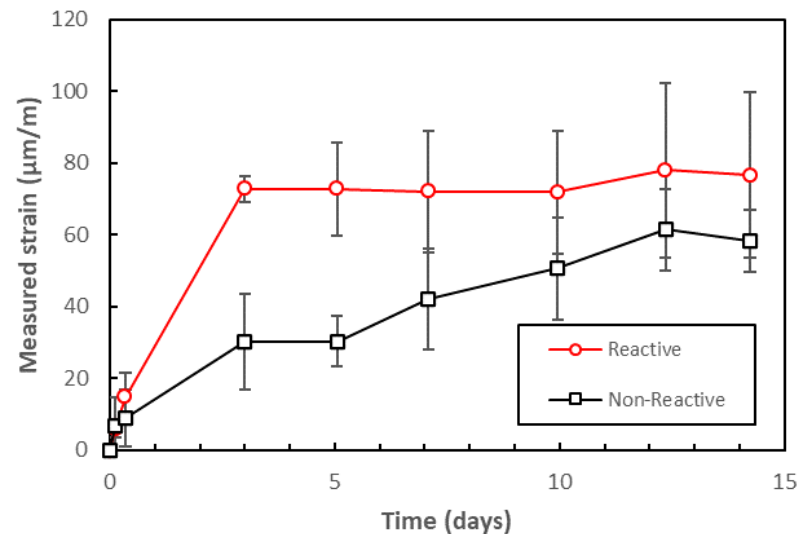
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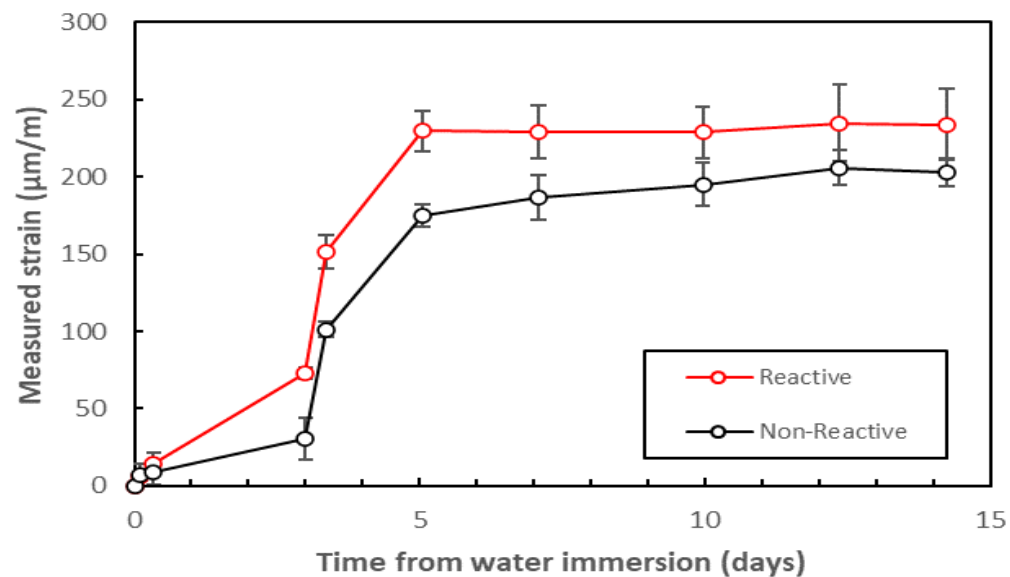
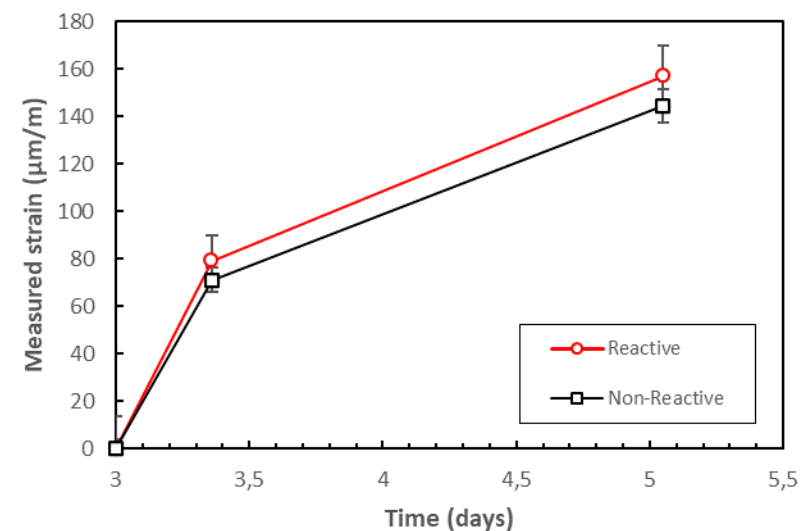
Hydro-thermal conditions

Water absorption



+

Thermal expansion



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Context and Literature

Hydro conditions

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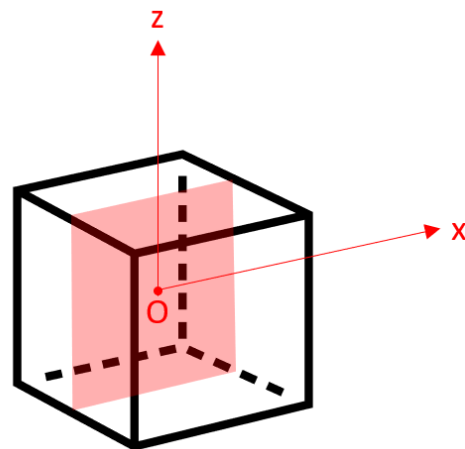
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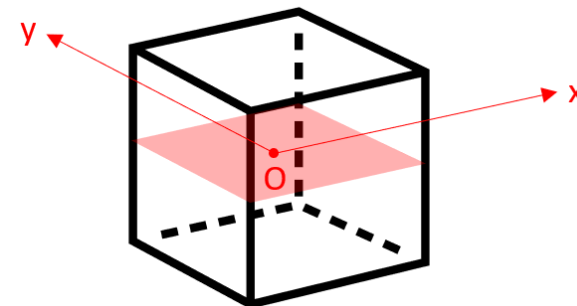
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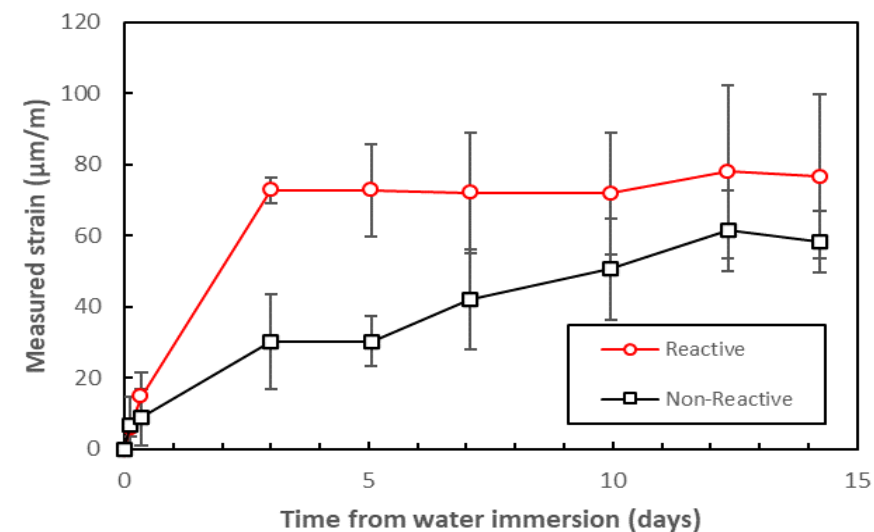
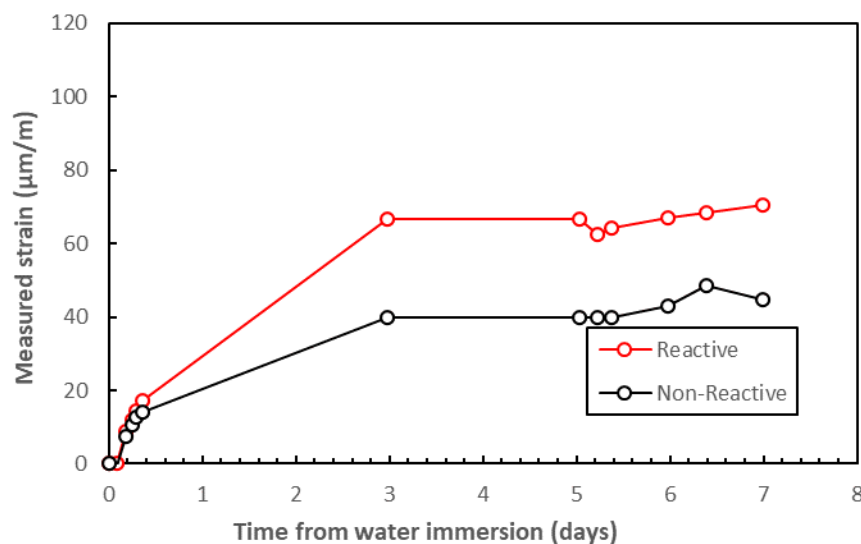
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Plan x-O-z



Plan x-O-y



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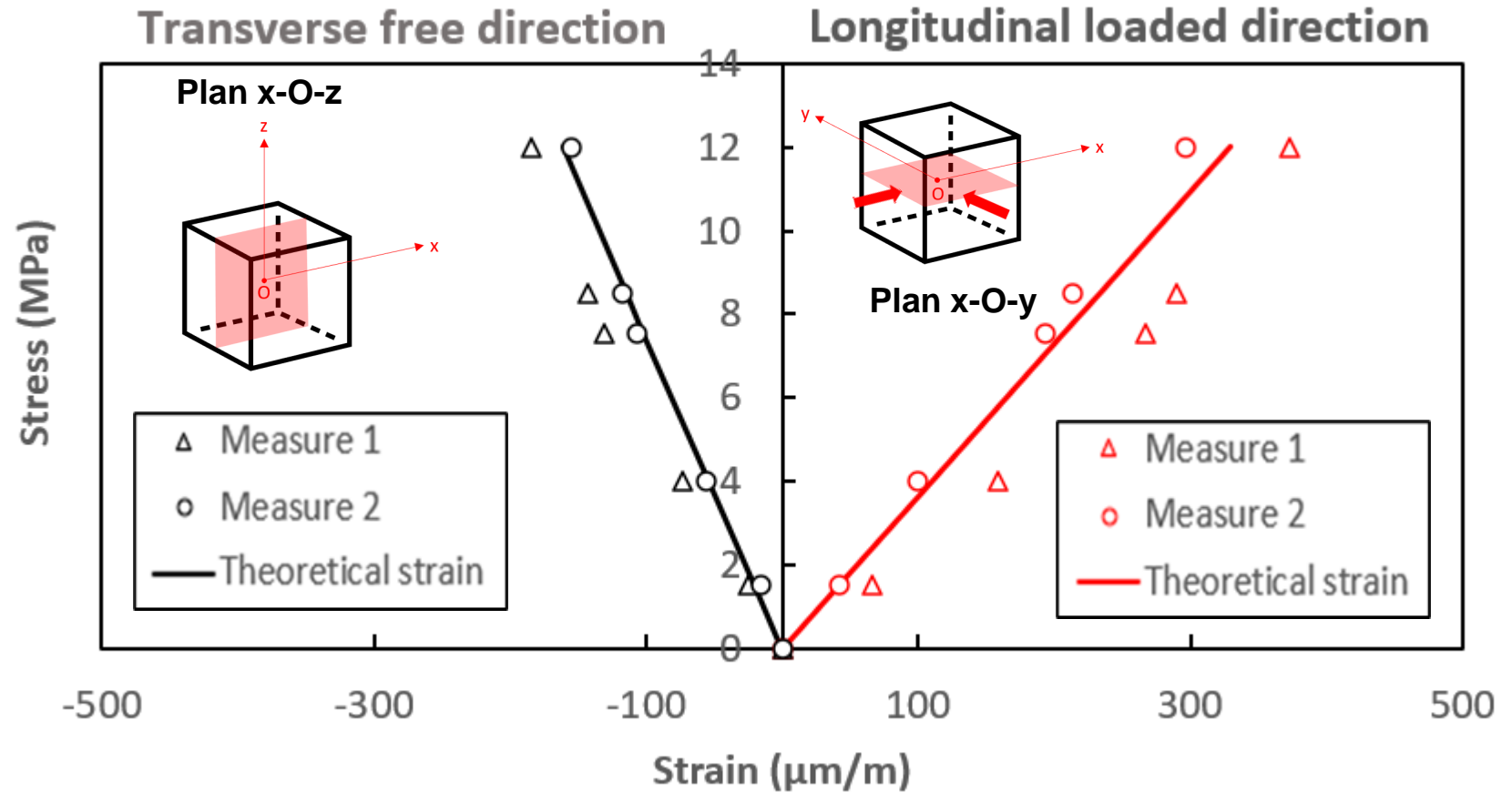
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Biaxial loading



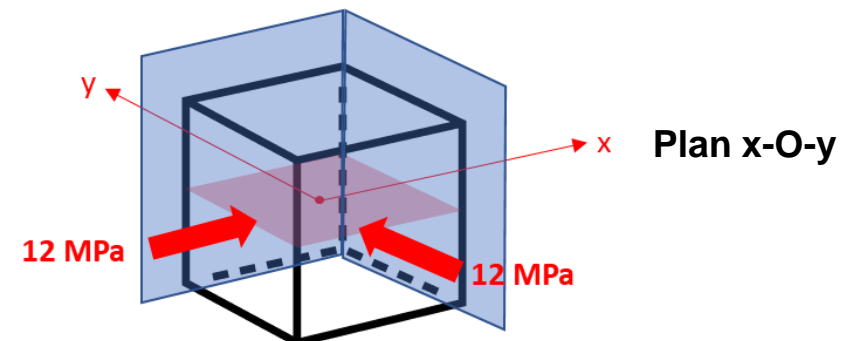
- No Teflon pads
- $T = 20\text{ }^{\circ}\text{C}$
- No water immersion

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Biaxial loading

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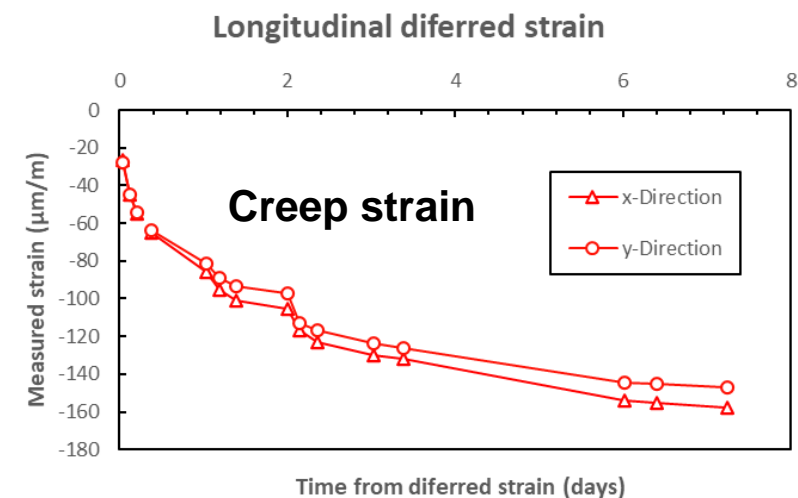
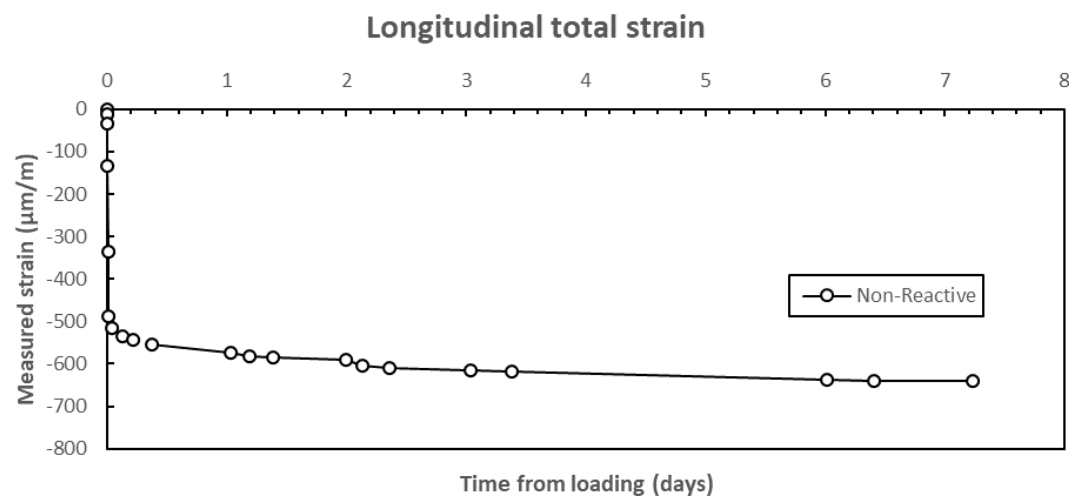
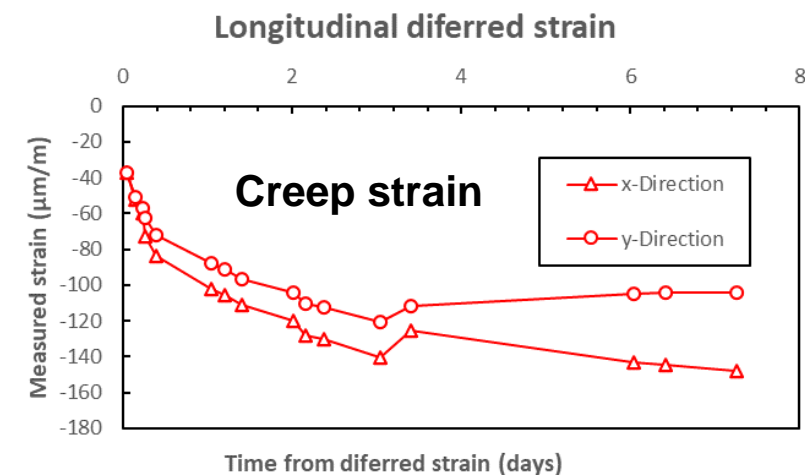
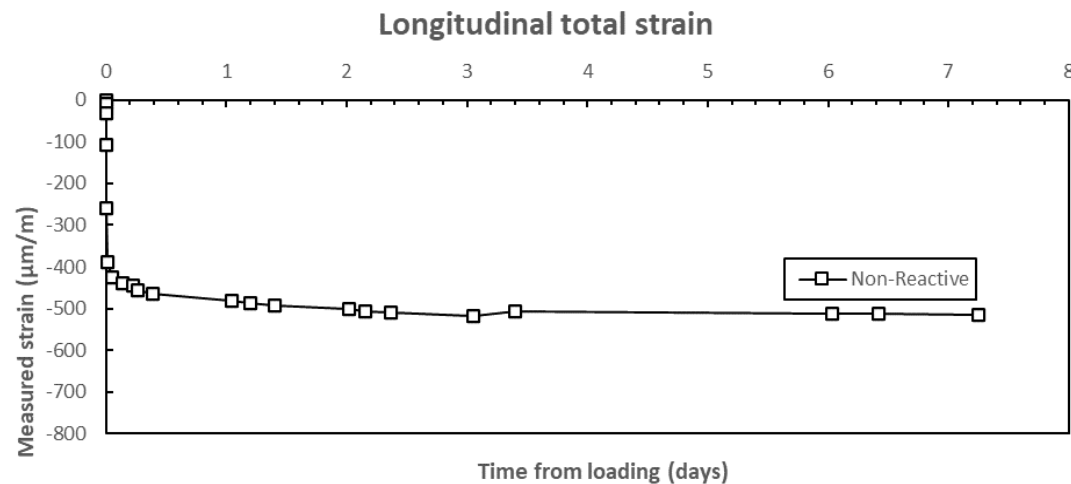
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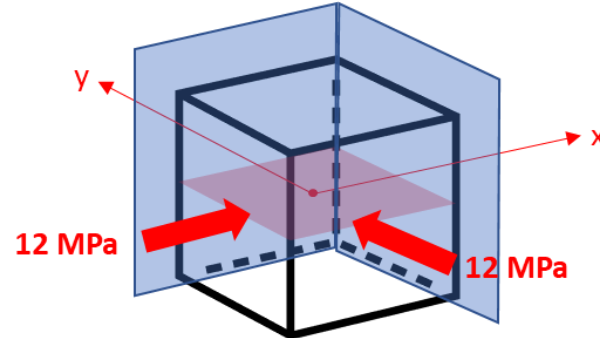


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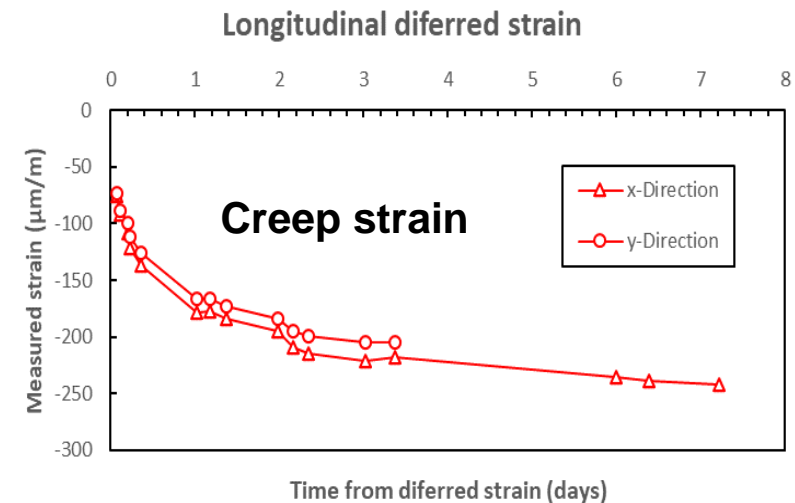
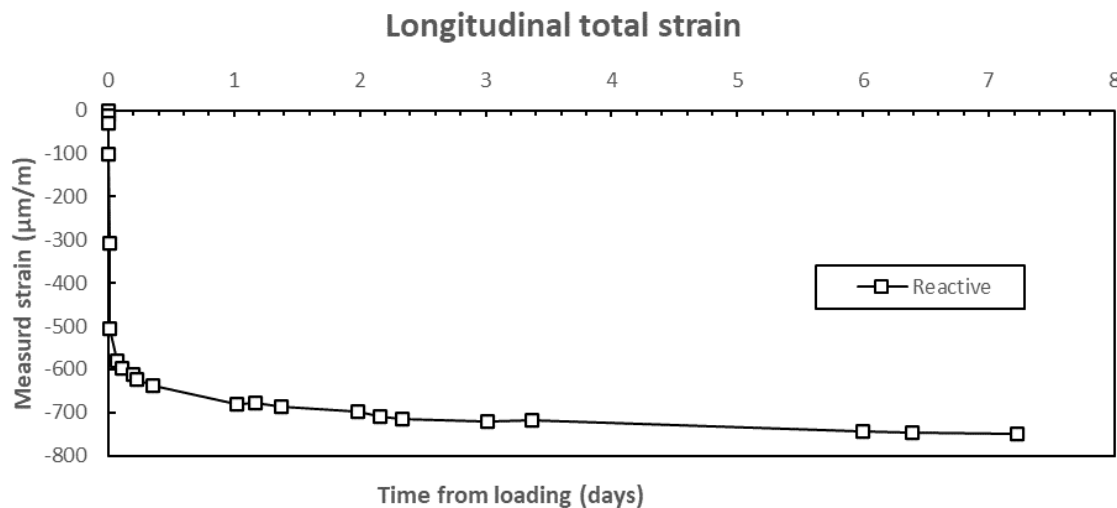
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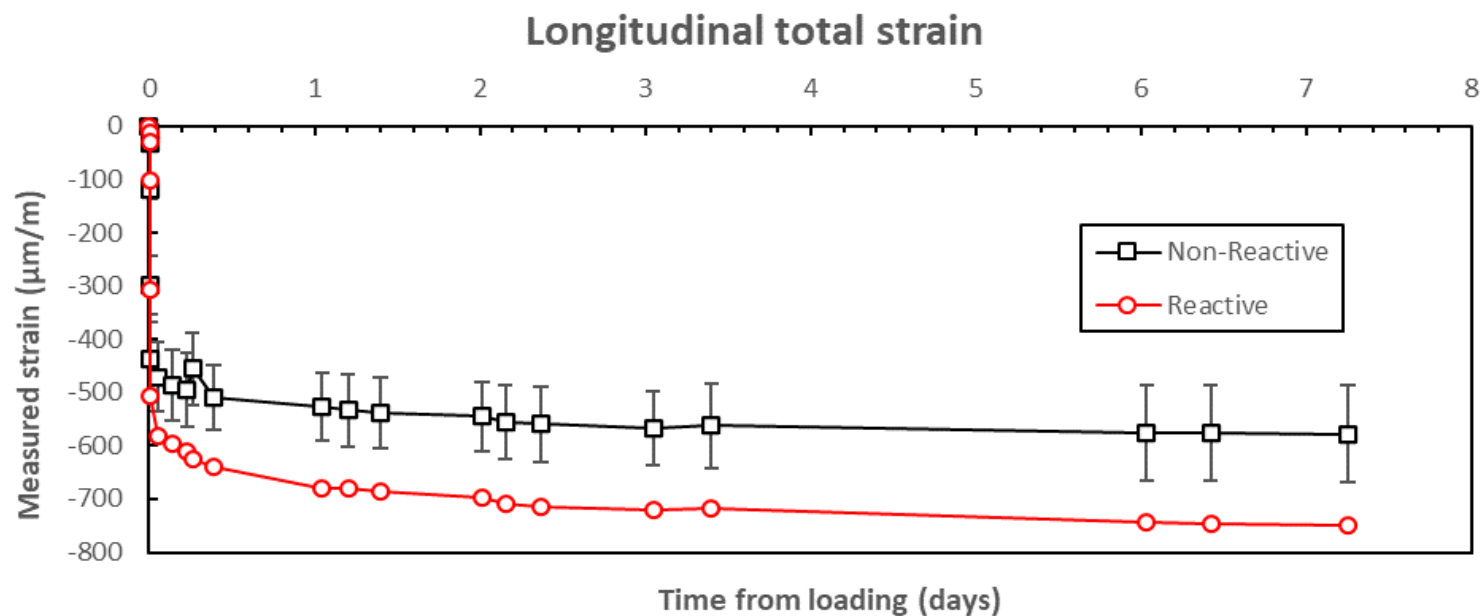
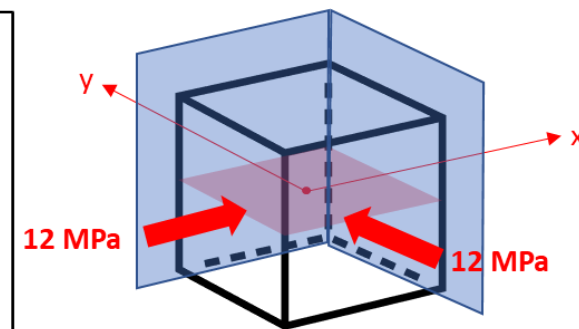
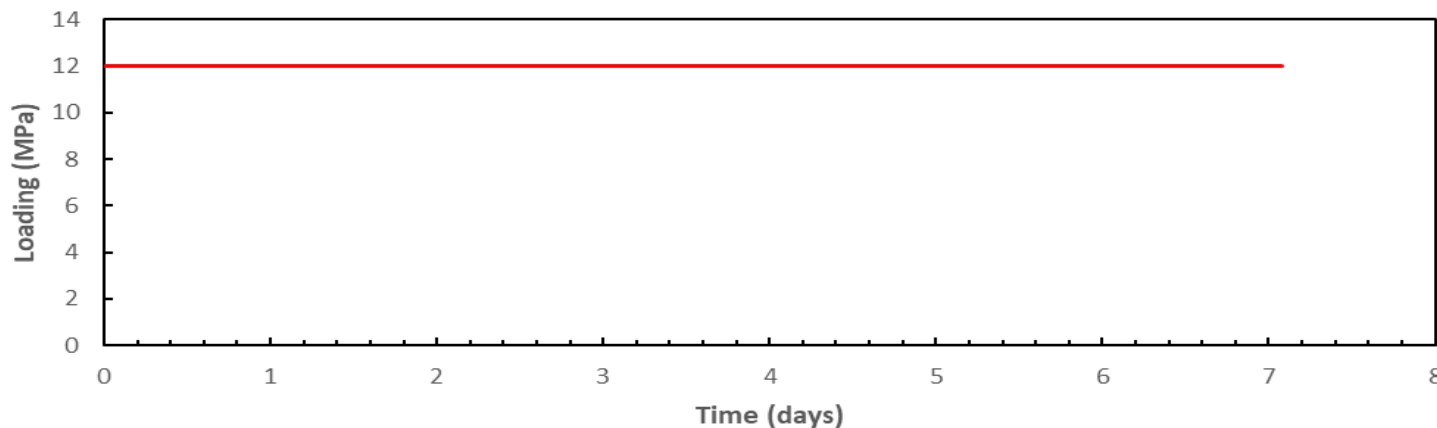
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Biaxial loading: reactive VS non-reactive specimens



Loaded direction

- Effect of thermal curing at early age

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Conclusion and perspectives

- The objective of this project is to study the coupling between creep and pathology, with the temperature effects.
- This work is ambitious and innovative, both in terms of the creep frames designed and the extensometric monitoring by optical fibers.
- A reliable and accurate tool for monitoring biaxial creep is available in conditions that are practical, reproducible and durable.
- Many criteria and requirements were set, defined by computations, to make the biaxial creep frame feasible.
- Different extensometer studies were done to equip the concrete specimen and measure its strain in 3 directions.

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Conclusion and perspectives

- Optical fibers is a new strain sensor technology that starts to be used more widely in civil engineering.
- The optical fiber's transfer length was simulated using a beam's flexural test.
- To test the functionality of this prototype, preliminary tests were done, and they verified the good functionality of the biaxial frame for concrete creep test as well as the reliability of the optical fiber measurements and the associated data acquisition system.
- The experimental program has been launched and concrete specimens were cast.
- Half of the concrete specimens were loaded biaxially, while the remaining half were left unloaded to measure their free swelling.

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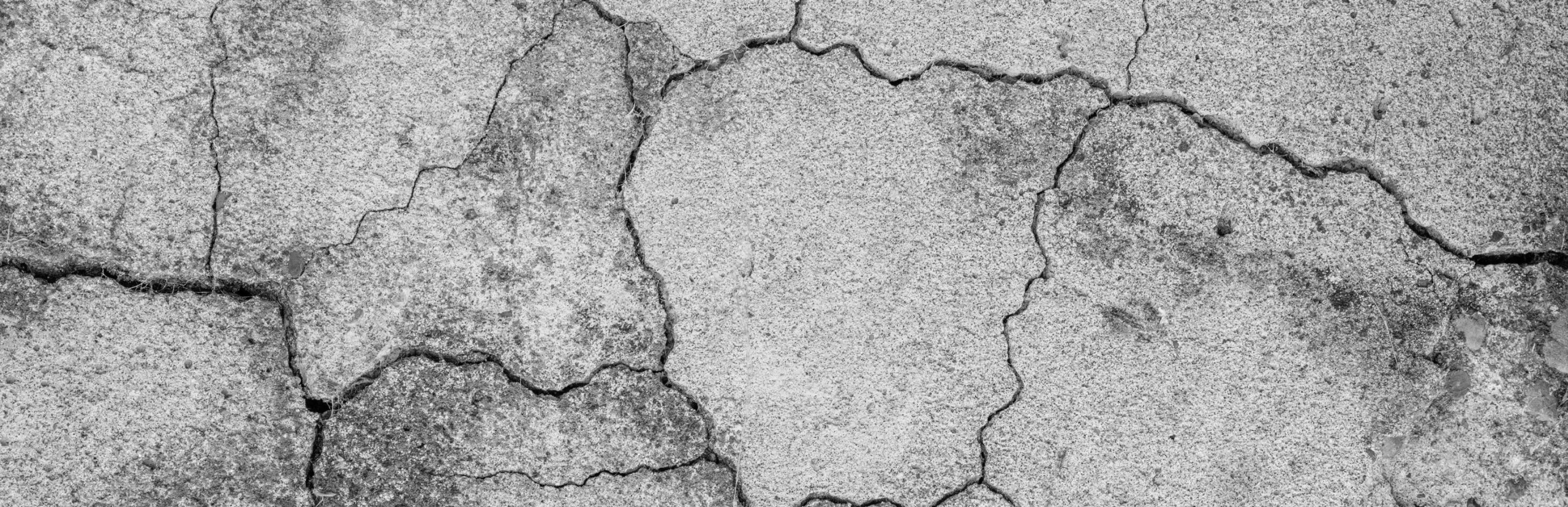
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Conclusion and perspectives

- A modification of the mechanical properties occurs after this thermal cycle because the compressive strength dropped by 35%.
- The value of the coefficient of thermal expansion of the cement paste when saturated, is much higher than a mature cement paste.
- Water absorption is isotropic in the 3 directions of the concrete specimens
- After several tests, no teflon pads will be used in biaxial charging
- A higher creep strain is shown in the specimens subjected to a thermal cycle at early age.
- 4 concrete specimens were casted recently and will be charged with 12 MPa in one direction and 8.5 MPa in the other, like containment building conditions.



Thank you for your attention Discussion and exchange

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