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Modelling the mechanical behavior at early-age: influence of the boundary conditions at the structure scale and multiscale estimation of ageing properties

Tulio HONORIO^{1,2} ; Benoit BARY¹ ; Farid BENBOUDJEMA²

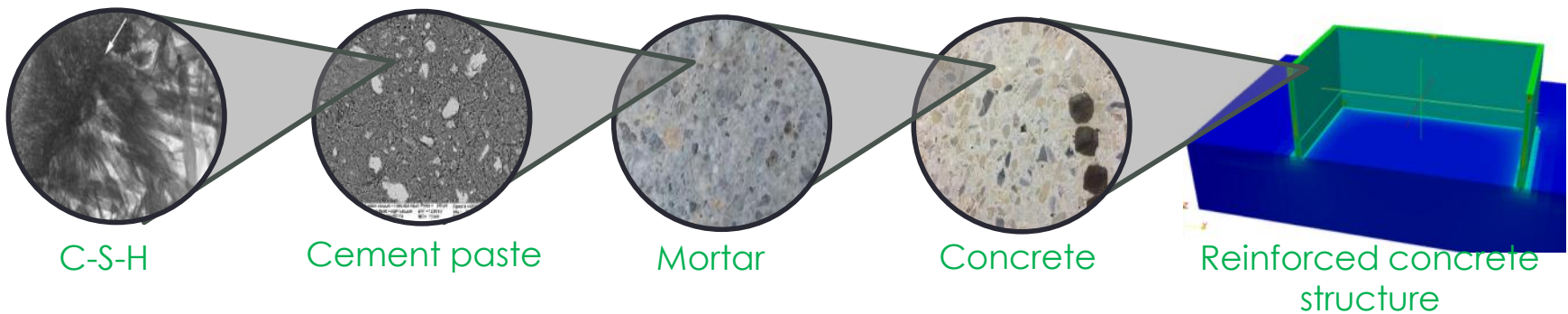
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Concrete at early-age

- Properties evolving at early age (ageing)
- Phenomena taking place at different space and time scales:

[Richardson 2004]



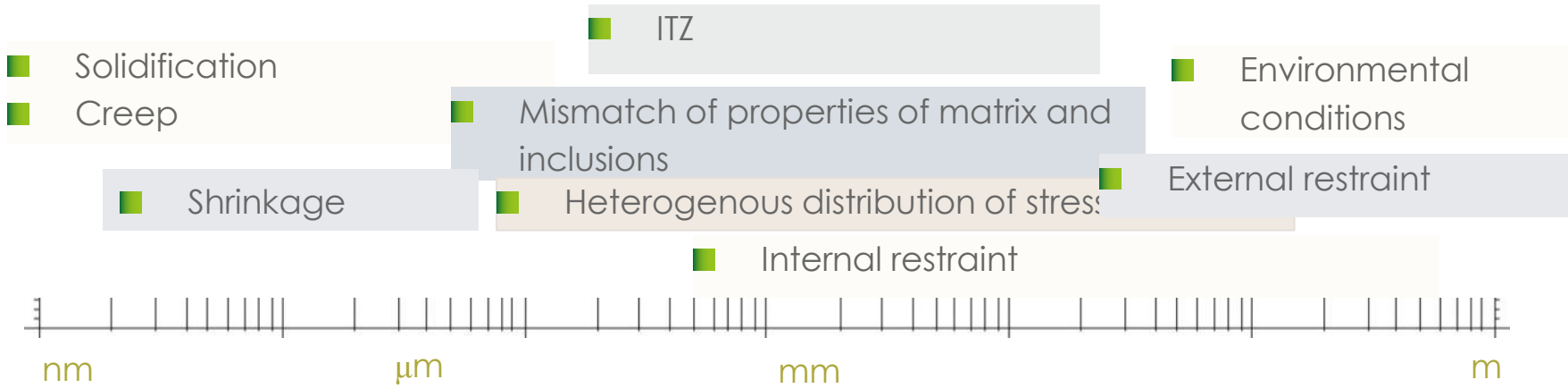
C-S-H

Cement paste

Mortar

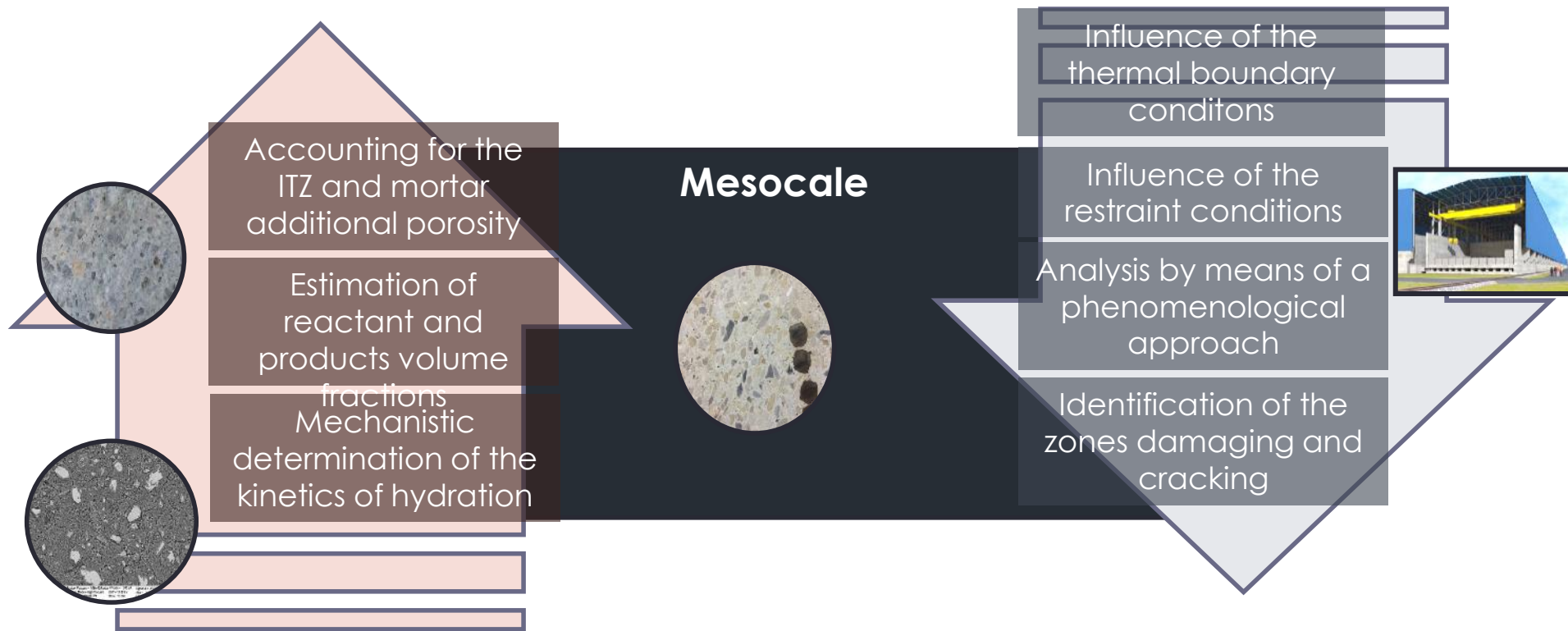
Concrete

Reinforced concrete structure



Different strategies

- **bottom-up** and **top-down**
- **phenomenological** and **mechanistic** approaches



CMS Workshop “Cracking of massive concrete structures”
Cachan, 17 March 2015

Thermo-chemo-mechanical analysis

A phenomenological approach at the structure
level

Chemo-thermal problem

- Heat balance

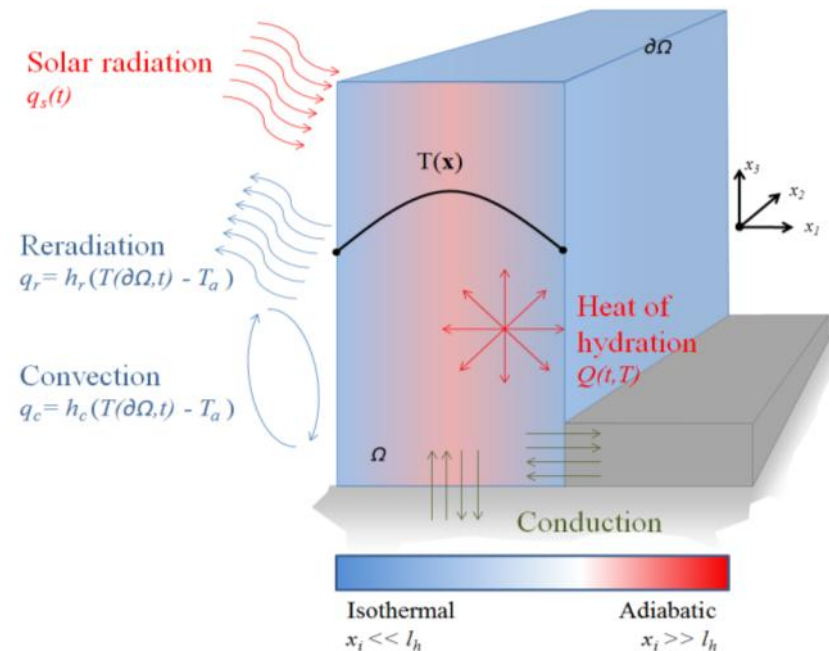
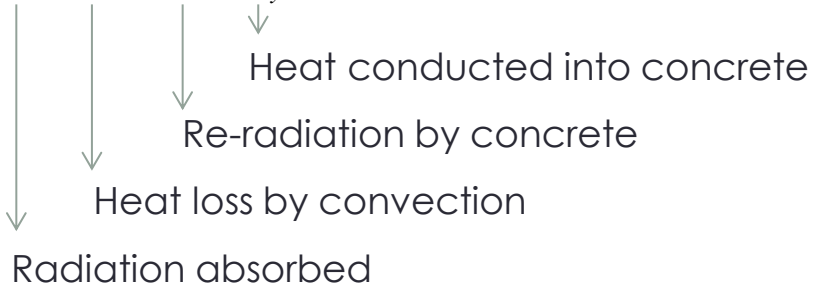
$$\dot{T}(\mathbf{x}, t) = D \nabla^2 T(\mathbf{x}, t) + Q \quad \begin{cases} T(\mathbf{x}, 0) = T_0 \\ \lambda \nabla T(\mathbf{x}, t) \cdot \mathbf{n} - k [T(\mathbf{x}, t) - T_a] = q_i(t) \end{cases} \quad \begin{array}{l} \forall \mathbf{x} \in \Omega_c \\ \forall \mathbf{x} \in \partial\Omega_i \end{array}$$

- Non-homogeneous PDE**
... with non-homogeneous BC

- Hydration $\dot{\alpha} = A(t) \cdot \exp[-Ea/T]$

- Boundary conditions

$$q_s - q_c - q_r - q_y = 0$$

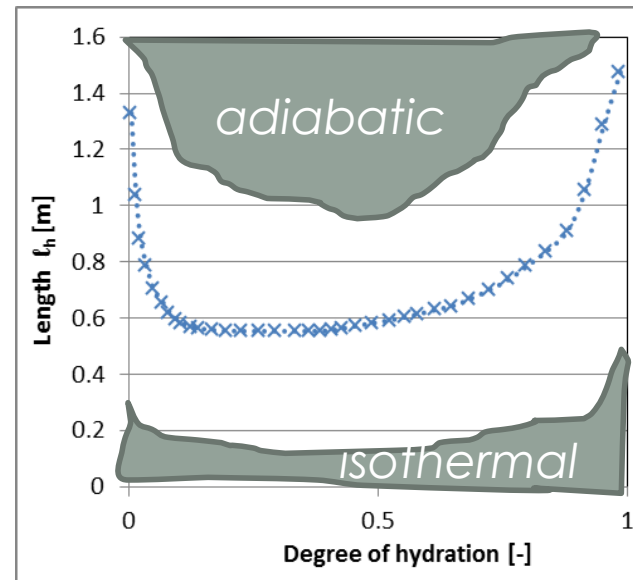


Analytical solutions

Why?

- Elucidates the role of the BC in the chemo-thermal problem
- Validates and allows some extrapolations from the numerical results

$$l_h = \sqrt{\frac{D}{A(\xi)} \exp\left[-\frac{E_a}{RT}\right]}$$



Analytical solutions

■ After some hypothesis and simplifications...

■ 1D solution in a semi-infinite domain non-homogeneous PDE with non-homogeneous BC:

$$T(x, t) \approx T_1(x, t) + T_2(x, t) + T_3(\xi, x, t)$$

$$T_1(x, t) = T_0 \left(1 - \operatorname{erfc} \left[\frac{x}{\sqrt{4 D t}} \right] + \exp \left[\frac{k}{D} (k t + x) \right] \operatorname{erfc} \left[\frac{2 k t + x}{\sqrt{4 D t}} \right] \right)$$

Temperature of concrete
at placement

$$T_2(x, t) = \left(T_a - \frac{\bar{q}_s}{k} \right) \left(\operatorname{erfc} \left[\frac{x}{\sqrt{4 D t}} \right] - \exp \left[\frac{k}{D} (k t + x) \right] \operatorname{erfc} \left[\frac{2 k t + x}{\sqrt{4 D t}} \right] \right)$$

Ambient temperature

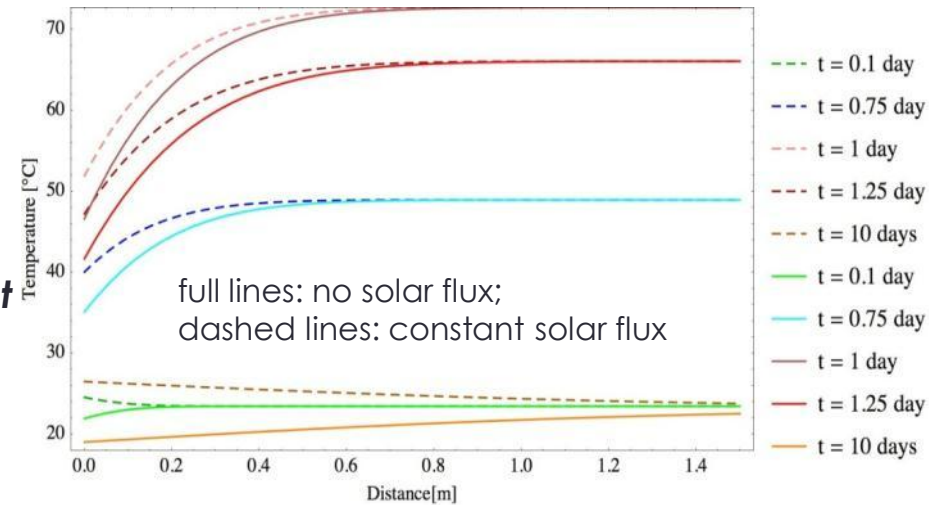
Variable flux on
boundaries (solar flux)

Reradiation and
Convection
equivalent
exchange coeff.

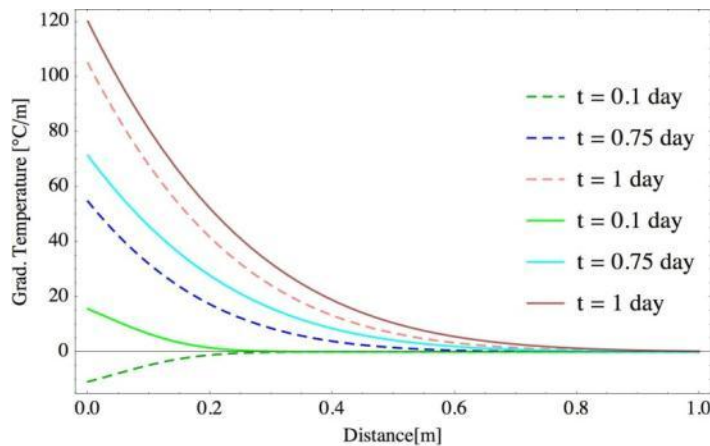
Solar flux

- Convection and reradiation
- T_a is kept constant.

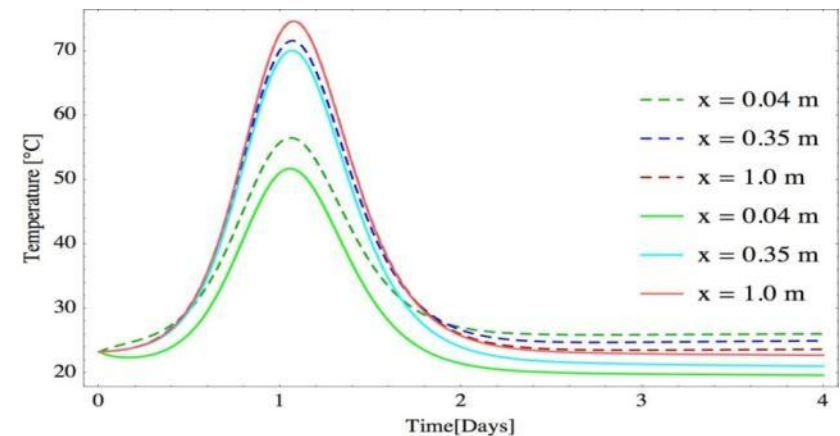
- **Evolution of the temperatures at different distances from the surface →**



- **Gradient of temperature ↓**



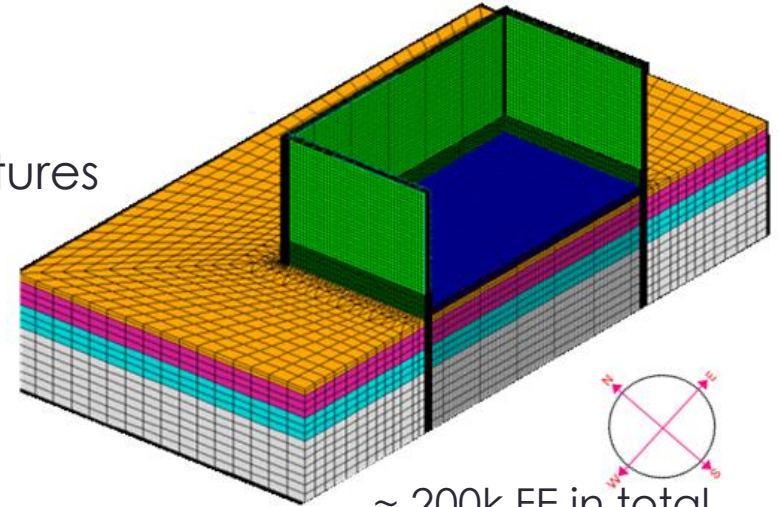
- **Profiles of temperatures at different times ↓**



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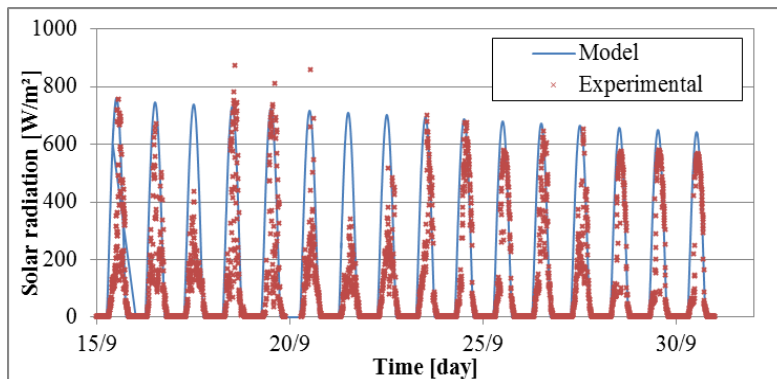
FEM analysis

- Goal: Determine concreting temperatures
- Asymmetric thermal loading induced by solar flux
- Test different T scenarios
 - Precooling?

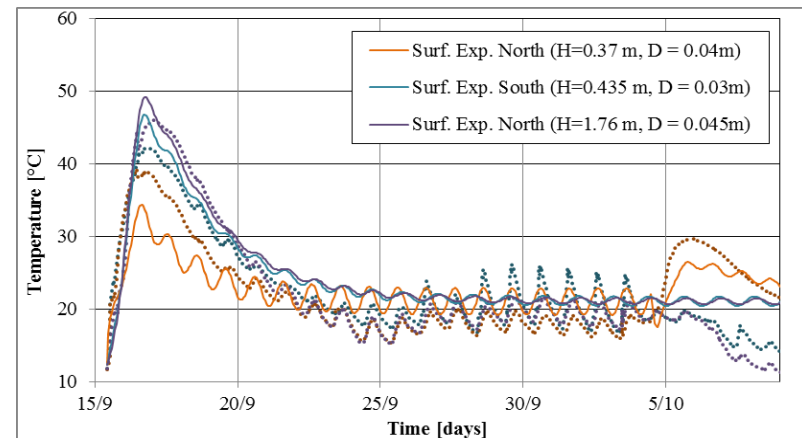


~ 200k FE in total
~ 100k FE for the wall

Solar flux

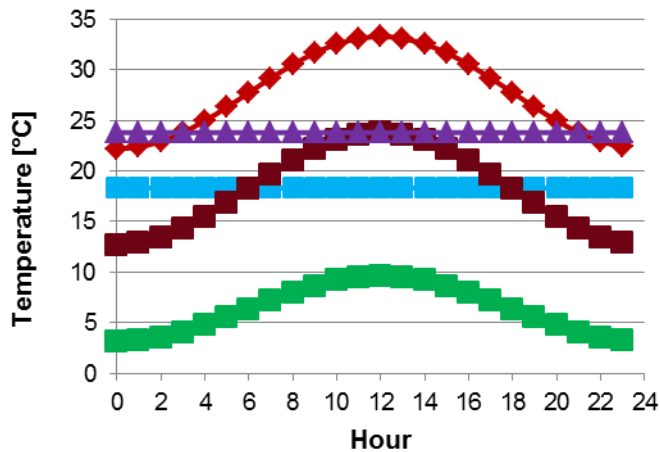


Validation

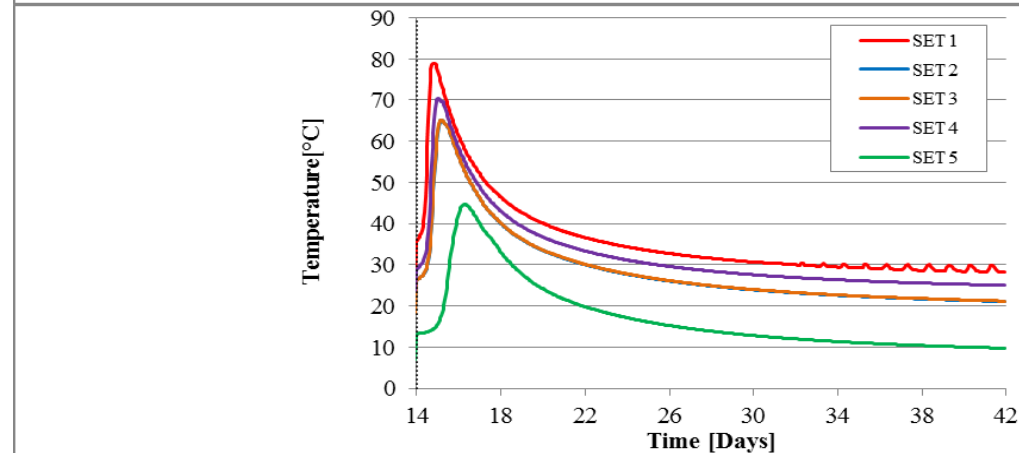
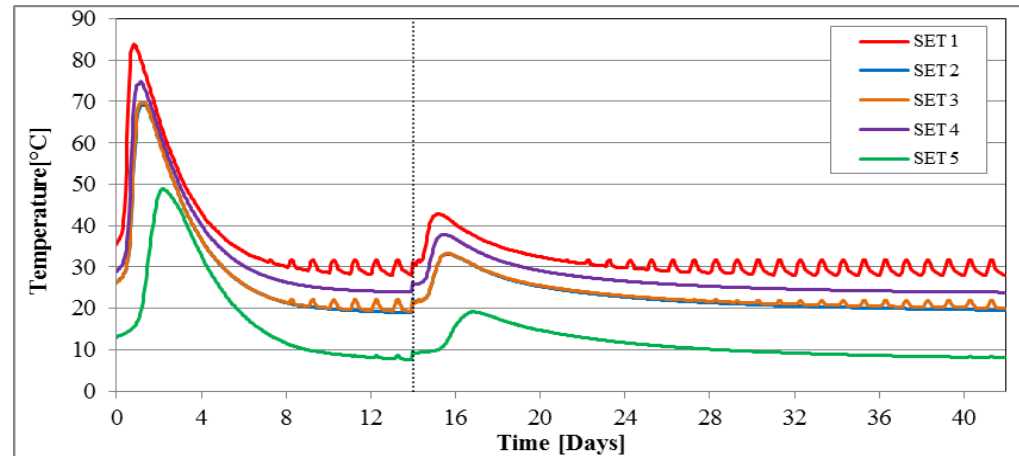


Ambient temperature

- Maximum \underline{T} to prevent DEF problems $T_{adm} = 70^\circ\text{C}$
- Maximum temperature reached within the structure varies almost linearly with T_a



Set of temperatures



Concreting temperatures

$$T(x, t) \approx T_1(x, t) + T_2(x, t) + T_3(\xi, x, t)$$

$$T_1(x, t) = T_0(\dots) \quad T_2(x, t) = \left(T_a - \frac{\bar{q}_s}{k}\right)(\dots)$$

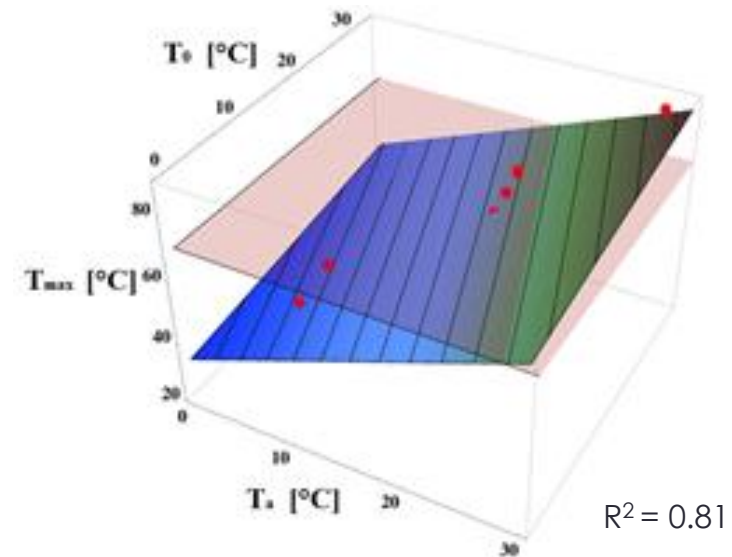
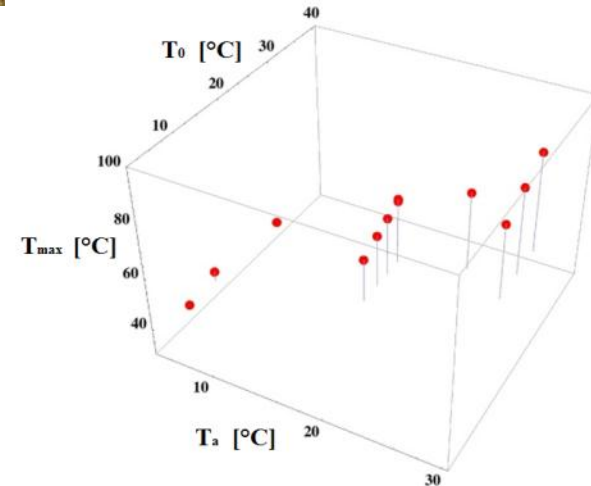


$$T_{max} = c_1 T_0 + c_2 T_a + c_3$$

Fitting parameters

[-]	1.28
[-]	0.359
[°C]	34.1

$$\rightarrow \Delta T_{ad} = 46.62 \text{ °C}$$



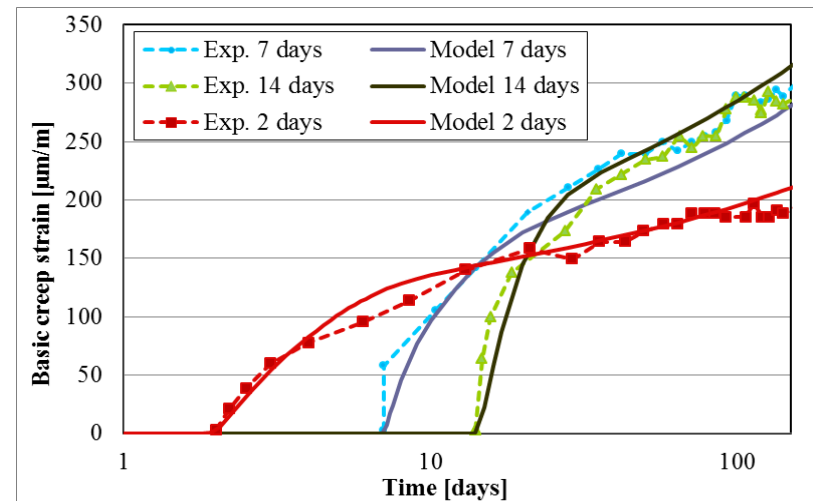
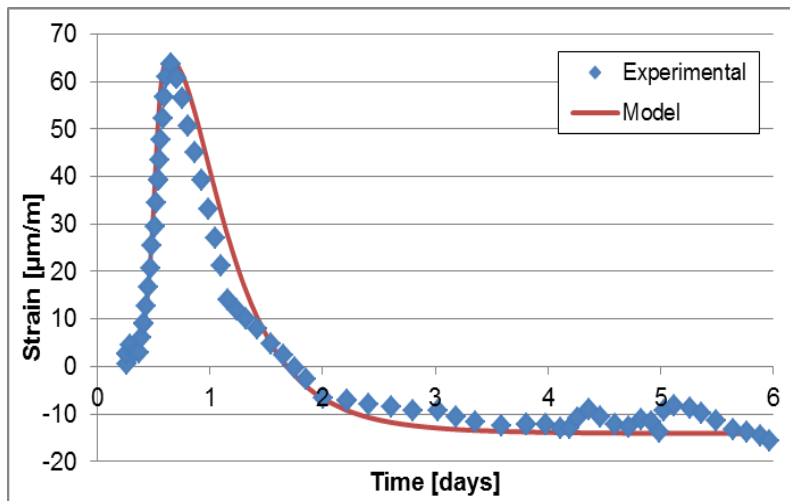
Mechanical model

$$\boldsymbol{\varepsilon}_{in} = \boldsymbol{\varepsilon}_{au} + \boldsymbol{\varepsilon}_{th} + \boldsymbol{\varepsilon}_{cr}$$

■ Rheological model

$$\tau_{bc}^i \ddot{\boldsymbol{\varepsilon}}_{bc} + \left(\tau_{bc}^i \frac{\dot{k}_{bc}^i(\xi)}{k_{bc}^i(\xi)} + 1 \right) \dot{\boldsymbol{\varepsilon}}_{bc} = \frac{\tilde{\boldsymbol{\sigma}}}{k_{bc}^i(\xi)}$$

$$\left\{ \begin{array}{l} k_{bc}^i(\xi) = k_{bc-\infty}^i \frac{0.473}{2.081 - 1.608 \xi} \bar{\xi}^{\psi} e^{\frac{E_{ac}}{R} \left(\frac{1}{T} - \frac{1}{T_0} \right)} \\ \tau_{bc}^i = \frac{\eta_{bc}^i(\xi)}{k_{bc}^i(\xi)} \end{array} \right.$$



Cracking index

- Probability of cracking as a function of the CI:

$$CI = \max_{\Omega} \left\langle \frac{\sigma_{ii}(t)}{f_t(t)} \right\rangle_+$$

$$P(CI) = 100 \times \left[1 - \exp \left[- \left(\frac{1}{CI} / 0.92 \right)^{-4.29} \right] \right]$$

The CI obtained from the simulation must be inferior to 54% so that $P(CI) \leq 5\%$

Other criteria existing \rightarrow B. Craeye (70%);
Fairbairn (100%)

Damage model

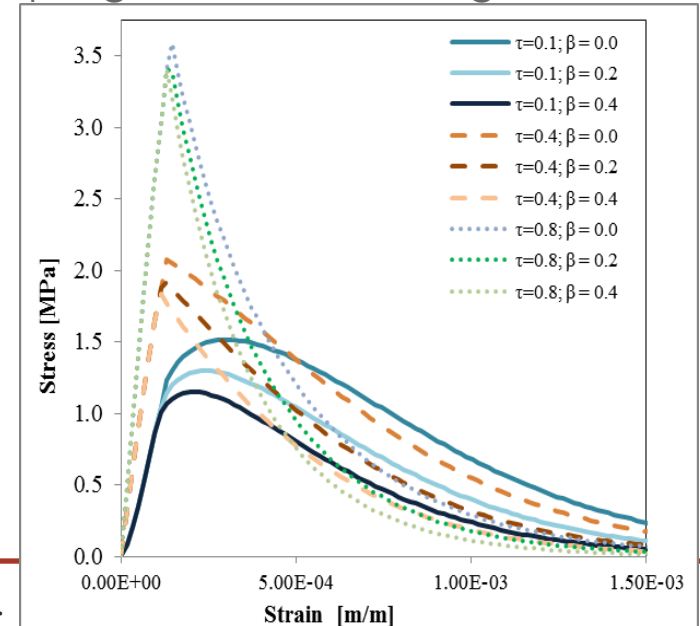
- Isotropic damage variable D

$$\boldsymbol{\sigma} = (1 - D)\tilde{\boldsymbol{\sigma}}$$

- Equivalent strain

$$\hat{\varepsilon} = \sqrt{\langle \varepsilon_e + \beta \varepsilon_{bc} \rangle_+ : \langle \varepsilon_e + \beta \varepsilon_{bc} \rangle_+}$$

- Coupling between damage and creep

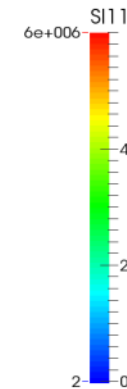
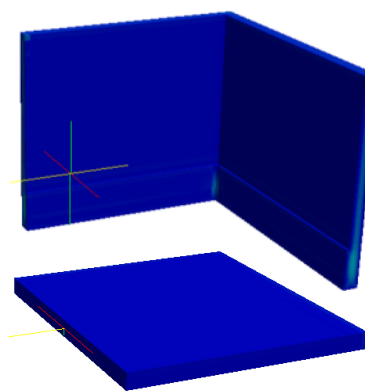
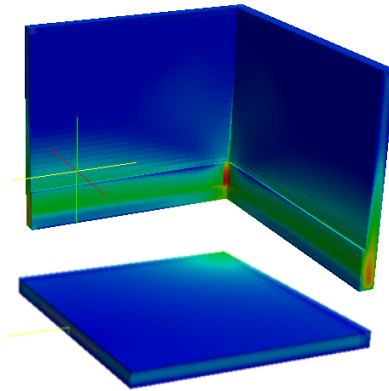
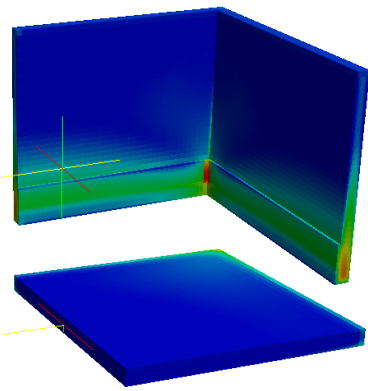


Thermal conditions: Cracking Index

Aug (oscillating)

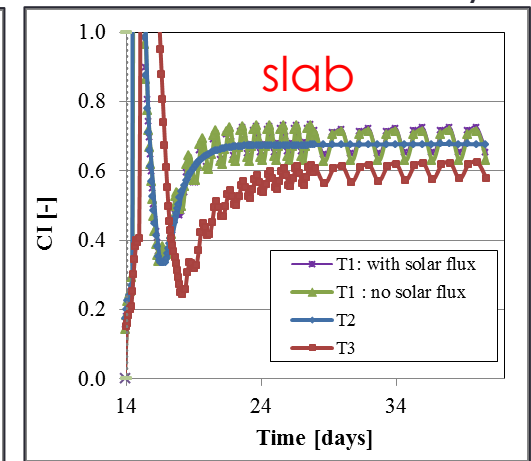
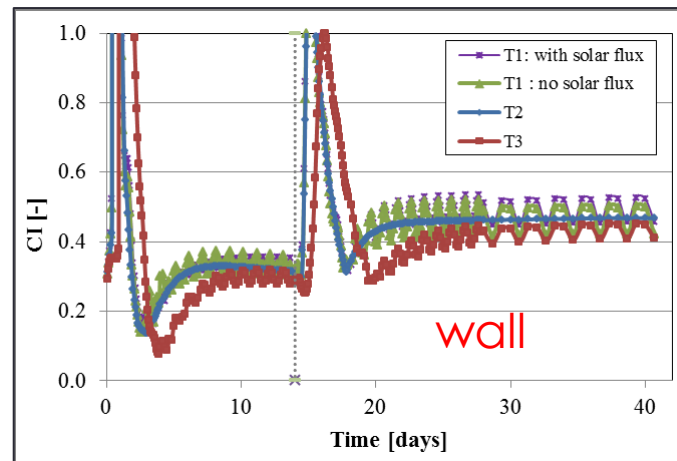
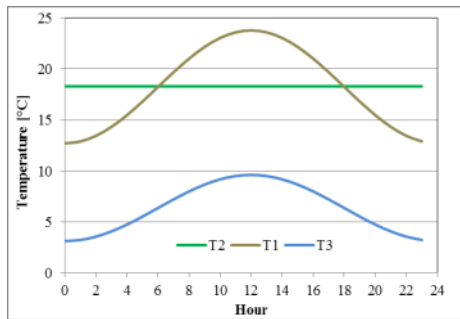
Aug (constant)

Nov (oscillating)



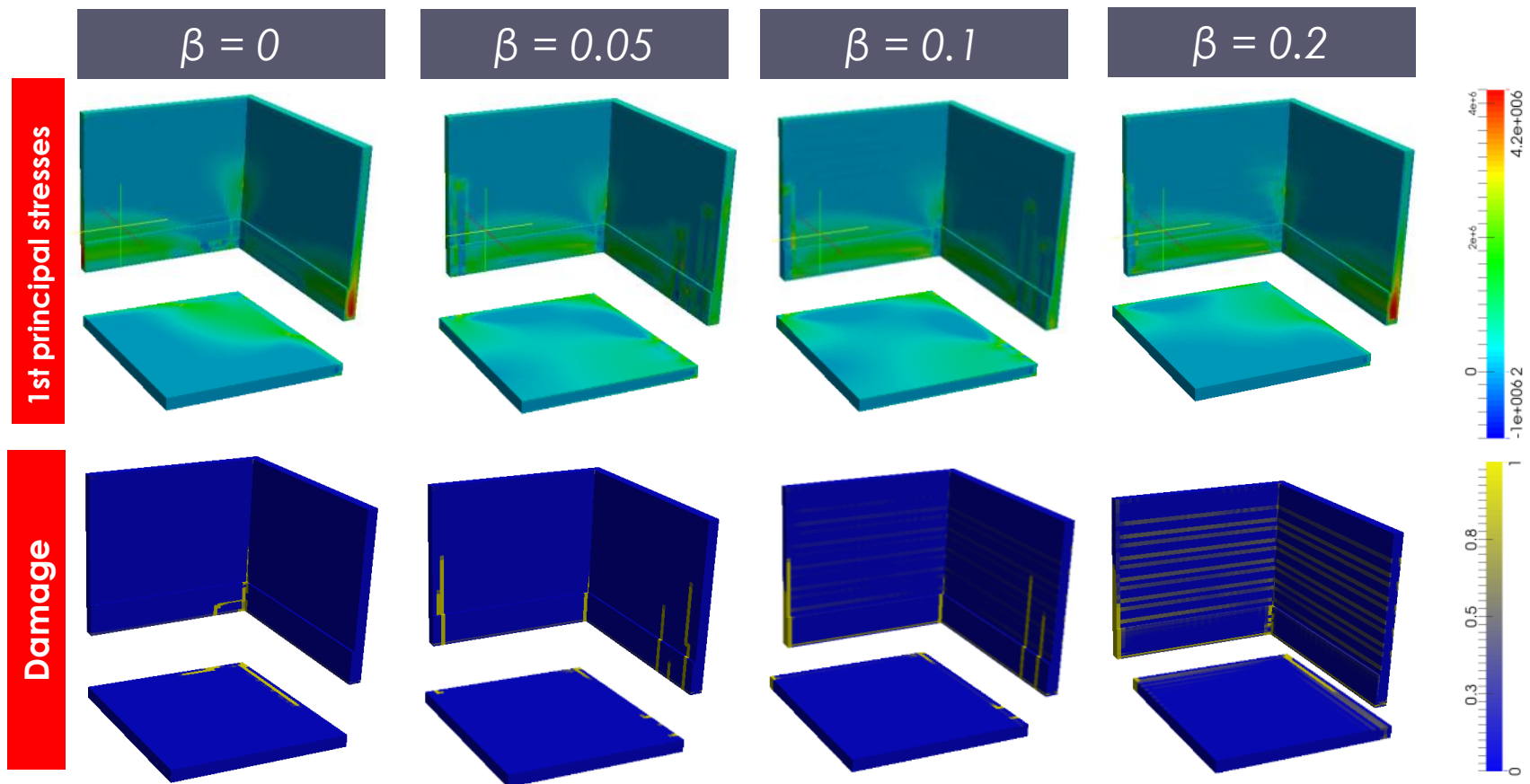
First (maximum) eigenstress according to the 3 thermal boundary conditions

$t = 15.08$ days



Coupling between creep and damage

August temperatures; $t = 15.08$ days

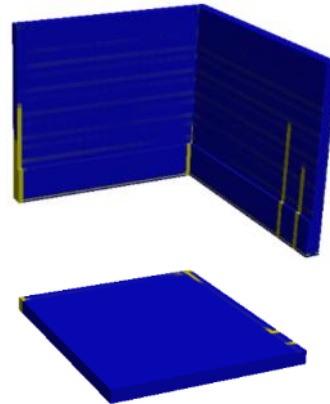


Thermal conditions: Damage and Crack opening

Aug (oscillating)

$$\beta = 0.1$$

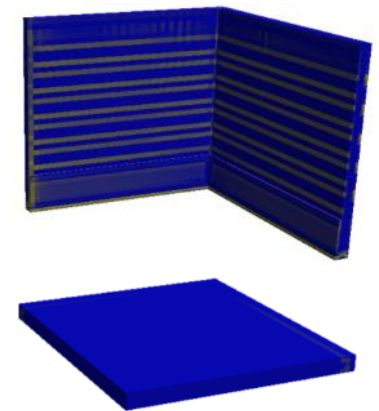
Damage →



Nov (oscillating)

$$\beta = 0.1$$

Damage →



[Mattalah et al. 2009]

Conclusions

- Phenomenological approaches:
 - It works!
 - *Ad hoc* character: difficult to extrapolate to other scenarios of interest
 - "enigmatic" parameter β
 - Small variations of β can lead to different damage patterns
- Mechanistic approaches to understand the underlying phenomena
 - Justify and improve phenomenological

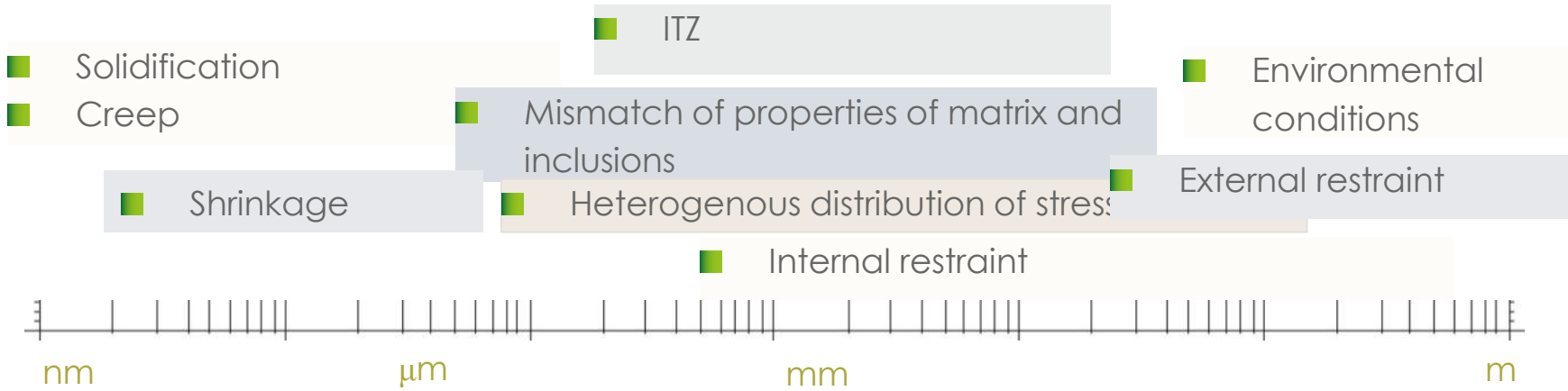
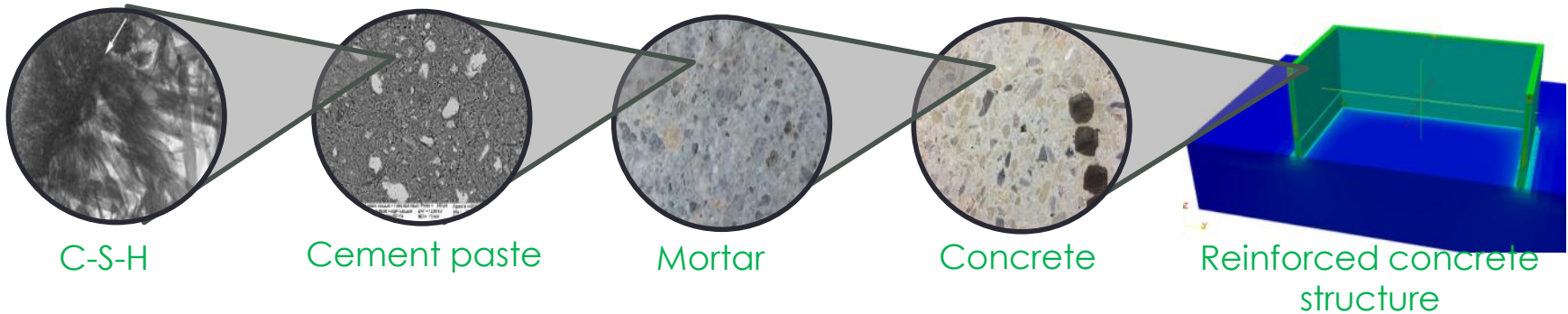
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Multiscale estimation of ageing properties

Concrete at early-age

- Properties evolving at early age (ageing)
- Phenomena taking place at different space and time scales:

[Richardson 2004]



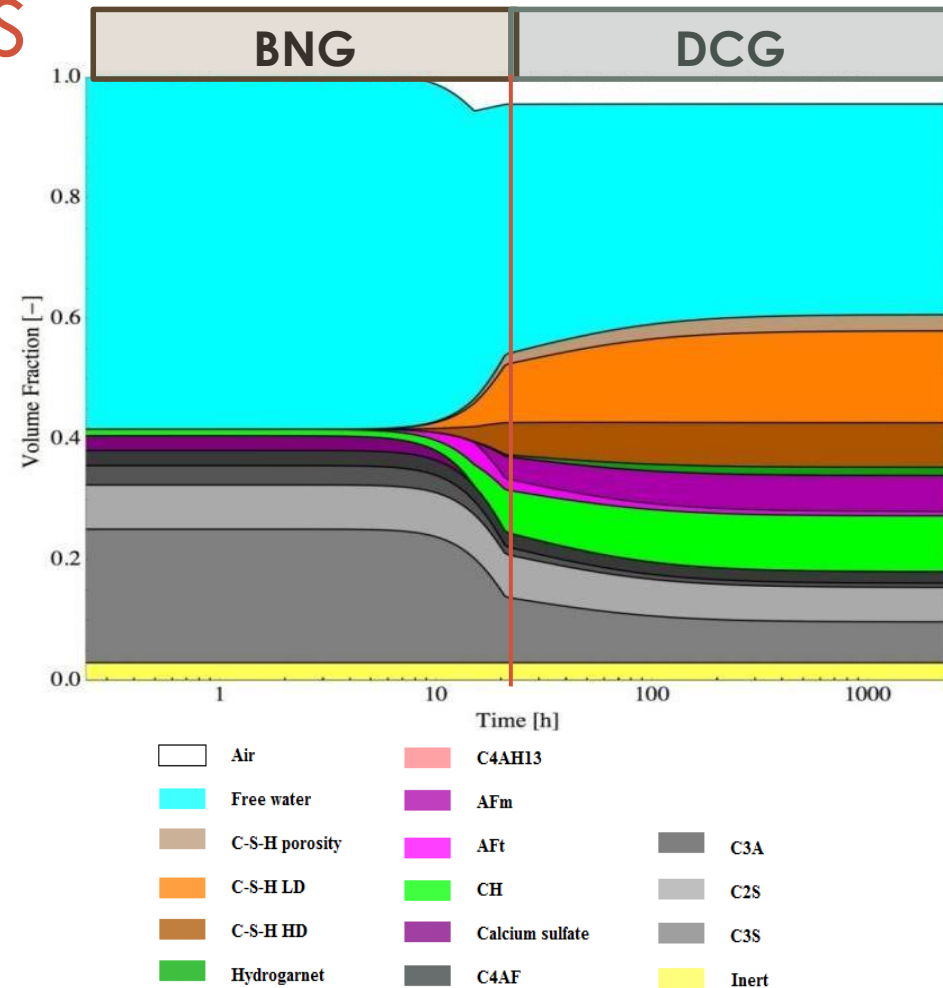
Hydration kinetics

Goals

- Determine the kinetics in from the main driving mechanisms
- Estimate the evolution of volume fraction →

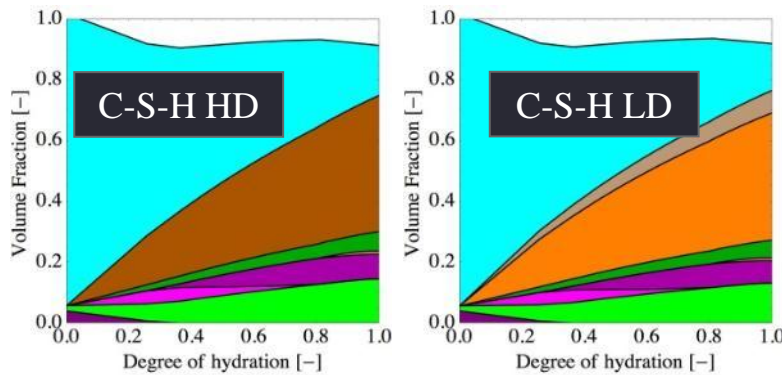
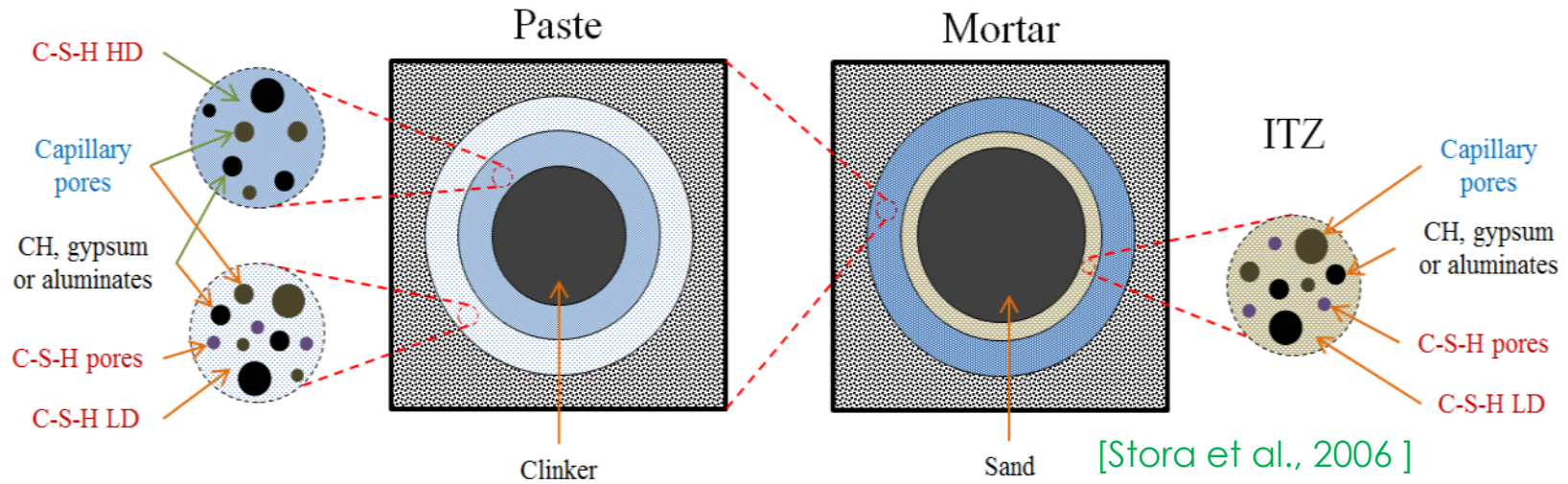
Approach

- 2 mechanisms governing hydration :
 - **Boundary nucleation and space-filling growth (BNG)**
 - **Diffusion controlled growth (DCG)**



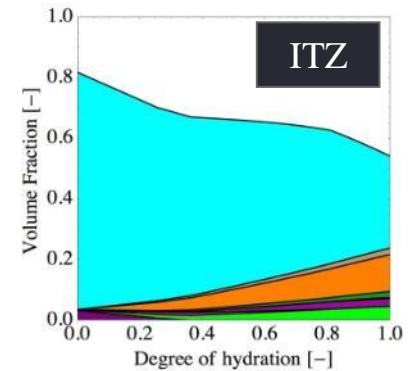
[Honorio et al. 2014c;
Honorio et al. Submitted]

Microstructure representation

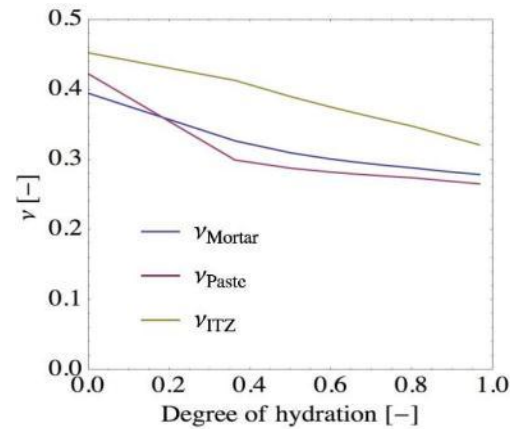
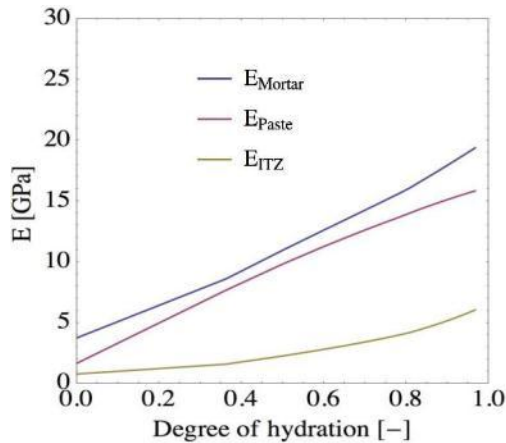


■ Repartition of products

[Honorio et al. 2014d]

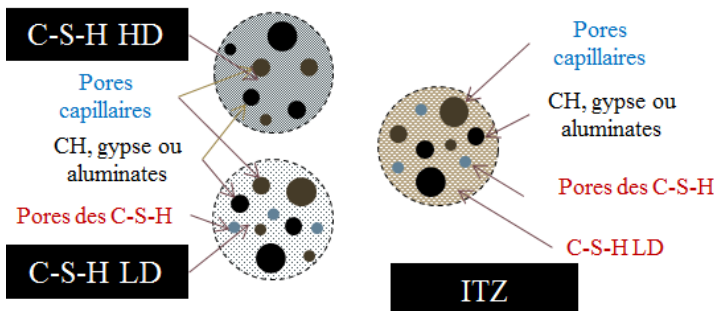


Solutions in elasticity



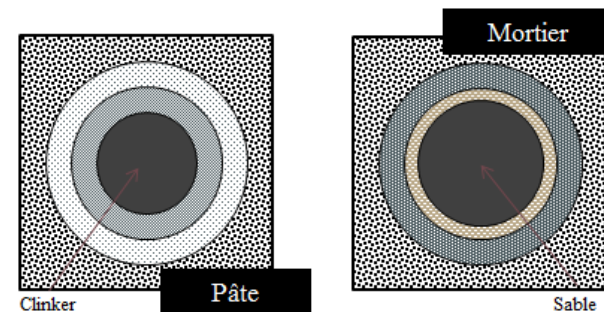
[Honorio et al. 2014d]

Mori-Tanaka



[Mori, Tanaka, 1973]

Generalized Self-Consistent



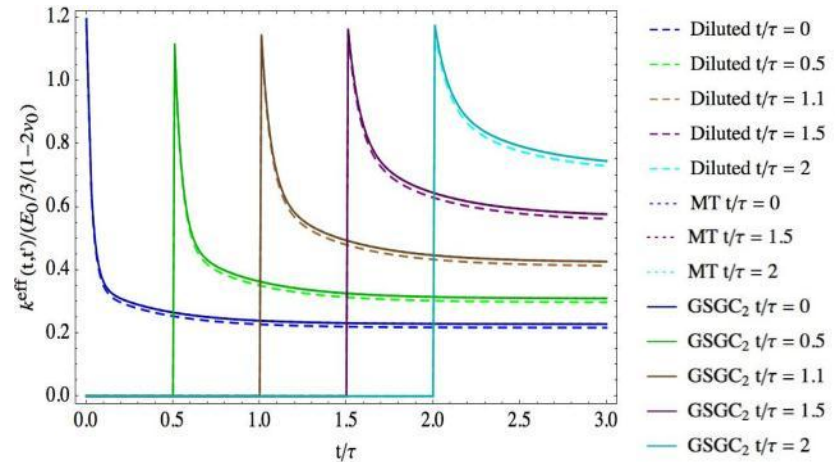
[Christensen, Lo 1979]

Ageing linear viscoelasticity

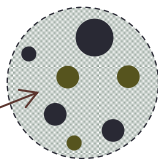
- Opérateur Intégral de Volterra :

$$(f \circ g)(t, \tau) \equiv \int_{t'=-\infty}^t f(t, t') d_t' g(t', \tau)$$

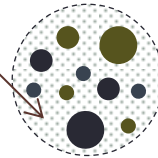
[Volterra 1887; Maghous et al. 2003; Sanahuja, 2013]



C-S-H HD



C-S-H LD



- C-S-H : viscoelastic behavior
 - Intrinsically ageing?
- Solidification → ageing behavior

Mori-Tanaka

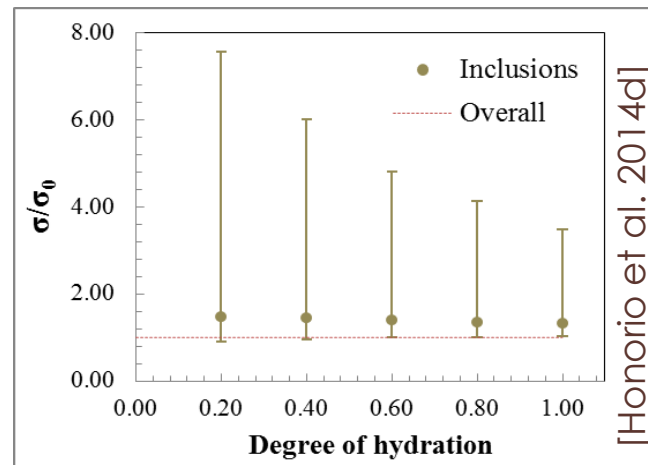
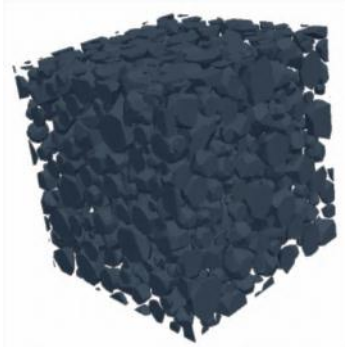
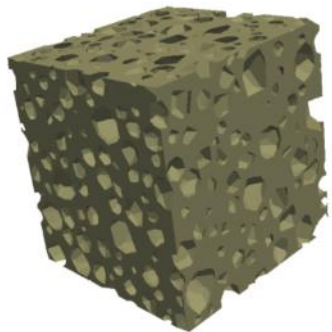
Generalized Self-Consistent

Numerical homogeneization

Goals:

- Investigate the influence of the aggregates
- Get local information
- Study more complex microstructures

Elasticité



Dispersion on stresses within the inclusions

Ageing linear viscoelasticity

[Bary et al. 2014]

- Matrix : cube (120x120x120)mm³
- Number of inclusions : 872
 - Equivalent diameters : 8-18 mm

Conclusions

■ Different strategies to investigate the behavior at early-age

- Mechanistic approach:
 - Some phenomena still need to be better understood (hot point!)
 - Some tools still to be developed

Perspectives

- Contribution to the study of the ageing viscoelastic behavior
 - Influence of the ageing mechanisms at the paste level
 - Influence of the aggregates (shape, PSD, vol. fraction)
 - Mismatch of matrix-inclusions properties
 - Thermal effects

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Acknowledgments

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