

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

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CMS Workshop "Cracking of massive concrete structures"

March 17, 2015, ENS-Cachan

Cachan, Île-de-France, FRANCE

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 BARY[1] ; Farid BENBOUDJEMA[2]

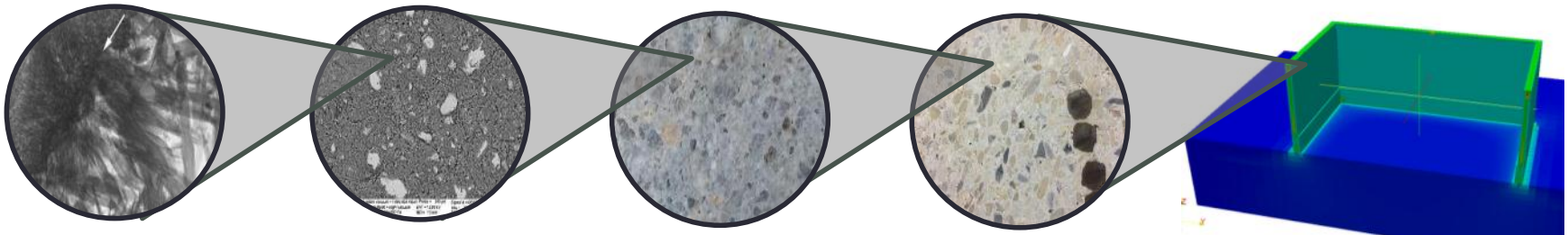
[1]*CEA, DEN, DPC, SECR, Laboratoire d'Etude du Comportement des Bétons et des Argiles, F-91191 Gif-sur-Yvette, France*

[2]*LMT (ENS Cachan, CNRS, Université Paris Saclay) 94235 Cachan, France*

Concrete at early-age

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

[Richardson 2004]



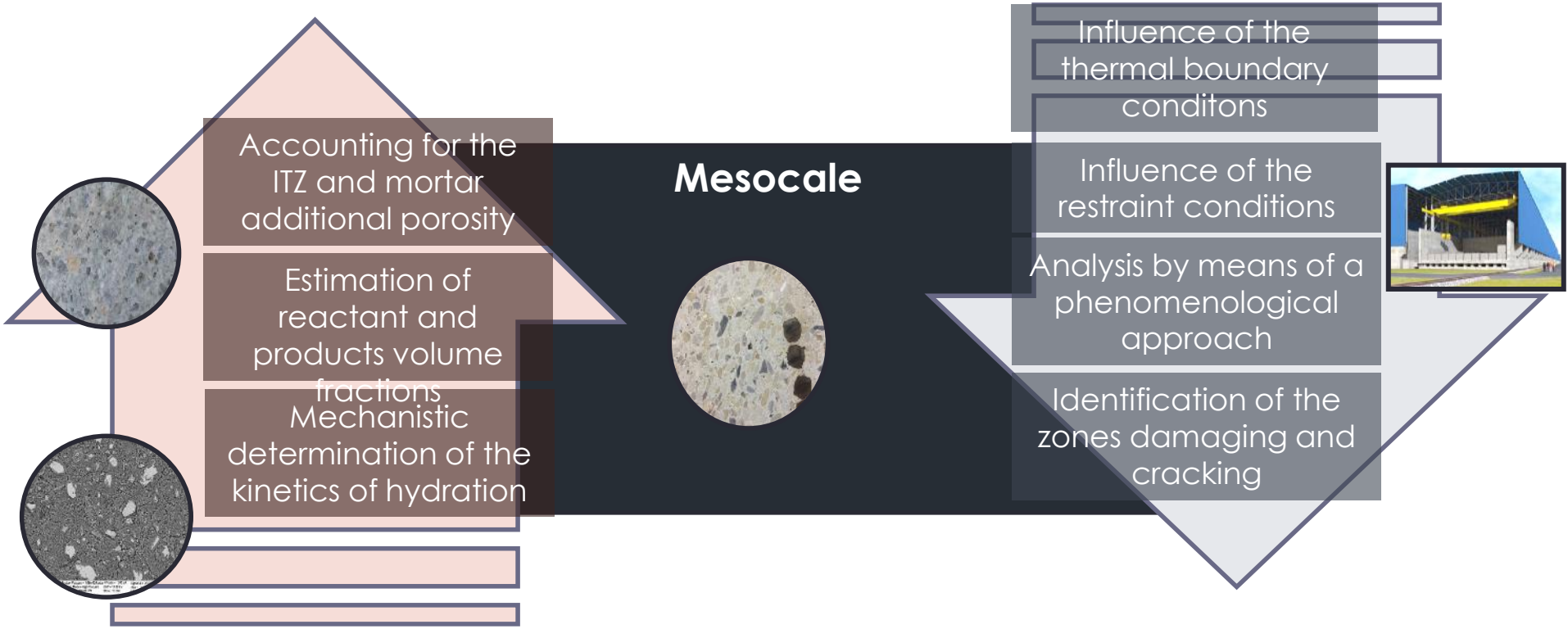
C-S-H | Cement paste | Mortar | Concrete | Reinforced concrete structure

- Solidification
- Creep
- Shrinkage
- ITZ
- Mismatch of properties of matrix and inclusions
- Heterogenous distribution of stress
- Internal restraint
- Environmental conditions
- External restraint

nm | µm | mm | m

Different strategies

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



Thermo-chemo-mechanical analysis

A phenomenological approach at the structure level

Chemo-thermal problem

- Heat balance

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

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

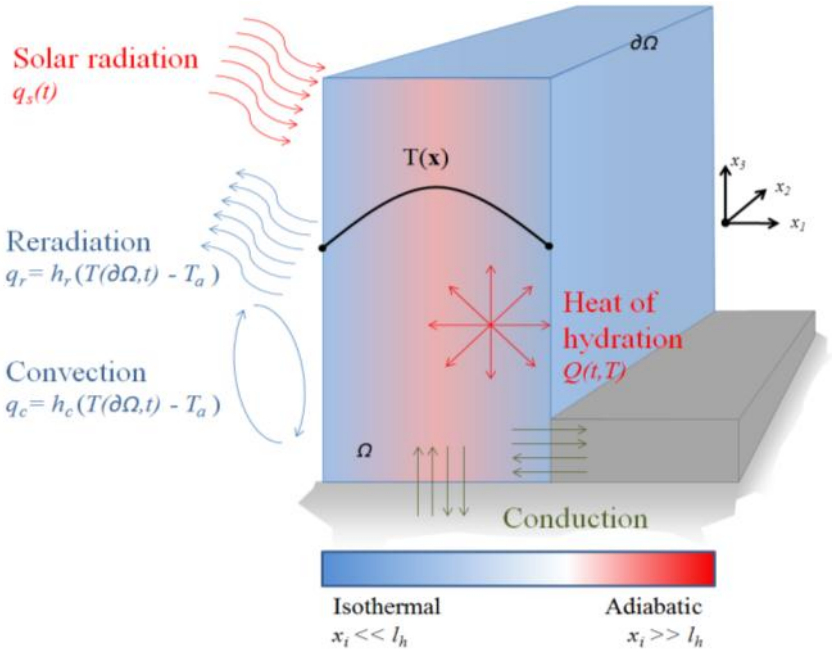
- Hydration

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

- Boundary conditions

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

  - q_y: Heat conducted into concrete
  - q_r: Re-radiation by concrete
  - q_c: Heat loss by convection
  - q_s: Radiation absorbed

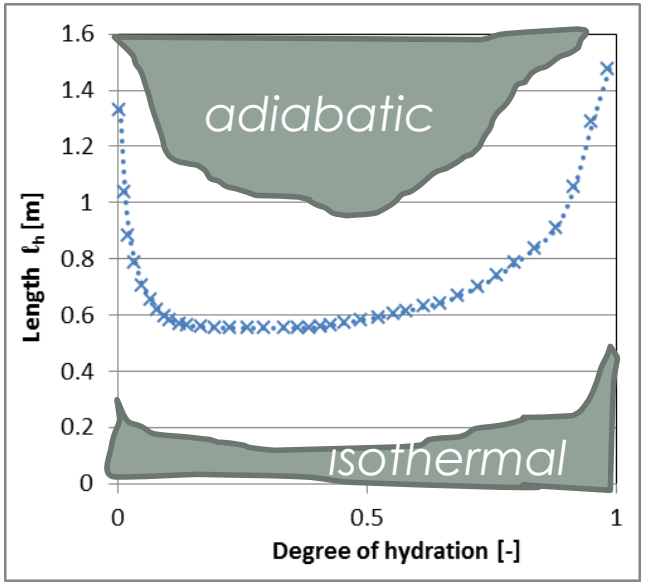


Analytical solutions

Why?

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

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





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

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

Reradiaiton and Convection equivalent exchange coeff.

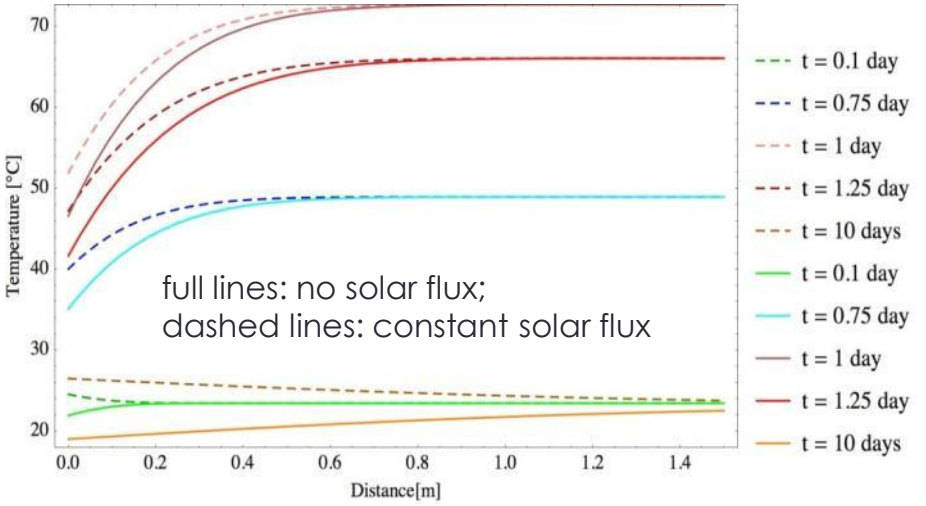
Ambient temperature

Variable flux on boundaries (solar flux)

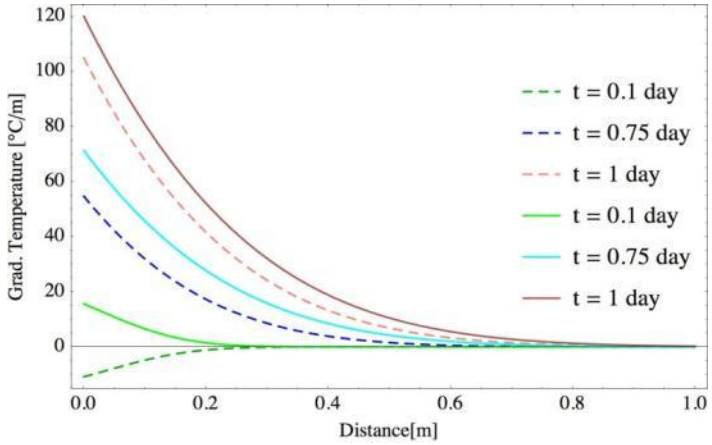
Solar flux

- Convection and reradiaiton
- T_a is kept constant.

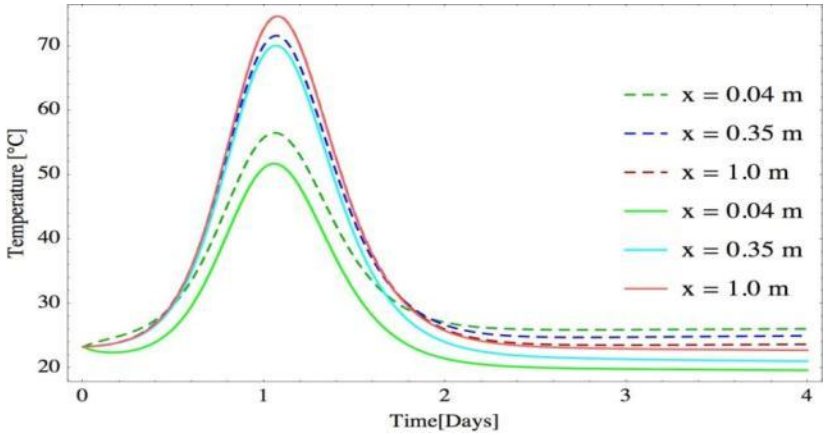
- ***Evolution of the temperatures at different distances from the surface →***



- ***Gradient of temperature ↓***

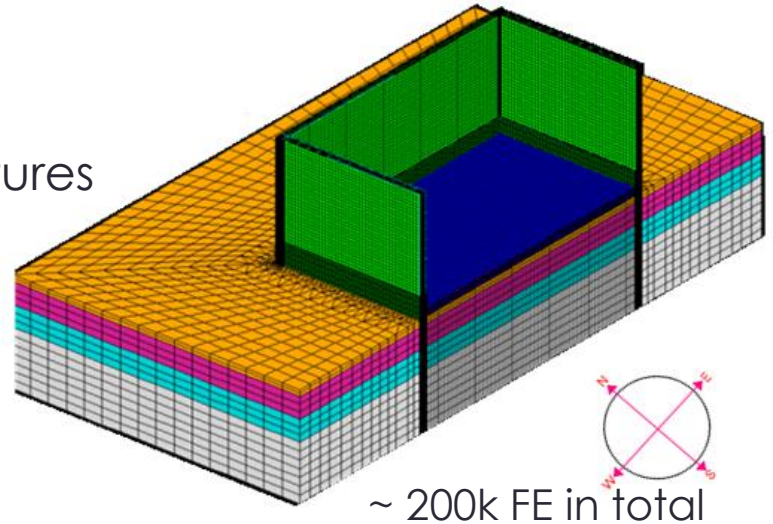


- ***Profiles of temperatures at different times ↓***



FEM analysis

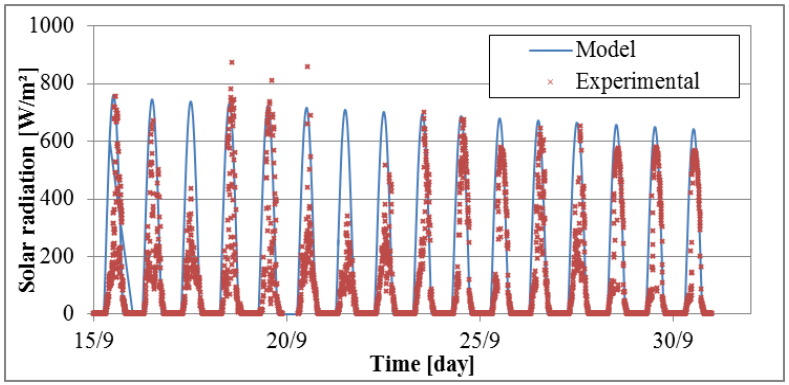
- Goal: Determine concreting temperatures



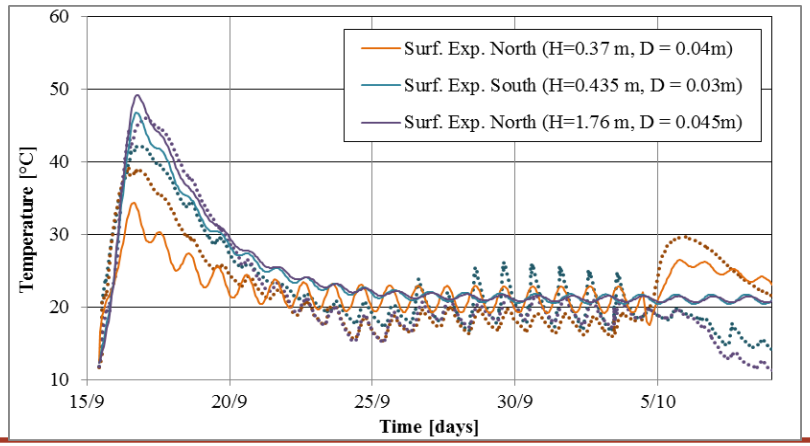
~ 200k FE in total
~ 100k FE for the wall

- Asymmetric thermal loading induced by solar flux
- Test different T scenarios
  - Precooling?

Solar flux

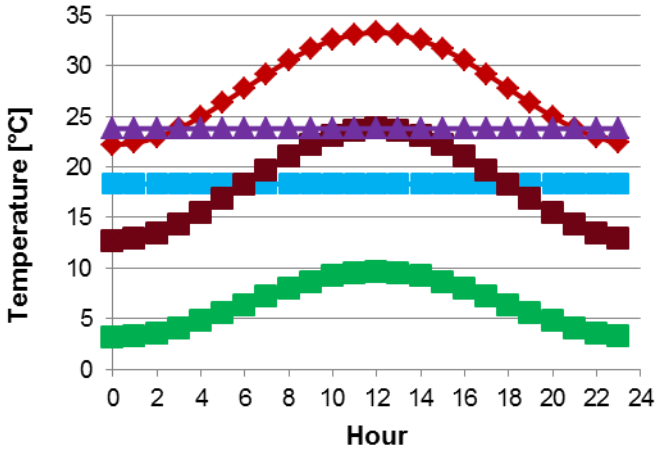


Validation

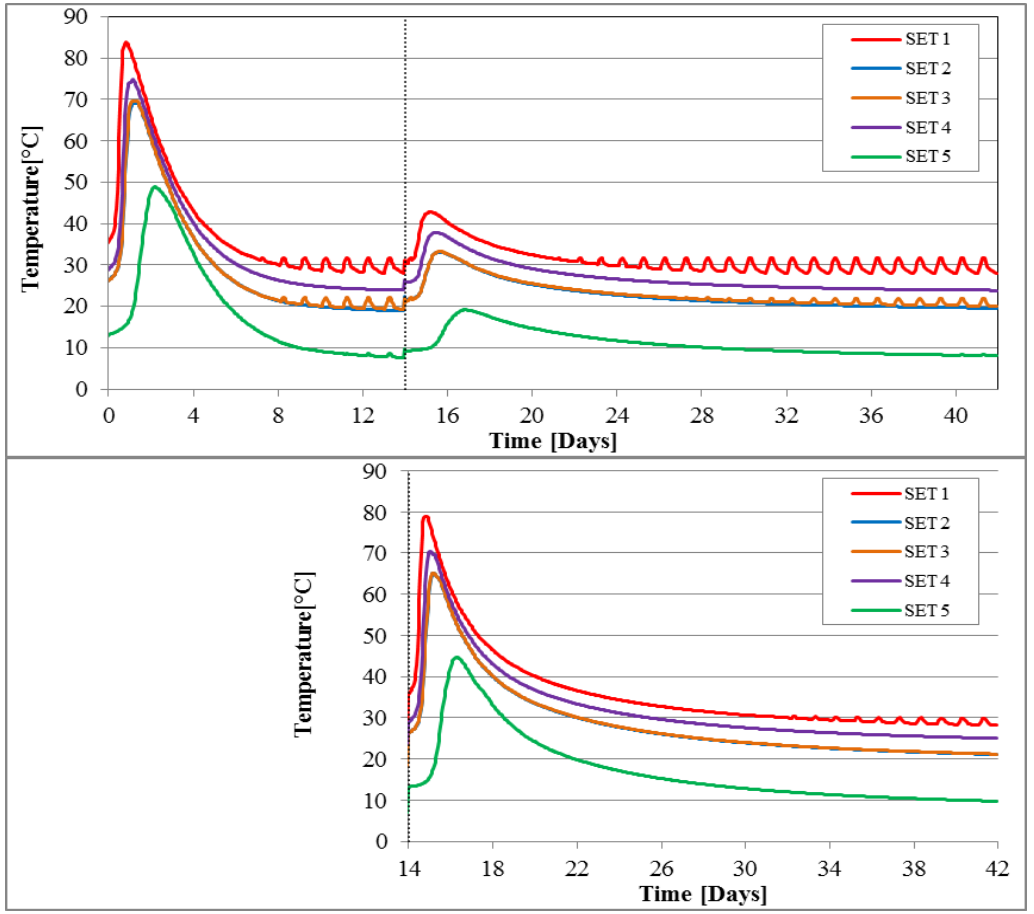


Ambient temperature

- *Maximum T to prevent DEF problems T_{adm}=70°C*
- Maximum temperature reached within the structure varies almost linearly with Ta



Set of temperatures



Concreting temperatures

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

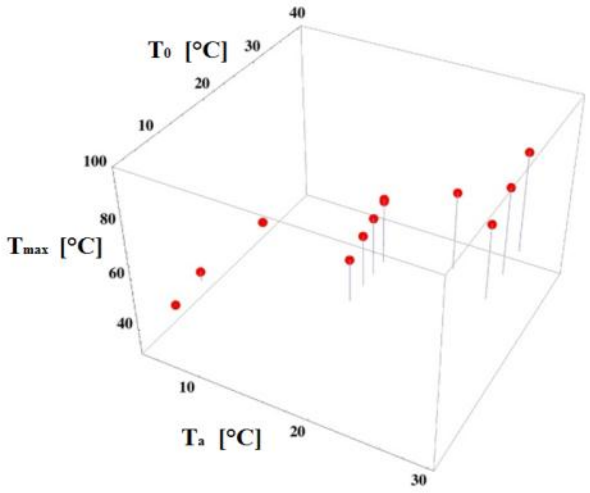
$$T_1(x,t) = T_0\,(\dots) \qquad T_2(x,t) = \left(T_a - \frac{\bar{q}_s}{k}\right)(\dots)$$

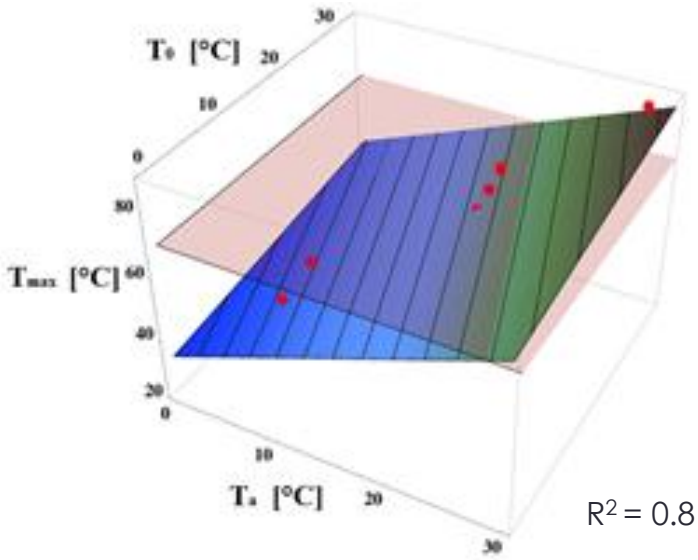
$$T_{max} = c_1\,T_0 + c_2\,T_a + c_3$$

Fitting parameters

[-]	1.28
[-]	0.359
[°C]	34.1

→ $\Delta T_{ad} = 46.62$ °C





$R^2 = 0.81$

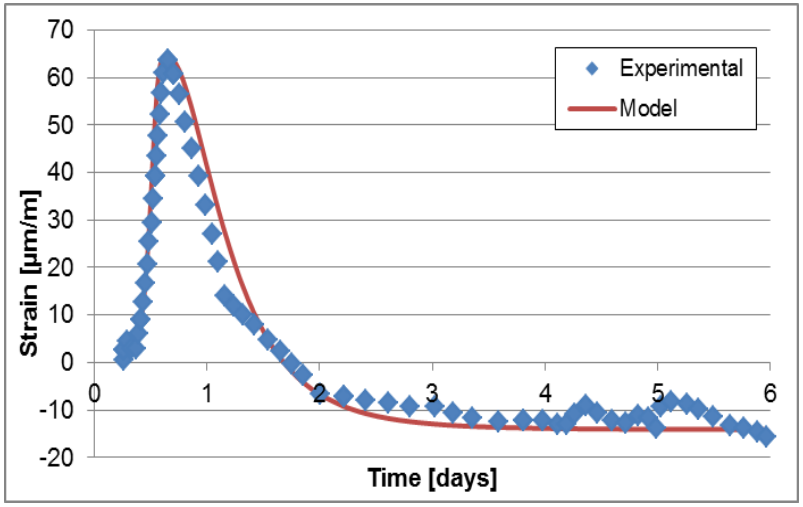
Mechanical model

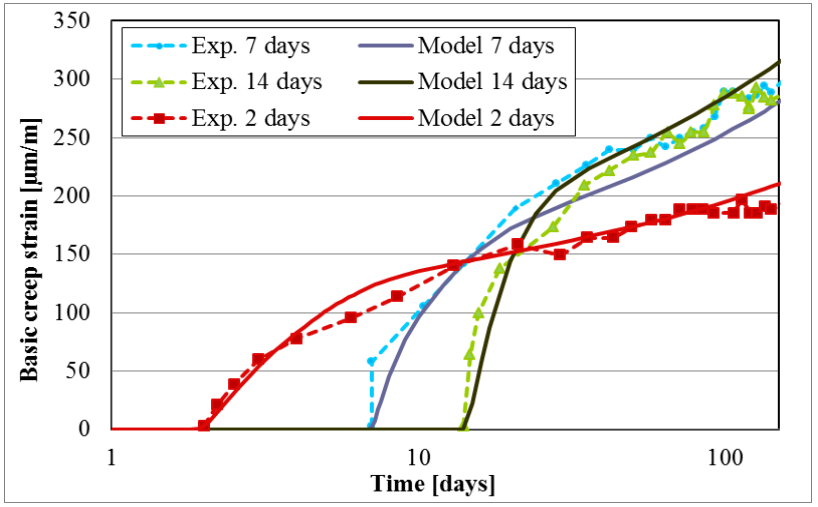
$$\boldsymbol{\varepsilon_{in} = \varepsilon_{au} + \varepsilon_{th} + \varepsilon_{cr}}$$

- Rheological model

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

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





Cracking index

- Probability of cracking as a function of the CI:

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

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

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

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

Damage model

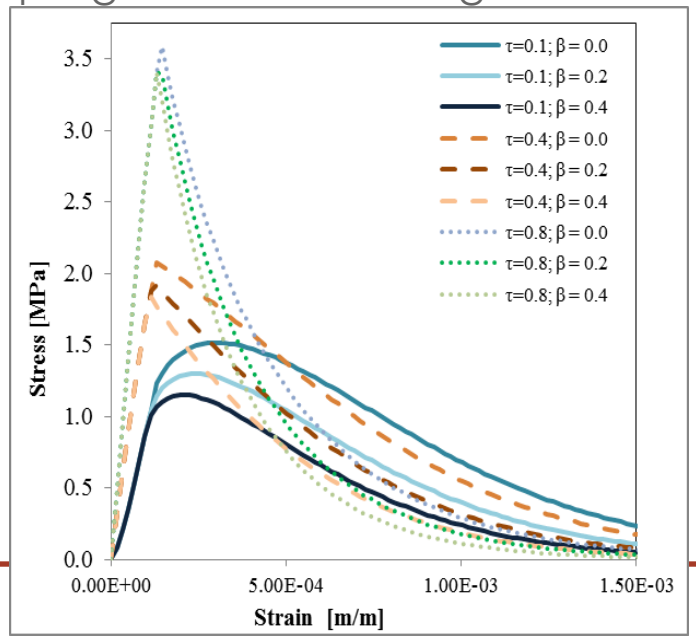
- Isotropic damage variable D

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

- Equivalent strain

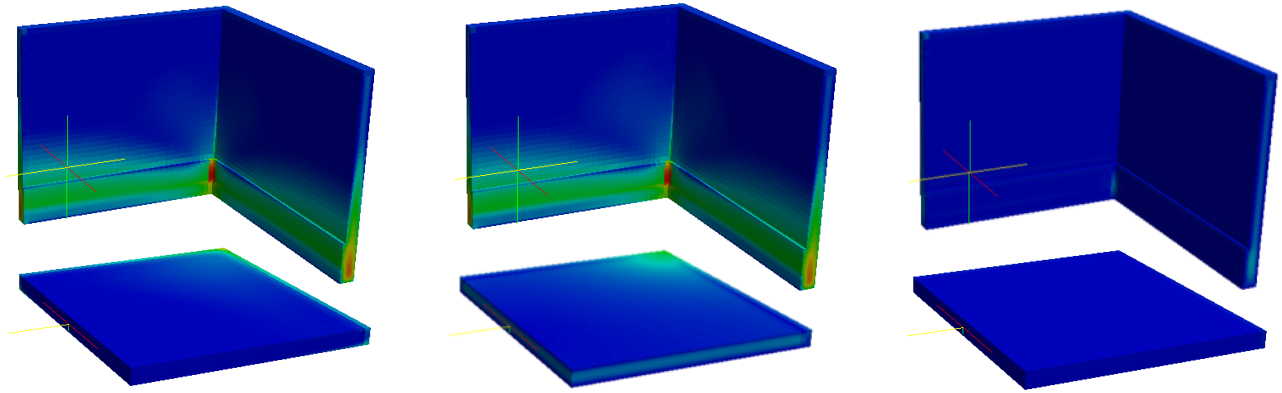
$$\hat{\varepsilon} = \sqrt{\langle \varepsilon_e + \beta \varepsilon_{bc} \rangle_+ : \langle \varepsilon_e + \beta \varepsilon_{bc} \rangle_+}$$

- Coupling between damage and creep



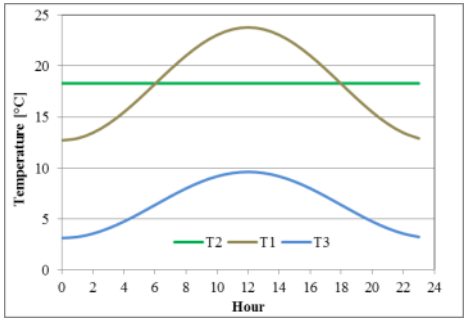
Thermal conditions: Cracking Index

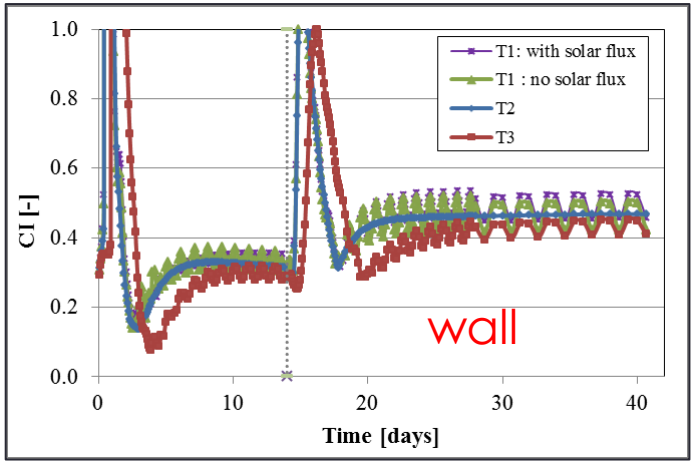
Aug (oscillating) *Aug (constant)* *Nov (oscillating)*

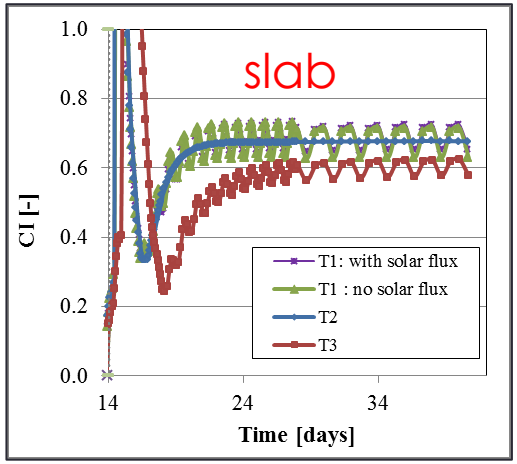


First (maximum) eigenstress according to the 3 thermal boundary conditions

t = 15.08 days

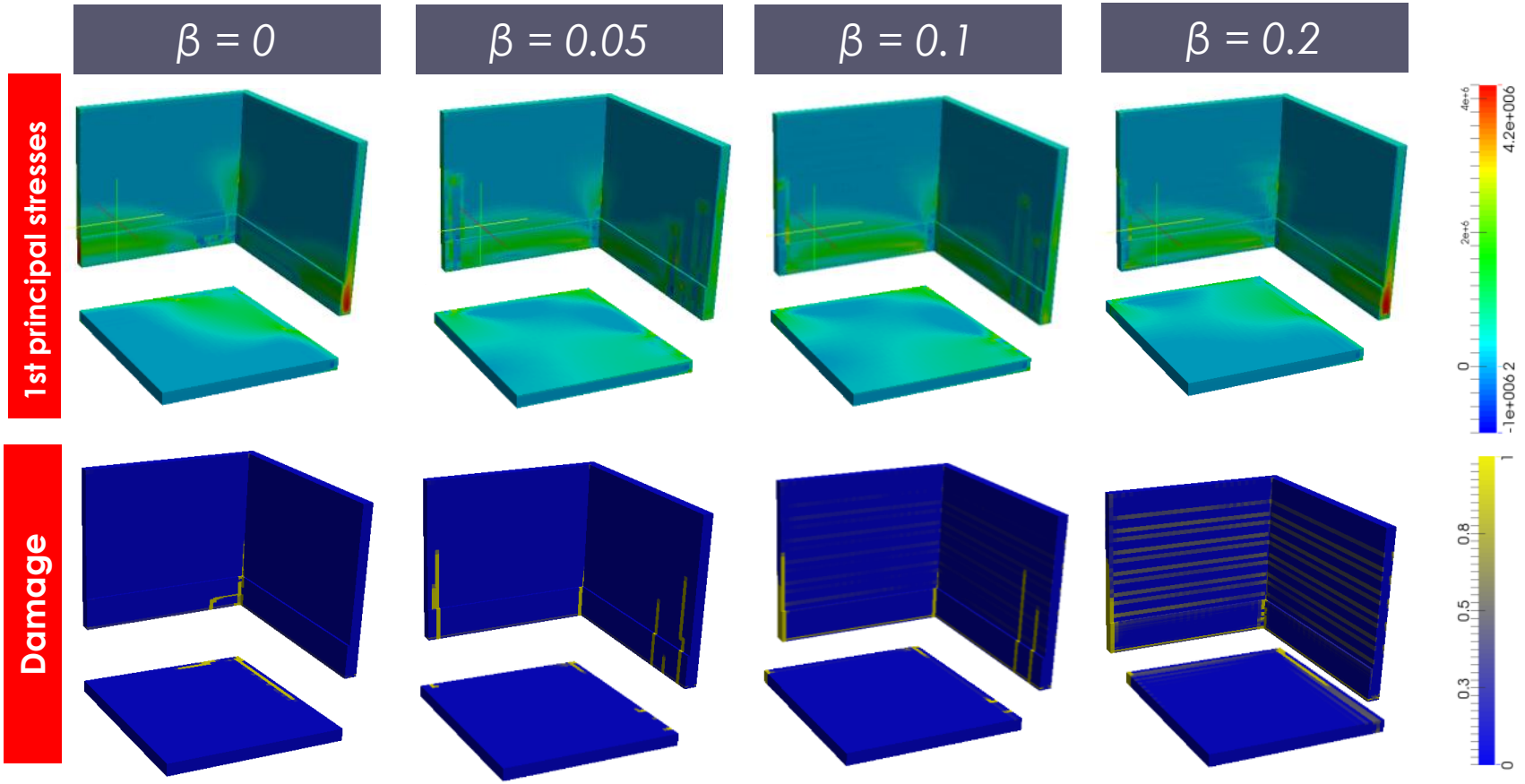






Coupling between creep and damage

August temperatures; t = 15.08 days



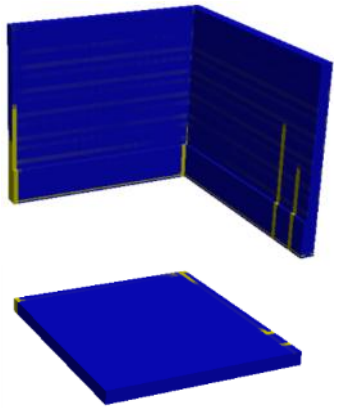
Thermal conditions: Damage and Crack opening

[Mattalah et al. 2009]

Aug (oscillating)

$\beta = 0.1$

Damage →



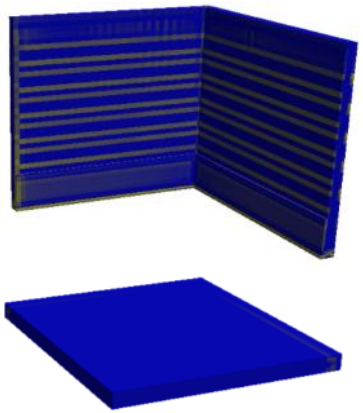


Crack opening

Nov (oscillating)

$\beta = 0.1$

Damage →





Crack opening

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

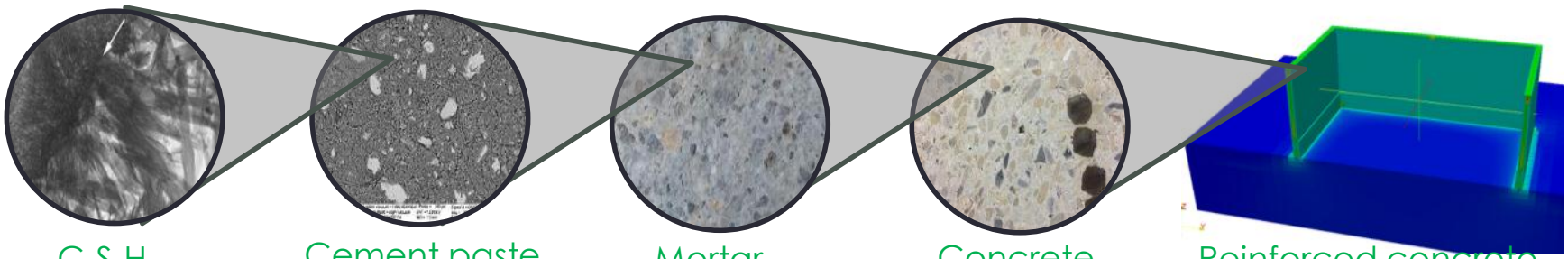
- Mechanistic approaches to understand the underlying phenomena
  - Justify and improve phenomenological

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]



C-S-H | Cement paste | Mortar | Concrete | Reinforced concrete structure

- Solidification
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- External restraint

nm | µm | mm | m

Hydration kinetics

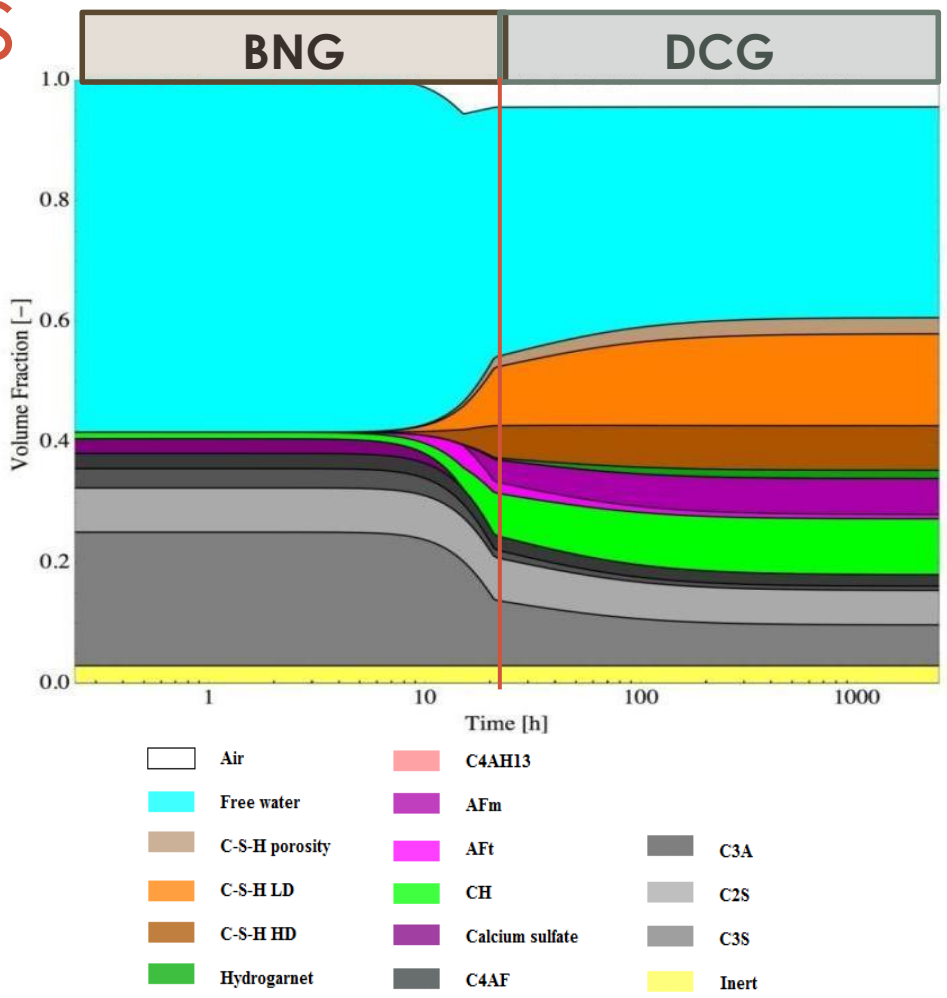
Goals

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

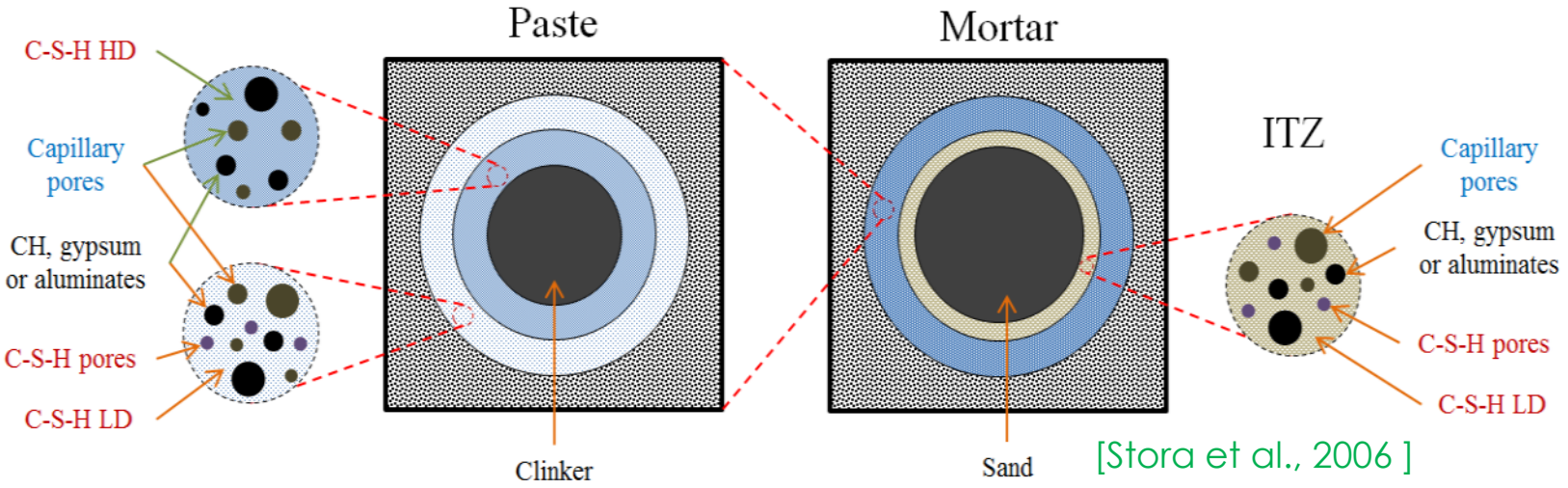
Approach

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

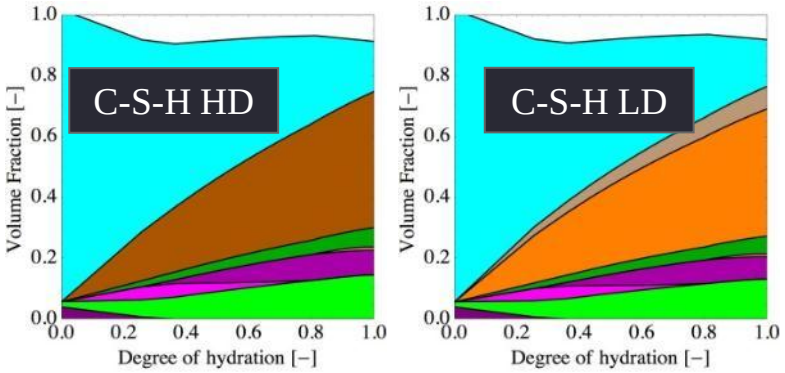
[Honorio et al. 2014c;
Honorio et al. Submitted]



Microstructure representation

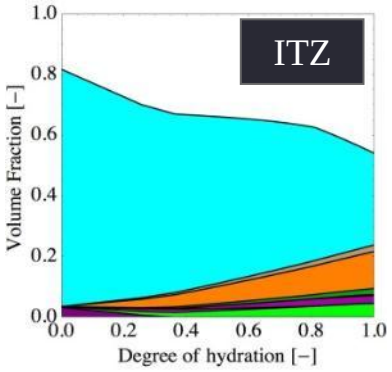


[Stora et al., 2006]

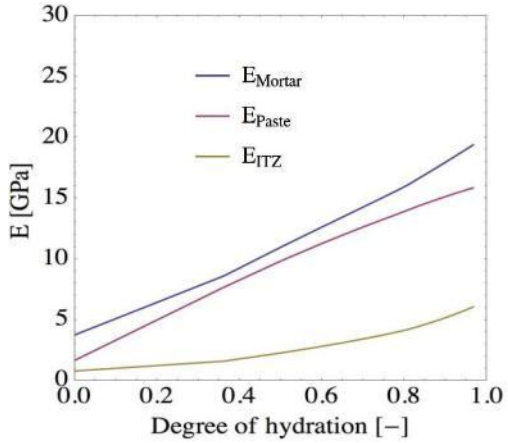


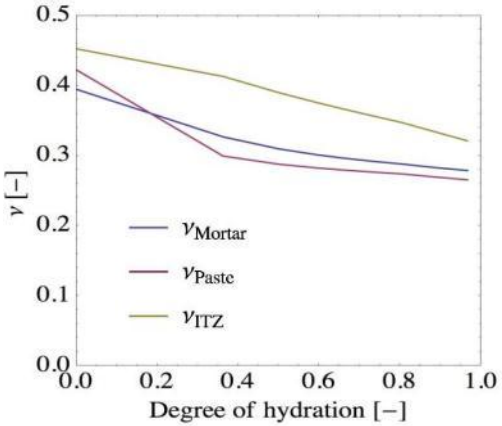
- Repartition of products

[Honorio et al. 2014d]



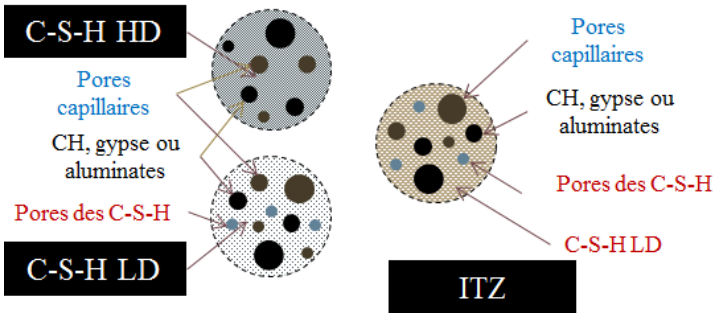
Solutions in elasticity





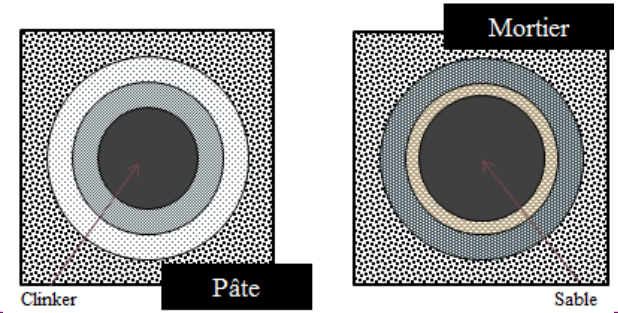
[Honorio et al. 2014d]

Mori-Tanaka



[Mori, Tanaka, 1973]

Generalized Self-Consistent



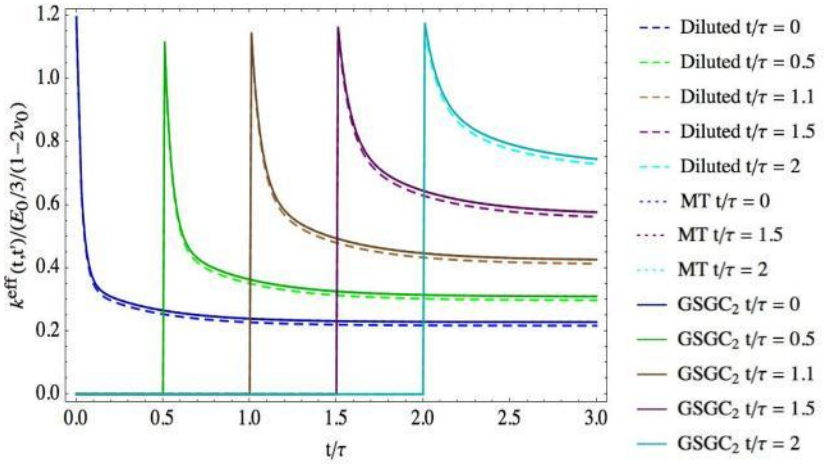
[Christensen, Lo 1979]

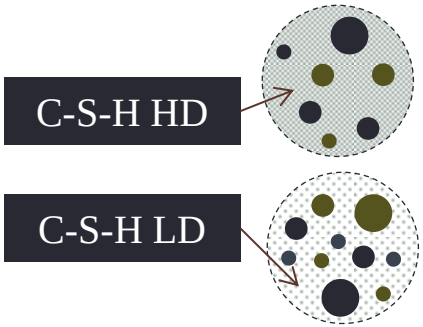
Ageing linear viscoelasticity

- 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 : viscoelastic behavior
  - Intrinsically ageing?
- Solidification → ageing behavior

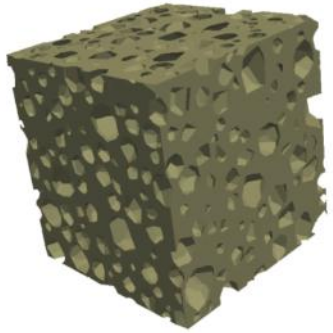
Mori-Tanaka	Generalized Self-Consistent

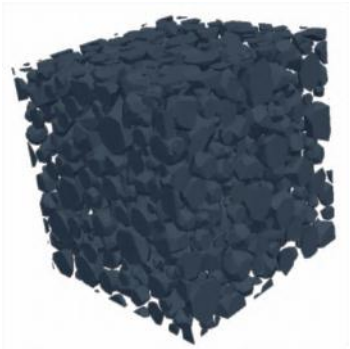
Numerical homogeneization

Goals:

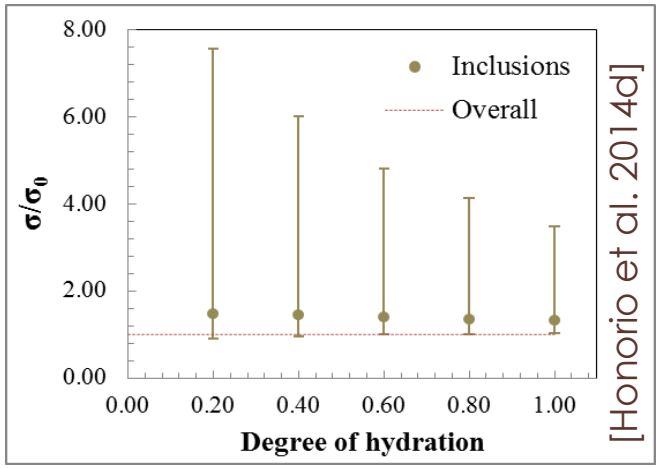
- Investigate the influence of the aggregates
- Get local information
- Study more complex microstructures

Elasticité





[Bary et al. 2014]



[Honorio et al. 2014d]

Dispersion on stresses within the inclusions

- Matrix : cube (120x120x120)mm^3
- Number of inclusions : 872
  - Equivalent diameters : 8-18 mm

Ageing linear viscoelasticity

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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