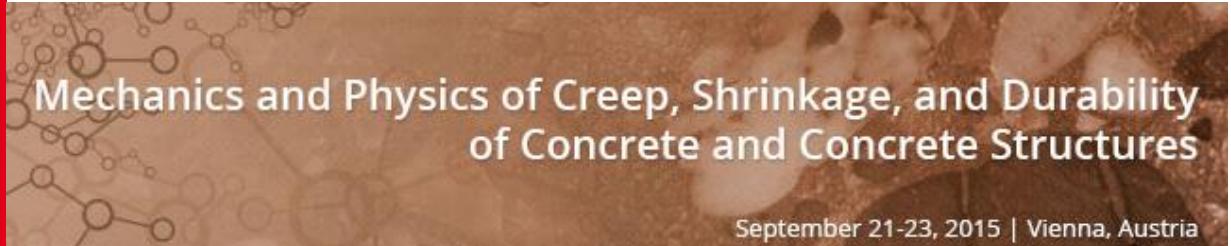


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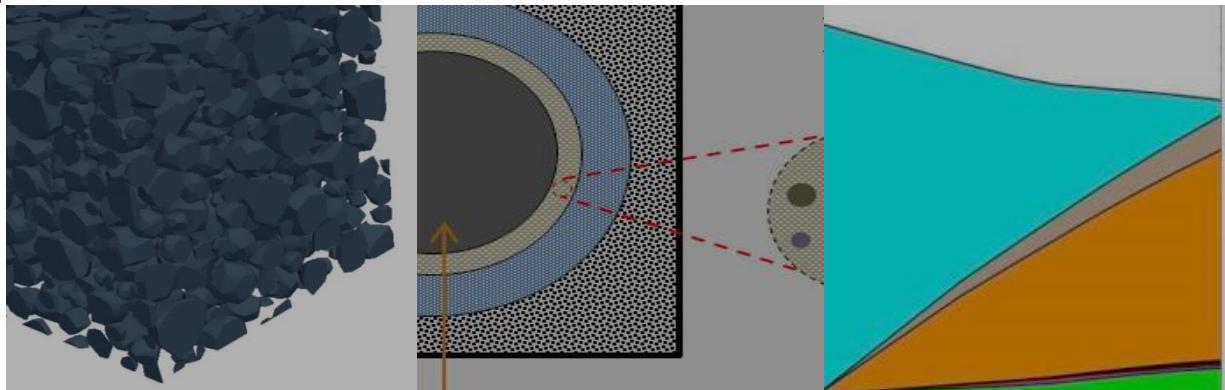
ONDRAF



Mechanics and Physics of Creep, Shrinkage, and Durability of Concrete and Concrete Structures

September 21-23, 2015 | Vienna, Austria

MULTISCALE ESTIMATION OF THE VISCOELASTIC PROPERTIES OF CEMENTITIOUS MATERIALS AT EARLY AGE: A COMBINED ANALYTICAL AND NUMERICAL APPROACH



Tulio Honorio^{1,2}; Benoit Bary¹ and Farid Benboudjema²

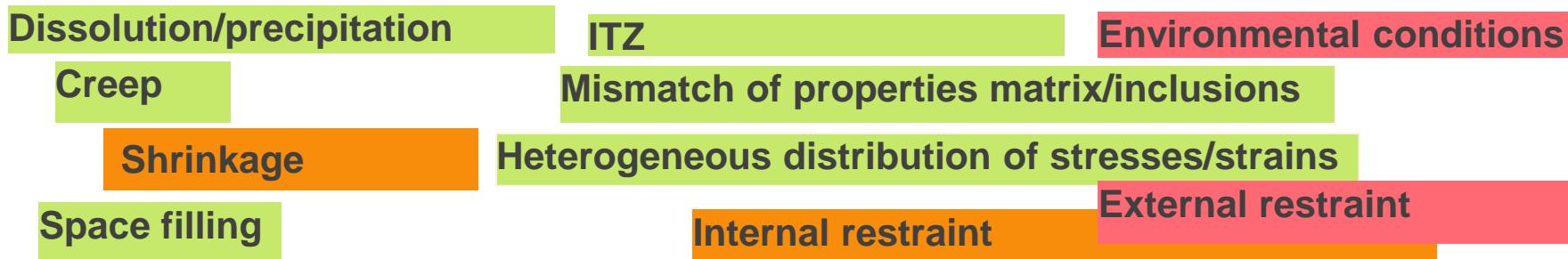
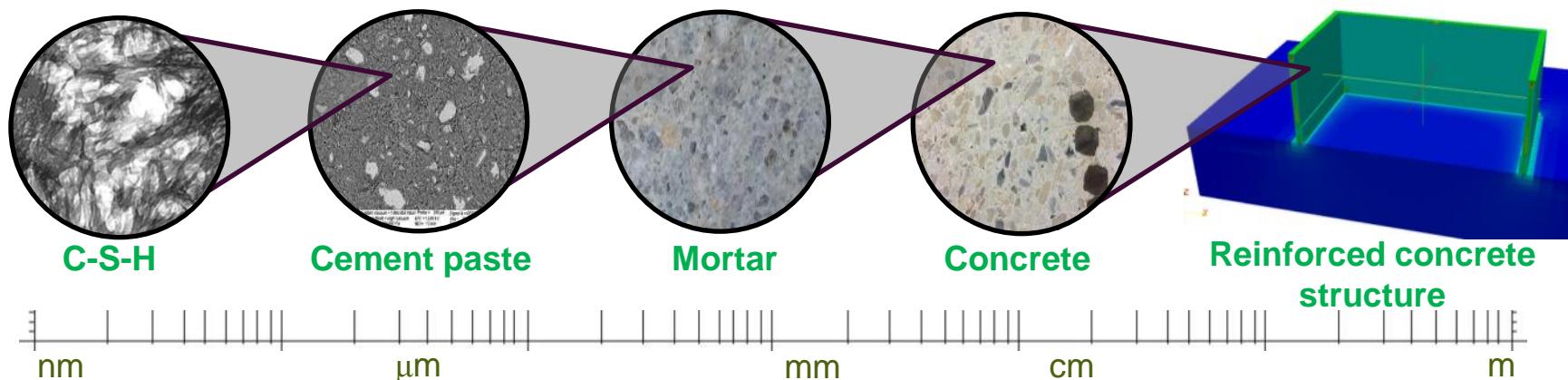
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SEPTEMBER 21ST 2015

Background**CEMENT-BASED MATERIALS: MULTISCALE CHARACTER AND AGEING BEHAVIOUR**

- Industrial applications ← good description of macroscopic properties at the relevant scale of application
 - Properties evolving at early age (ageing)
 - Differents phenomena taking place at different time and space scales:



AGEING LINEAR VISCOELASTIC BEHAVIOUR

- Constitutive behaviour at ageing linear viscoelasticity:

$$\boldsymbol{\varepsilon}(t) = \int_{t'=-\infty}^t \mathbb{S}(t, t') : d\boldsymbol{\sigma}(t') \quad \boldsymbol{\sigma}(t) = \int_{t'=-\infty}^t \mathbb{R}(t, t') : d\boldsymbol{\varepsilon}(t')$$

Ageing aspect → Dependence of the time of loading

- Non-ageing case

$$\boldsymbol{\varepsilon}(t) = \int_{t'=-\infty}^t \mathbb{S}(t - t') : d\boldsymbol{\sigma}(t') \quad \boldsymbol{\sigma}(t) = \int_{t'=-\infty}^t \mathbb{R}(t - t') : d\boldsymbol{\varepsilon}(t')$$

- Volterra integral operator : $(f \circ g)(t, \tau) \equiv \int_{t'=-\infty}^t f(t, t') d_t' g(t', \tau)$ [Volterra 1887]

$$\boldsymbol{\varepsilon}(t) = \mathbb{S}(t, .) \overset{\circ}{\dot{\vdash}} \boldsymbol{\sigma}(.), \quad \boldsymbol{\sigma}(t) = \mathbb{R}(t, .) \overset{\circ}{\dot{\vdash}} \boldsymbol{\varepsilon}(.),$$

Similar form as in Elasticity → **Correspondance principle**

- Method to evaluate Volterra integrals: **Trapeizodal rule** [Bazant, 1972]
 - Mori-Tanaka Scheme in ageing linear viscoelasticity [Sanahuja, 2013]
 - Implement in FEM Code → B. Bary Cast3M

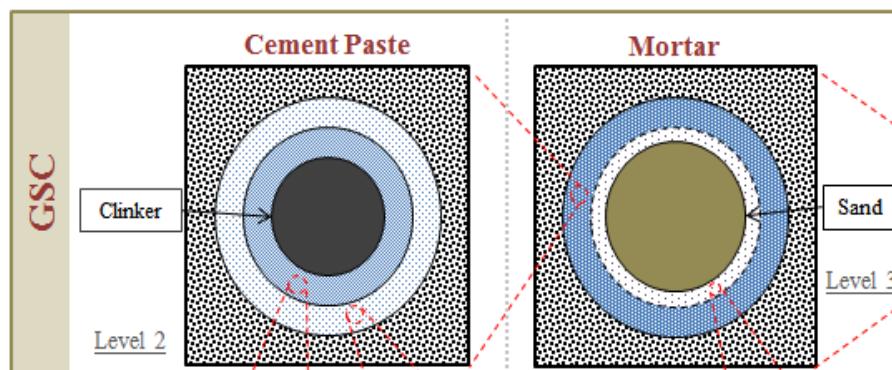
GOALS AND STRATEGY

Goals

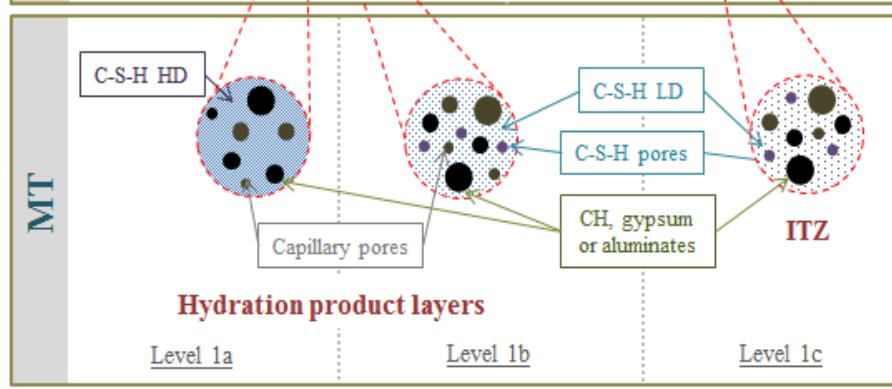
- Estimate the ageing properties of concrete from the composition of the cement paste
- Focus on the role of the coarse aggregates but without neglecting the effects related to the other scales within the material

Approach

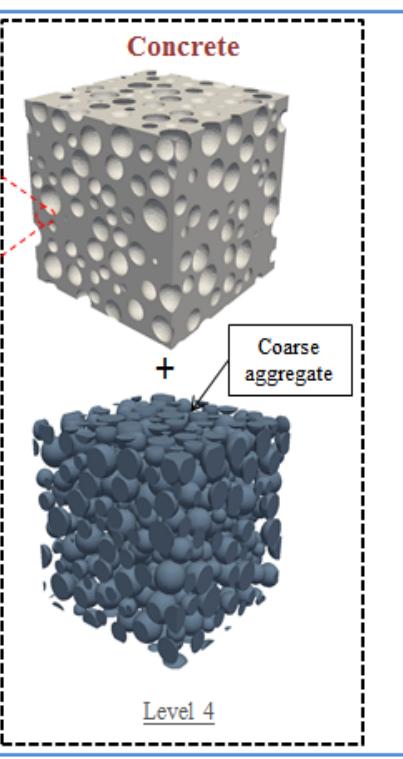
*Generalized Self
consistent scheme
(GSC)*



*Mori-Tanaka
scheme (MT)*



Analytical homogenization



ANALYTICAL HOMOGENIZATION

Derivation of Mori-Tanaka scheme

- Obtained by Sanahuja [2013]

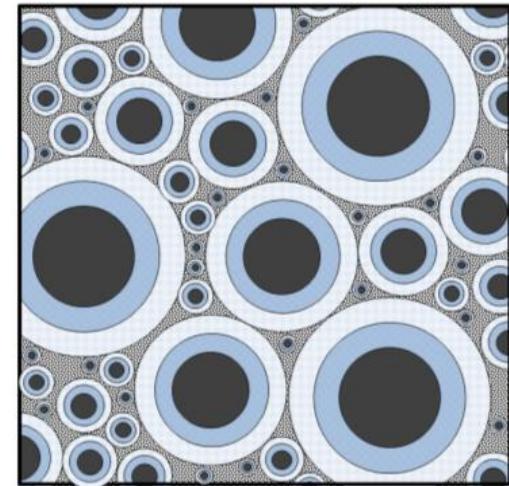
Derivation of Generalize Self-Consistent scheme

- Following Herve and Zaoui [1992]

Bulk relaxation function

- For $n = 2$ (1 layer):

$$\begin{aligned} k_{(2)}^{eff} = & [R_2^{-3}k_2 \circ [4\mu_2 + 3k_2]^{-1} \circ [4\mu_2 + 3k_1] - 4\mu_2 \circ [4\mu_2 + 3k_2]^{-1} \\ & \circ [R_1^{-3}(k_2 - k_1)]] \\ & \circ [R_2^{-3}[4\mu_2 + 3k_2]^{-1} \circ [4\mu_2 + 3k_1] + 3[4\mu_2 + 3k_2]^{-1} \\ & \circ [R_1^{-3}(k_2 - k_1)]]^{-1} \end{aligned}$$



Shear relaxation function

- Problem: Inversion of a matrix with non-commutative elements
 - Schur complement
 - NCAlgebra (package for Mathematica)

[Honorio et al. under review]

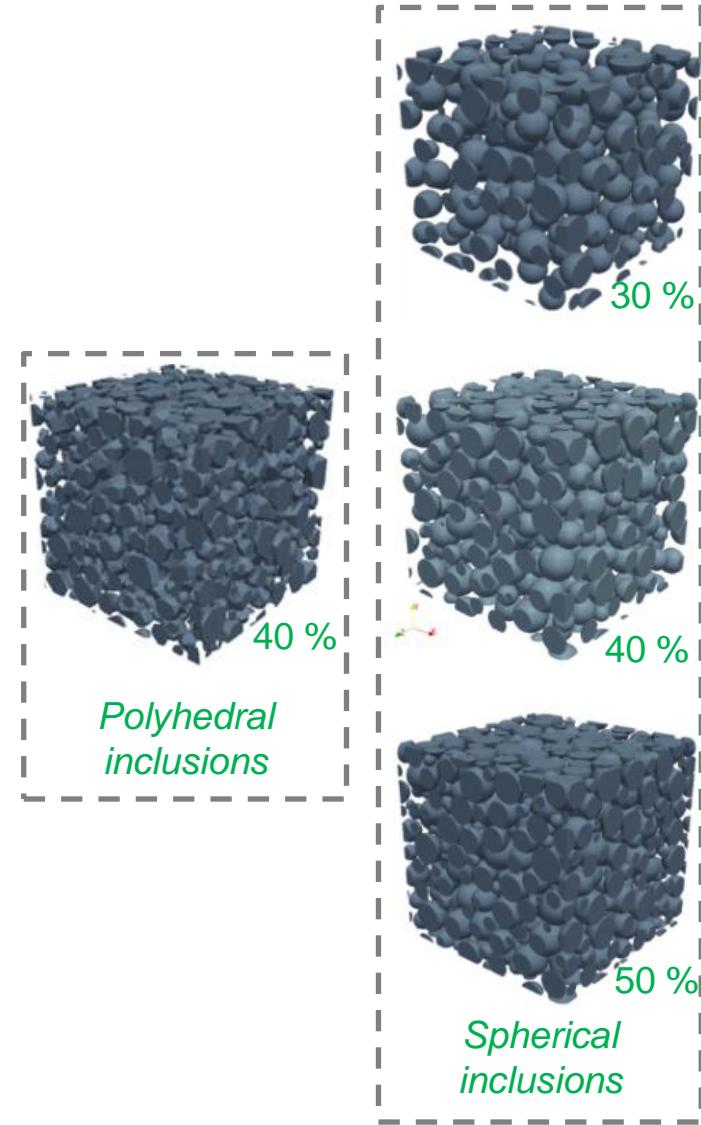
NUMERICAL HOMOGENIZATION

Goals

- Get local information
- Study more complex microstructures
- Validation of the analytical derivations

Definitions and strategy

- Generation of numerical samples with **Salome** [Bary et al. 2013; de Larrard et al. 2013]
- Classical FE method → **Cast3M** (CEA)
- Ageing linear viscoelastic behaviour implemented with **MFront** code generator
 - Maxwell rheological model coupled with an ageing function
 - Based on trapezoidal rule [Bazant, 1972]



DEFINITION OF C-S-H VISCOELASTIC BEHAVIOUR

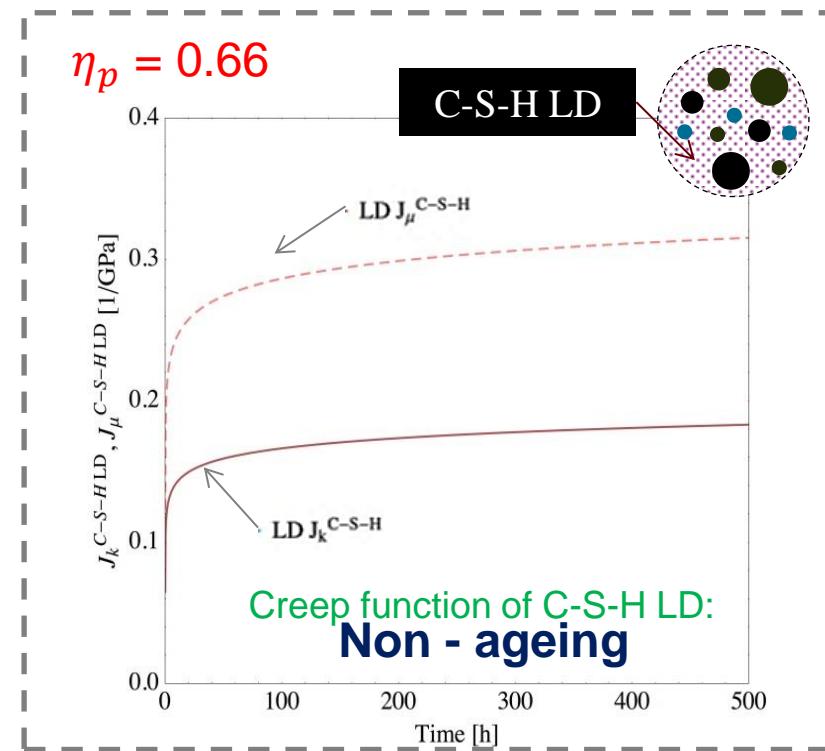
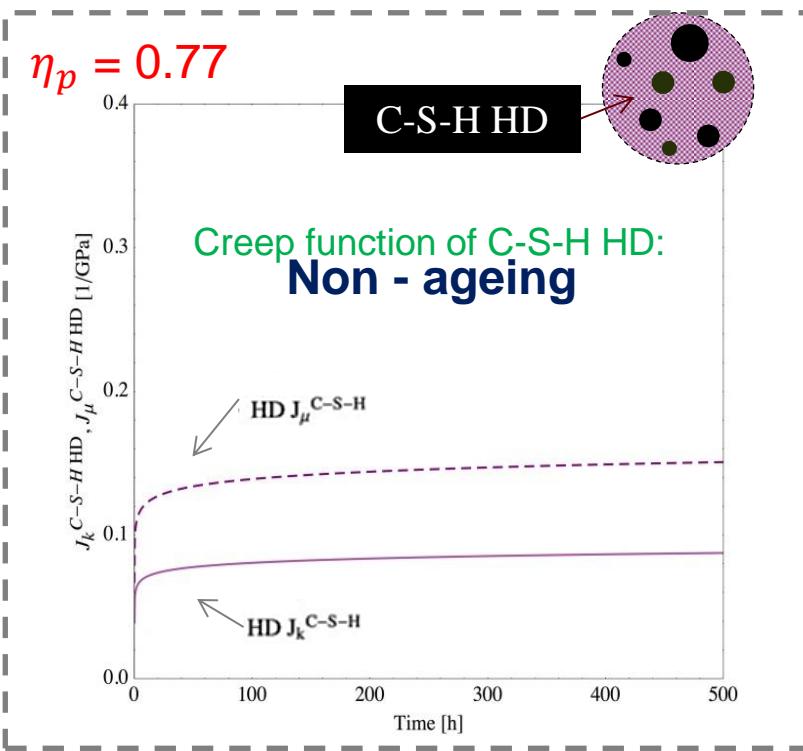
- From nanoindentation results: [Vandamme, Ulm 2009]

$$J_{un}(t, t_0) = \frac{1}{E} + \frac{1}{C_v(1 + v^2)} \ln \left[1 + \frac{t - t_0}{\tau} \right]$$

$$C_v(\eta_p) = 1588.9(\eta_p - 0.5)_+^{1.597}$$

Packing density

C-S-H Non-ageing behaviours:



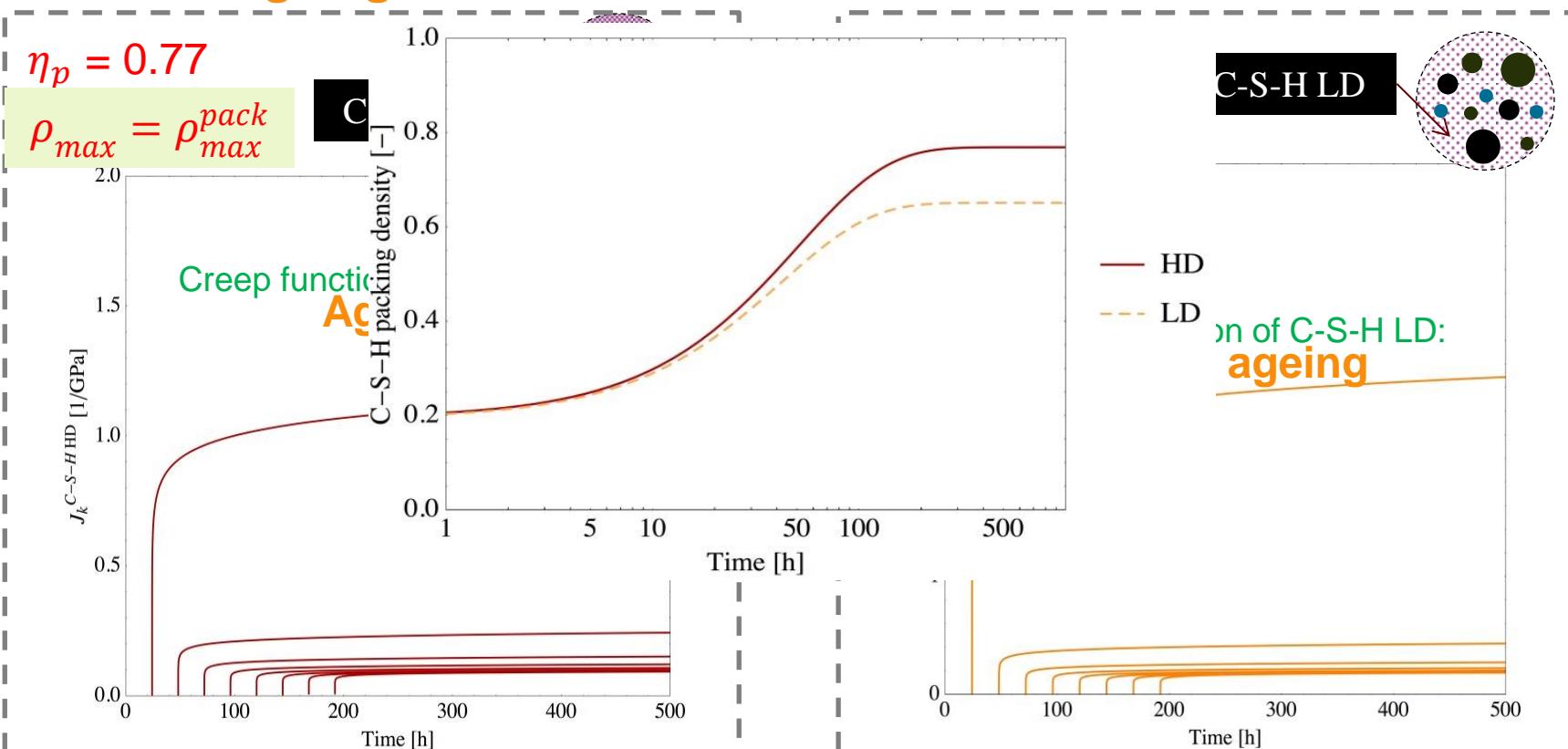
DEFINITION OF C-S-H VISCOELASTIC BEHAVIOUR

- Coupling with a space-filling process [Bishnoi, Scrivener 2009; Do, 2013]

$$\eta_p = \frac{\rho(t^s)}{\rho_{max}^{pack}} = 1 - \frac{(\rho_{max} - \rho_{min})}{\rho_{max}} \exp \left[\frac{-k_{DEN}}{\rho_{max} - \rho_{min}} (t^s) \right]$$

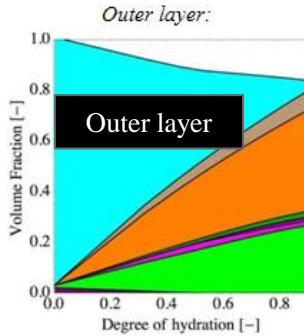
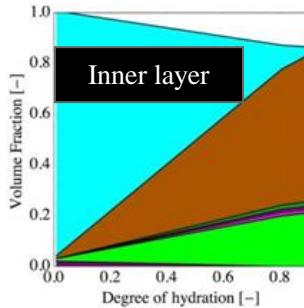
$$\rho_{max}^{pack} = 2.2 \text{ g/cm}^3$$

C-S-H Ageing behaviours:

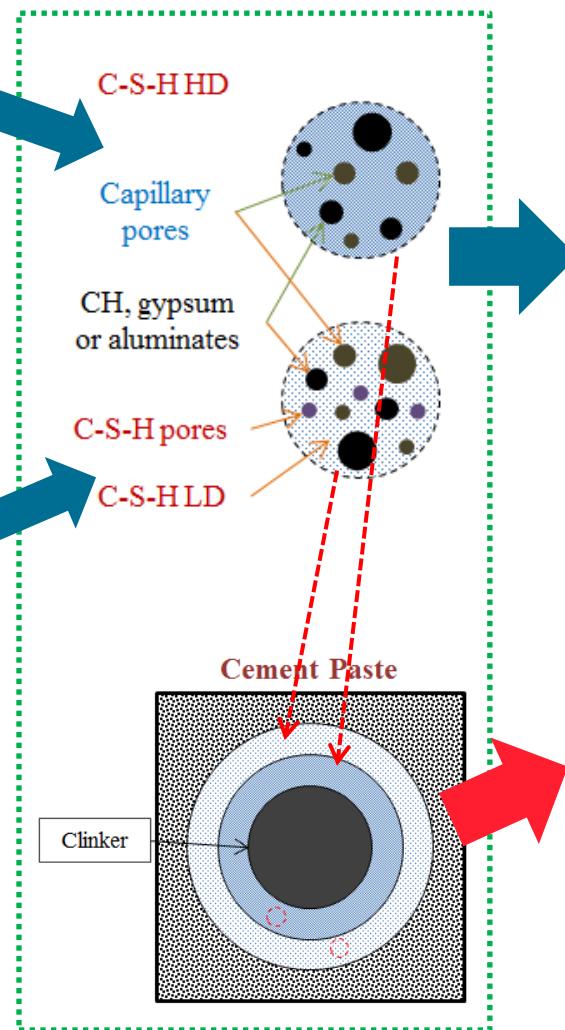


Estimation of the ageing properties of cement-based materials

ESTIMATION OF THE CEMENT PASTE BEHAVIOUR



Evolution of volume fractions for each layer

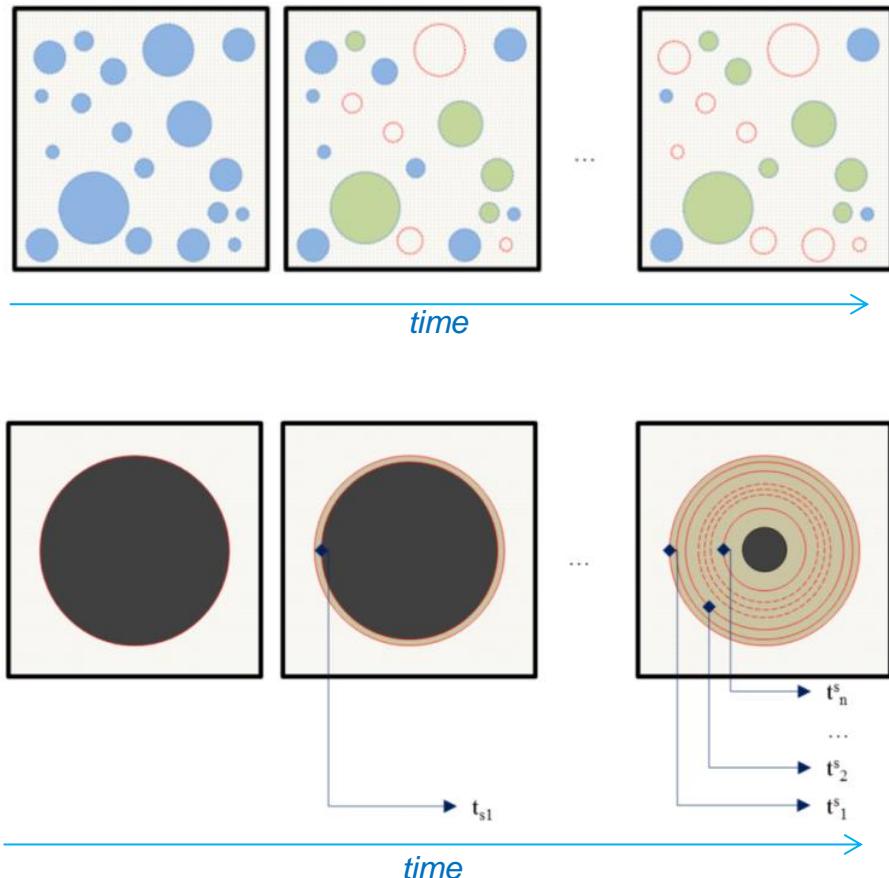


Representations of the microstructure

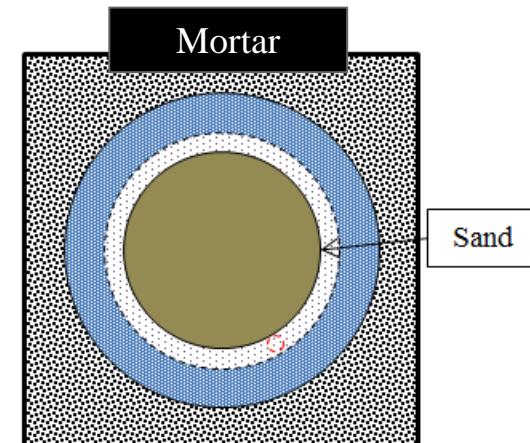
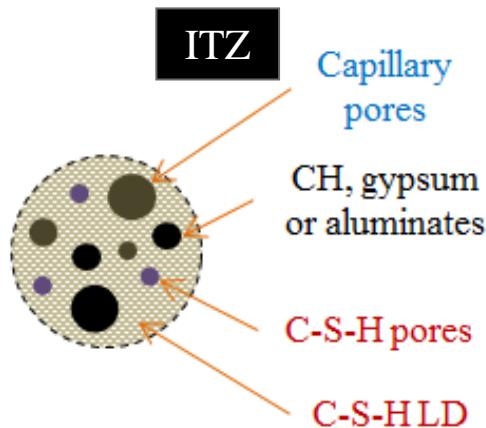
Solidification mechanisms

$$\mathbb{R}_i(t, t_0) = \mathbb{R}_s(t - t_0) H(t_0 - t_i^s)$$

[Bazant, 1977;
Sanahuja, 2013b]



ESTIMATION OF THE MORTAR BEHAVIOUR

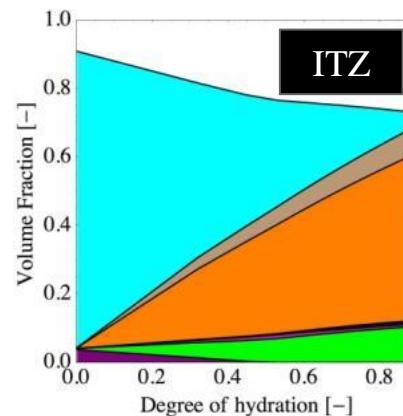


Representations of the microstructure

ITZ description

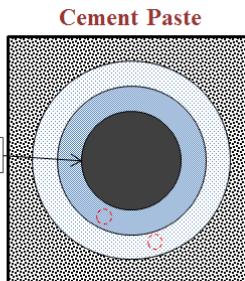
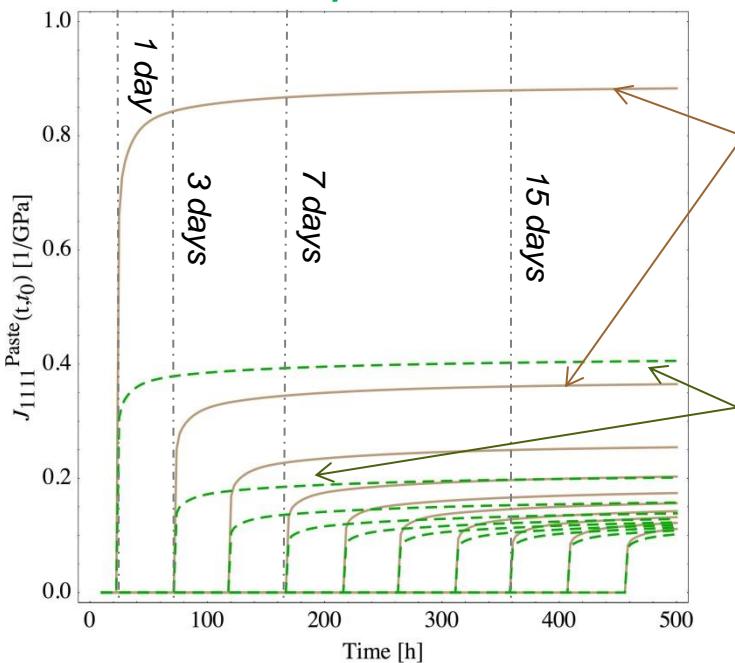
- Composition: porosity, CH, AF phases...
- Size
 - Thickness $e_{ITZ} = 20 \mu\text{m} \rightarrow$
 - Interpenetration of neighbouring ITZ

[Garboczi and Bentz 1997]



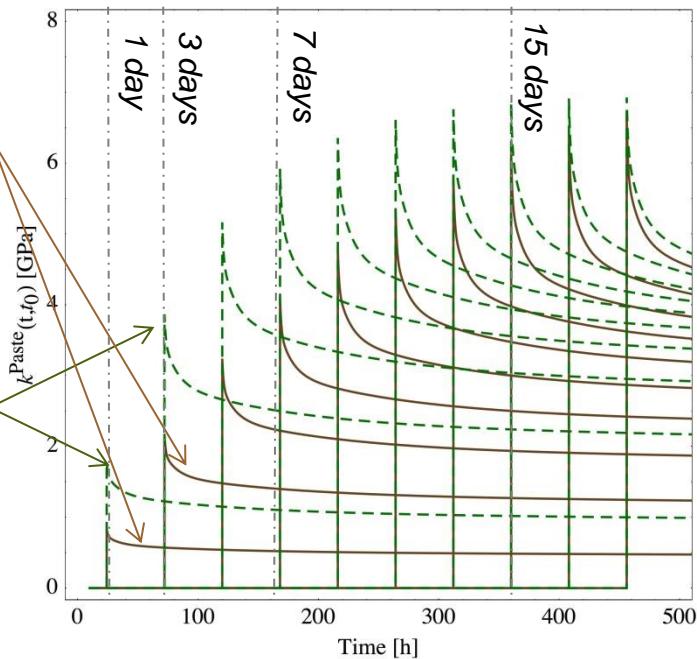
Results

EFFECTIVE PROPERTIES OF CEMENT PASTE

*Creep function*

**With space-filling:
Ageing C-S-H behaviour**

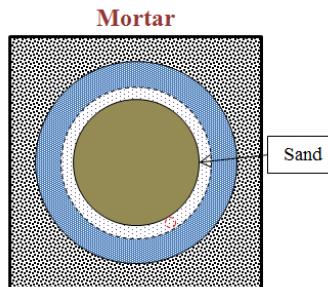
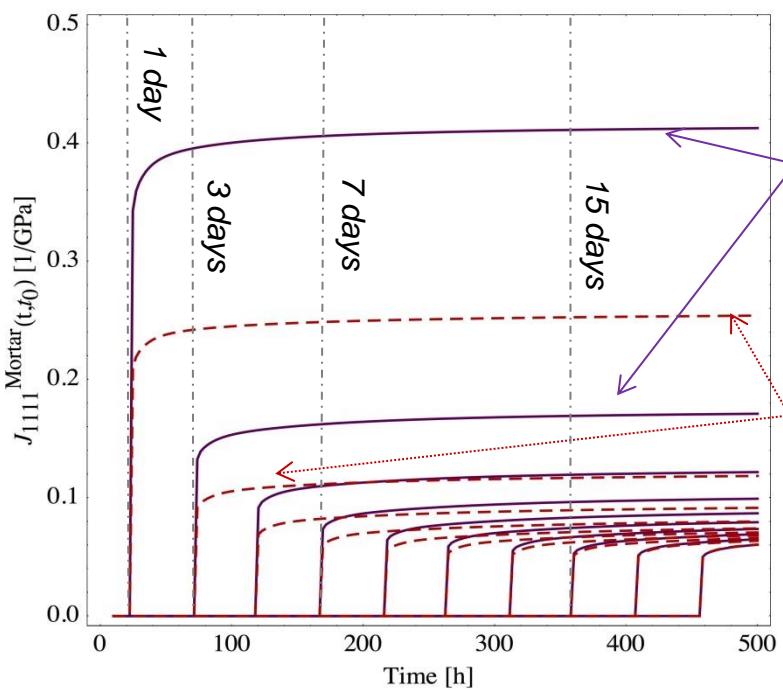
**Non-ageing C-S-H behaviour:
NO space-filling**

Bulk relaxation function

- Scenario with space-filling → more creep at early age
- Ageing character almost vanishes after 15 days

EFFECTIVE PROPERTIES OF MORTAR

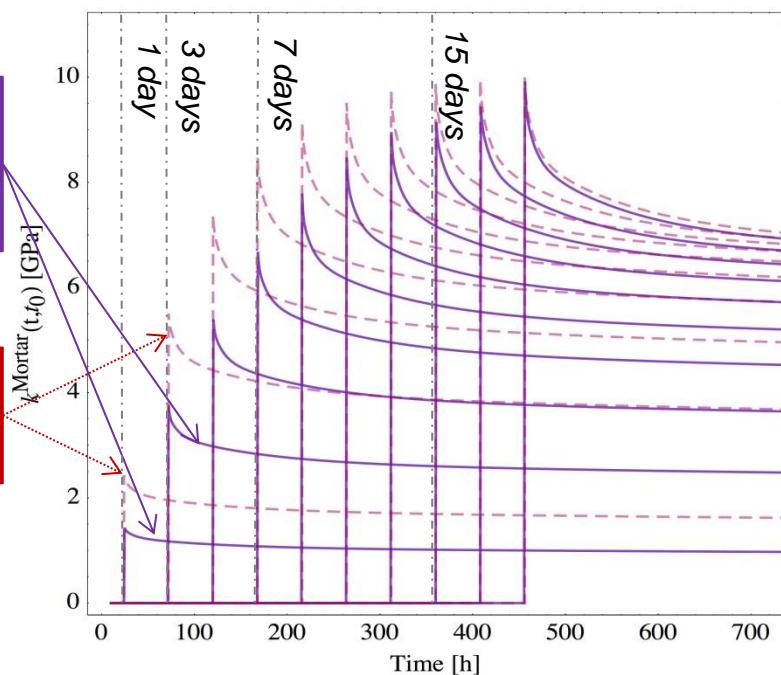
Creep function



With space-filling:
Ageing C-S-H
behaviour

Non-ageing C-S-H
behaviour:
NO space-filling

Bulk relaxation function

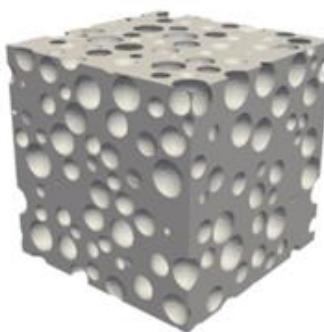
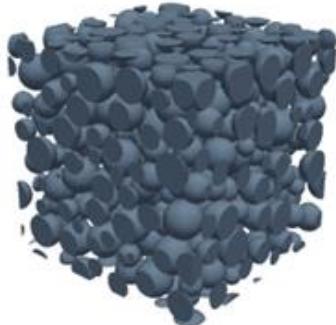


- Cement paste creeps more than mortar
- Scenario with space-filling → more creep at early age
- Ageing character almost vanishes after 15 days

ESTIMATION OF CONCRETE BEHAVIOUR

- Two numerical samples studied:

- $f_{Gra} = 40\%$
- SUBC

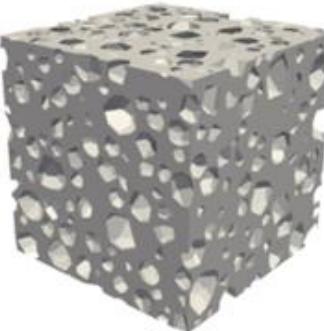
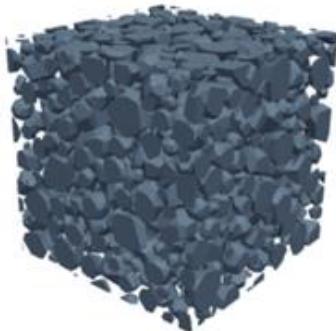
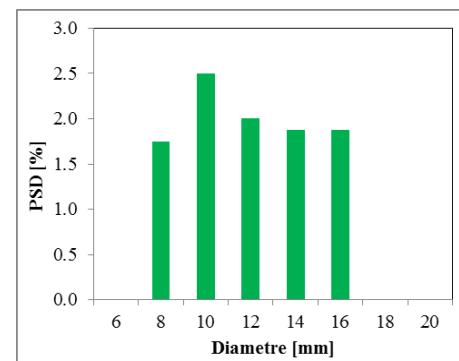


(a) Spherical inclusions:

Number: 556

1.81 million tetrahedral Finite Elements

Box = 100^3 mm 3

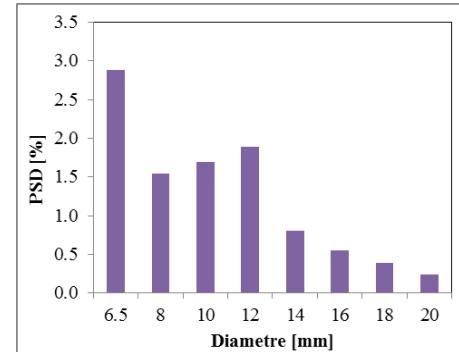


(b) Voronoi inclusions:

Number: 1124

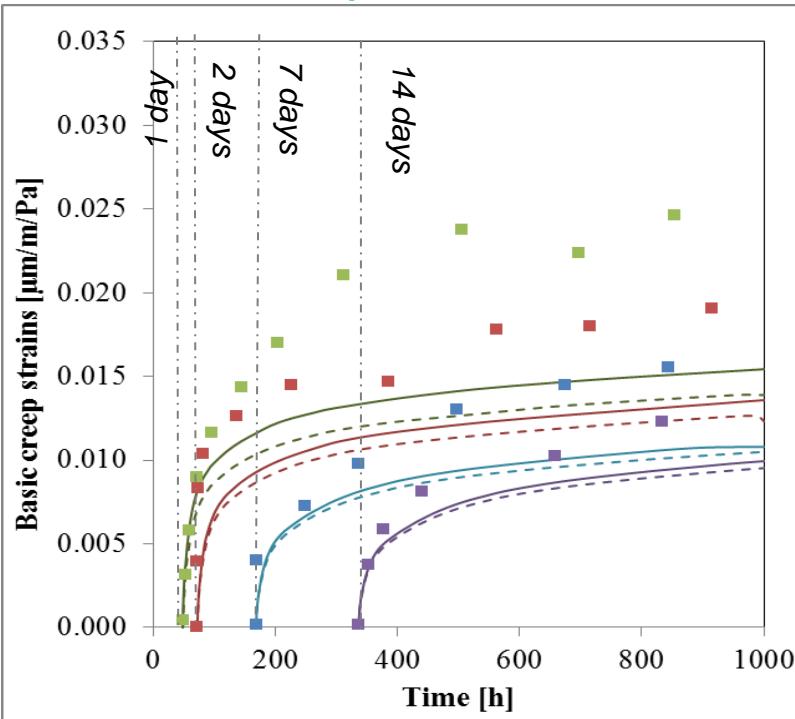
2.23 million tetrahedral Finite Elements

Box = 120^3 mm 3



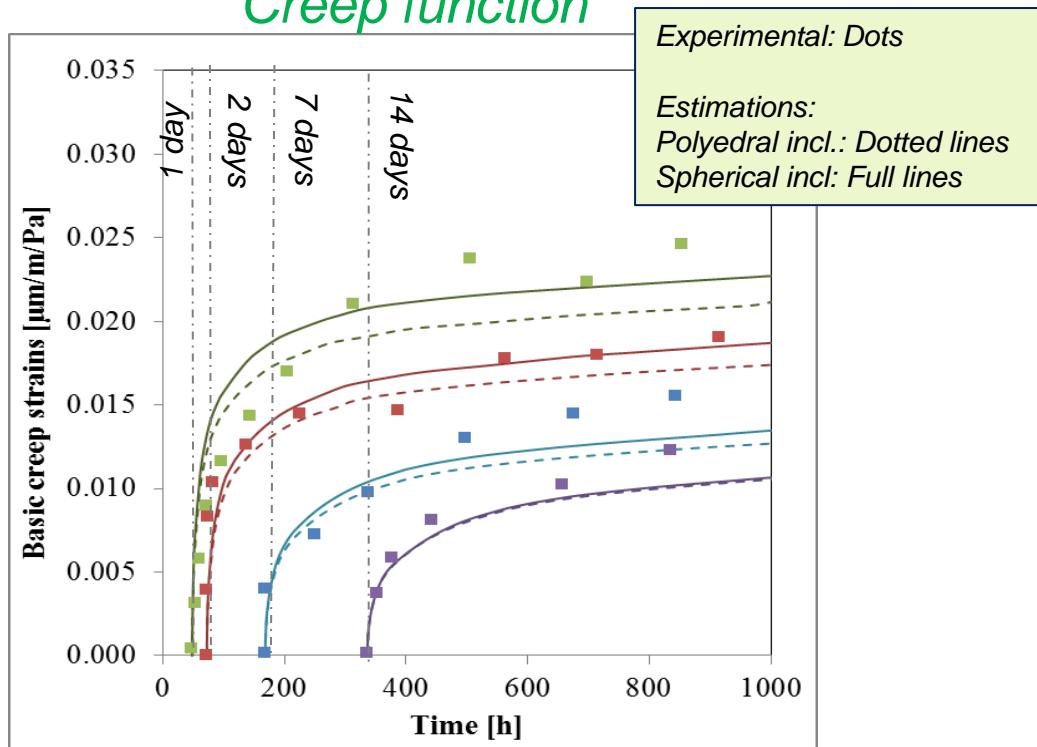
EFFECTIVE PROPERTIES OF CONCRETE

Creep function



With space-filling:
Ageing C-S-H behaviour

Creep function

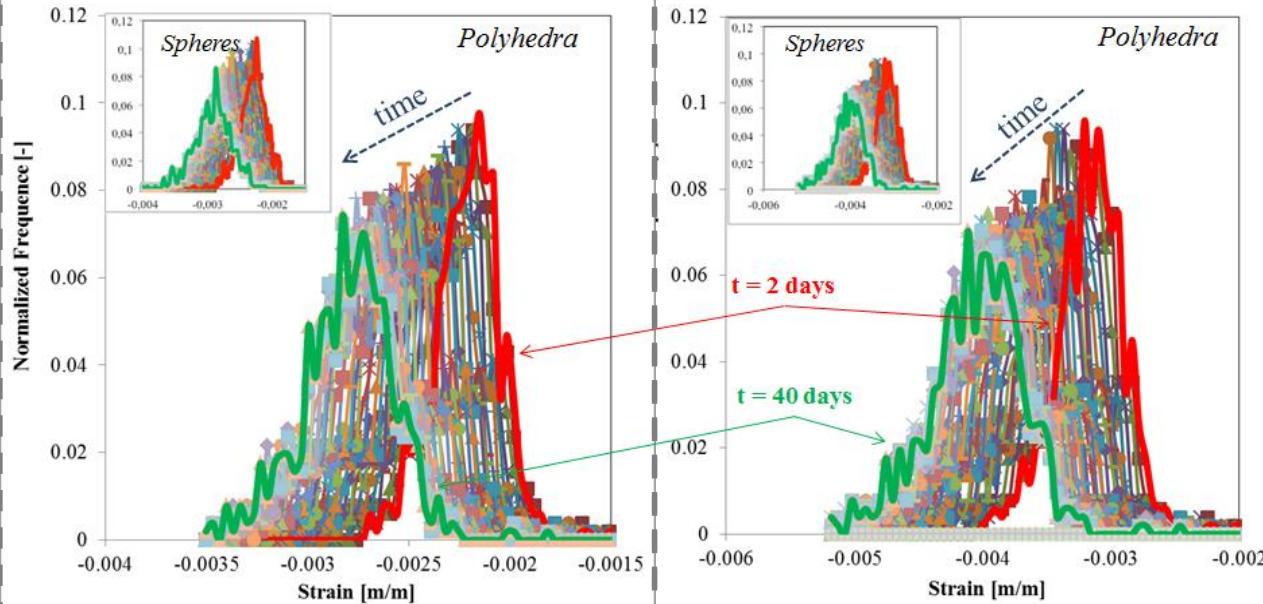


Non-ageing C-S-H behaviour:
NO space-filling

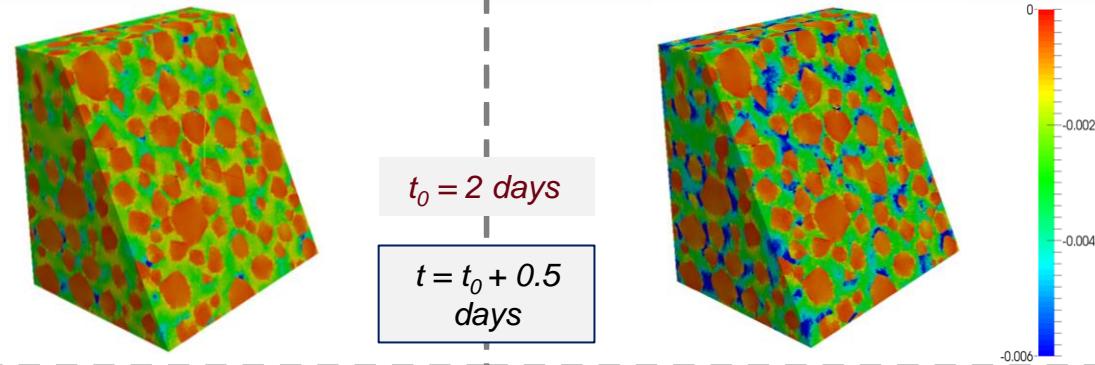
- Adequate estimations of basic creep
- Further investigations needed to compare behaviours with and without space-filling

Results

LOCAL INFORMATION

With space-filling:
Ageing C-S-H behaviourNon-ageing C-S-H behaviour:
NO space-filling

← Distribution of the uniaxial strain for the matrix: comparison between microstructures with spherical and Voronoi inclusions



← Strains (in the direction of the loading) within aggregates and mortar matrix

- Similar behaviour between both aggregates shapes
 - Larger dispersion of strains with time

CONCLUSIONS AND PERSPECTIVES

- Development of tool to estimate the evolution of ageing properties of concrete, especially the viscoelastic properties.
- Reasonable agreement between experimental and estimated viscoelastic properties at early-age
- Towards a better understanding of the mechanisms affect the mechanical behaviour at early-age

Perspectives:

- Multiscale experimental campaign: viscoelastic behaviour measures at cement past, mortar and concrete scales)
 - Inverse analysis: determine C-S-H behaviours; ITZ behaviour
- Formal treatment to define the coupled size and the boundary conditions effects in (ageing) linear viscoelasticity
- Robust thermodynamic derivation of thermal properties and a study about the dependency of the temperature

THANK YOU FOR YOUR ATTENTION



Acknowledgements

This present work has been performed as part of the project on disposal of LILW-SL that is carried out by ONDRAF/NIRAS, the Belgian Agency for Radioactive Waste and enriched Fissile Materials.

Peer reviewed journals

1. Honorio, T.; Bary, B. Benboudjema, F. *Evaluation of the contribution of boundary and initial conditions in the chemo-thermal analysis of a massive concrete structure.* **Engineering Structures** 80, 2014.
2. Honorio, T.; Bary, B. Benboudjema, F. *Factors affecting the thermo-chemo-mechanical behaviour of massive concrete structures at early-age.* **Materials and Structures**, 2015.
3. Honorio, T.; Bary, B; Benboudjema, F.; Poyet, S.. *Modelling hydration kinetics based on boundary nucleation and space-filling growth in a fixed confined zone.* **Cement and Concrete Research (accepted)**
4. Honorio, T.; Bary, B; Benboudjema, F. *Estimation of the effective properties of n-coated composite spheres assemblage in an ageing linear viscoelastic framework.* (**under review**)
5. Honorio, T.; Bary, B; Benboudjema, F. *Multiscale estimation of ageing viscoelastic properties of cement-based materials: a combined analytical and numerical approach to estimate the behaviour at early age.* (**under review**)
6. Honorio, T.; Bary, B; Benboudjema, F. *Multiscale estimation of thermal properties of cement-based materials at early-age.* (**manuscript in preparation**)

Conference papers

1. Honorio, T.; Bary, B.; Benboudjema, F. Multiscale estimation of the viscoelastic properties of cementitious materials at early age: a combined analytical and numerical approach. CONCREEP15, Wien, 2015.
2. Honorio, T. ; Bary, B.; Benboudjema, F. Estimation of elastic properties of cement based materials at early age based on a combined numerical and analytical multiscale micromechanics approach. CONMOD, Beijing, 2014
3. Honorio, T.; Bary, B.; Benboudjema, F. Influence of the particle size distribution on hydration kinetics: a mechanistic analytical approach. CONMOD, Beijing, 2014
4. Honorio, T.; Bary, B.; Benboudjema, F. Analysis of the thermo-chemo-mechanical behavior of massive concrete. EURO-C, St Anton am Arlberg, 2014
5. Honorio, T.; Bary, B.; Benboudjema, F. Modélisation de l'hydratation basée sur la cinétique de nucléation et de croissance. AUGC, Cachan, 2013 (French)
6. Honorio, T. ; Bary, B. Benboudjema, F. Modeling hydration kinetics : the influence of particle size distribution and inert additions. Poster, Workshop Strains induced by phase change in porous solids. ENPC, 2013