Concrete poromechanics

Implementation of a hygro-thermo-viscoelastic-damage formulation in Cast3M

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Club Cast3M, 24 November 2023

université de BORDEAUX

UGA Université Grenoble Alpes

IUF institut universitaire de France

Multi-physics modeling of concrete behavior

Early ages behavior

Aging

Accident

Proposition of an unified formulation

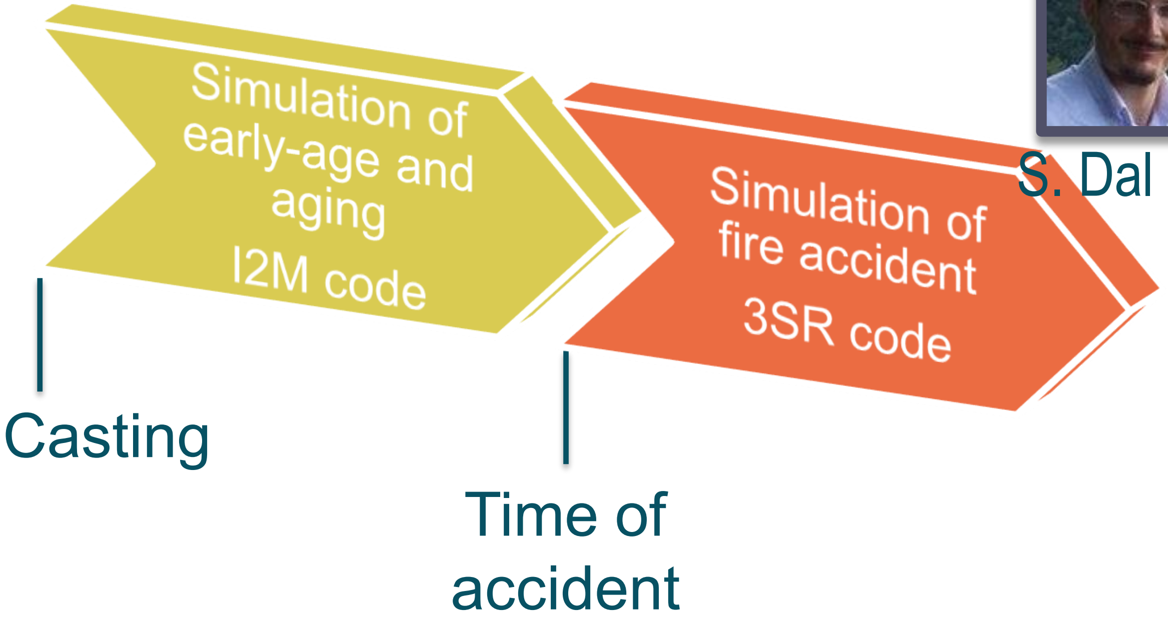
What is the initial HTM state of the specimen?

Initial idea:

Sequential solution

Problems

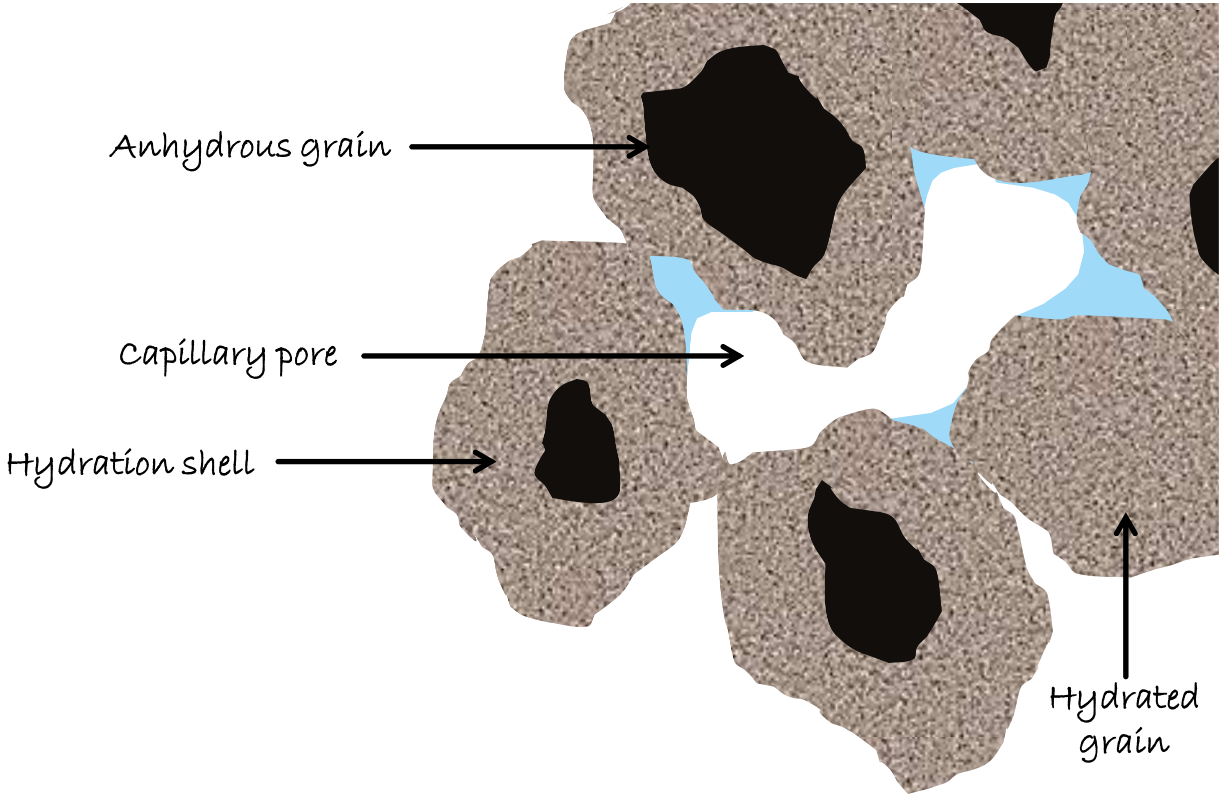
- Early-age / aging solution no totally compatible as initial condition;
- Not practical methodology.



S. Dal Pont

Alternative:

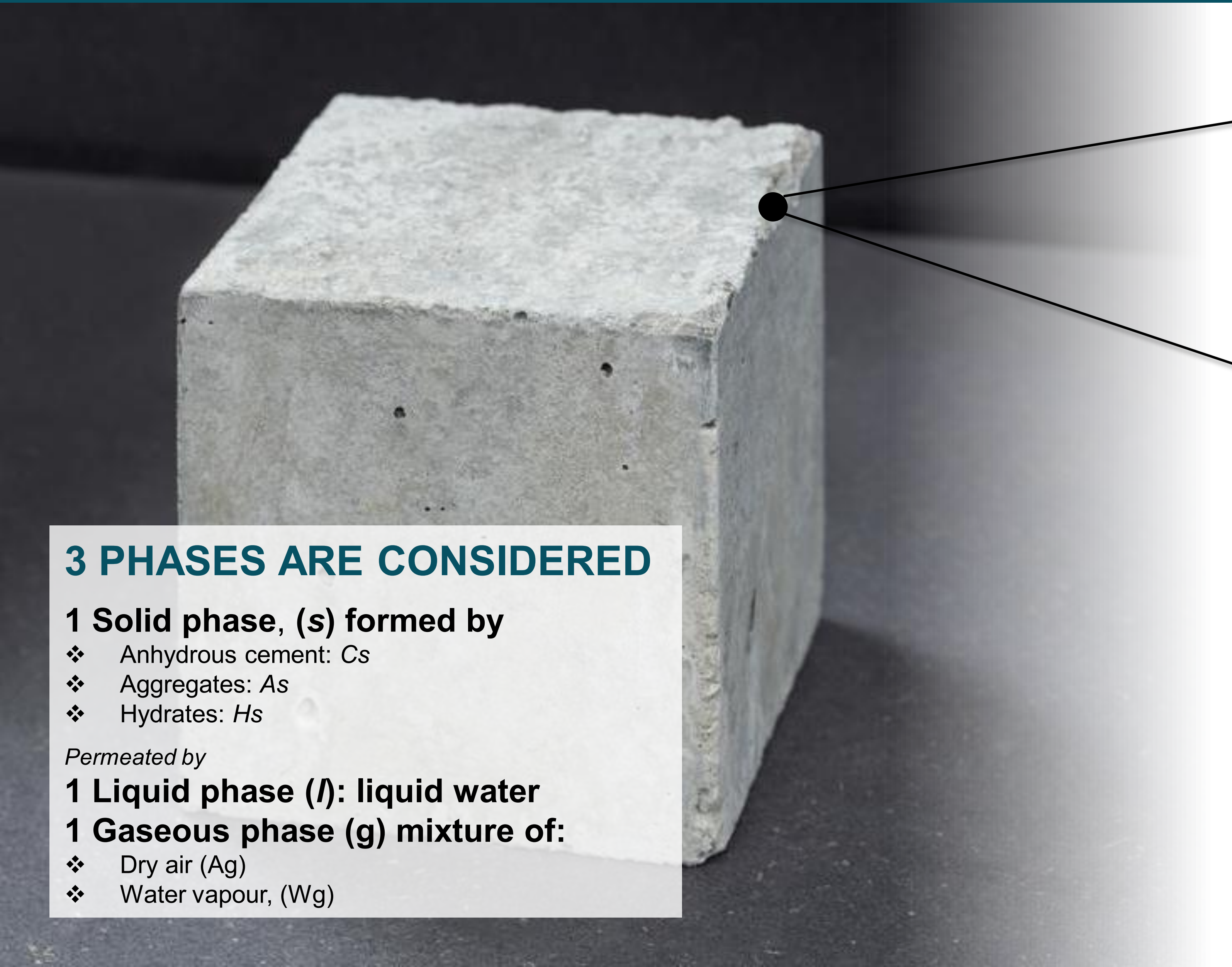
Development of a **unified mathematical model** accounting for early age, aging and high temperature behavior; The task has been realized with care (no just merging the two codes) to obtain a compact and consistent physical model for concrete

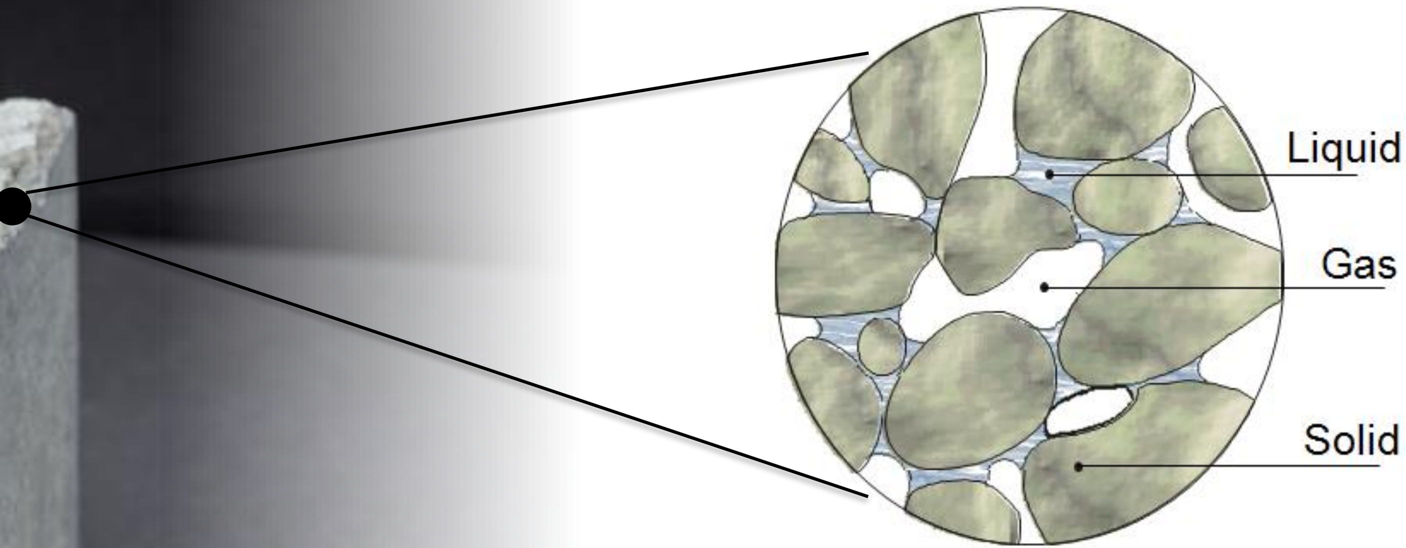


The multiphase system

- Definition of phases & governing equations

Micro → Macro approach *via* averaging theories





Representative Elementary Volume **(REV)**

3 PHASES ARE CONSIDERED

1 Solid phase, (*s*) formed by

- Anhydrous cement: *Cs*
- Aggregates: *As*
- Hydrates: *Hs*

Permeated by

1 Liquid phase (*l*): liquid water

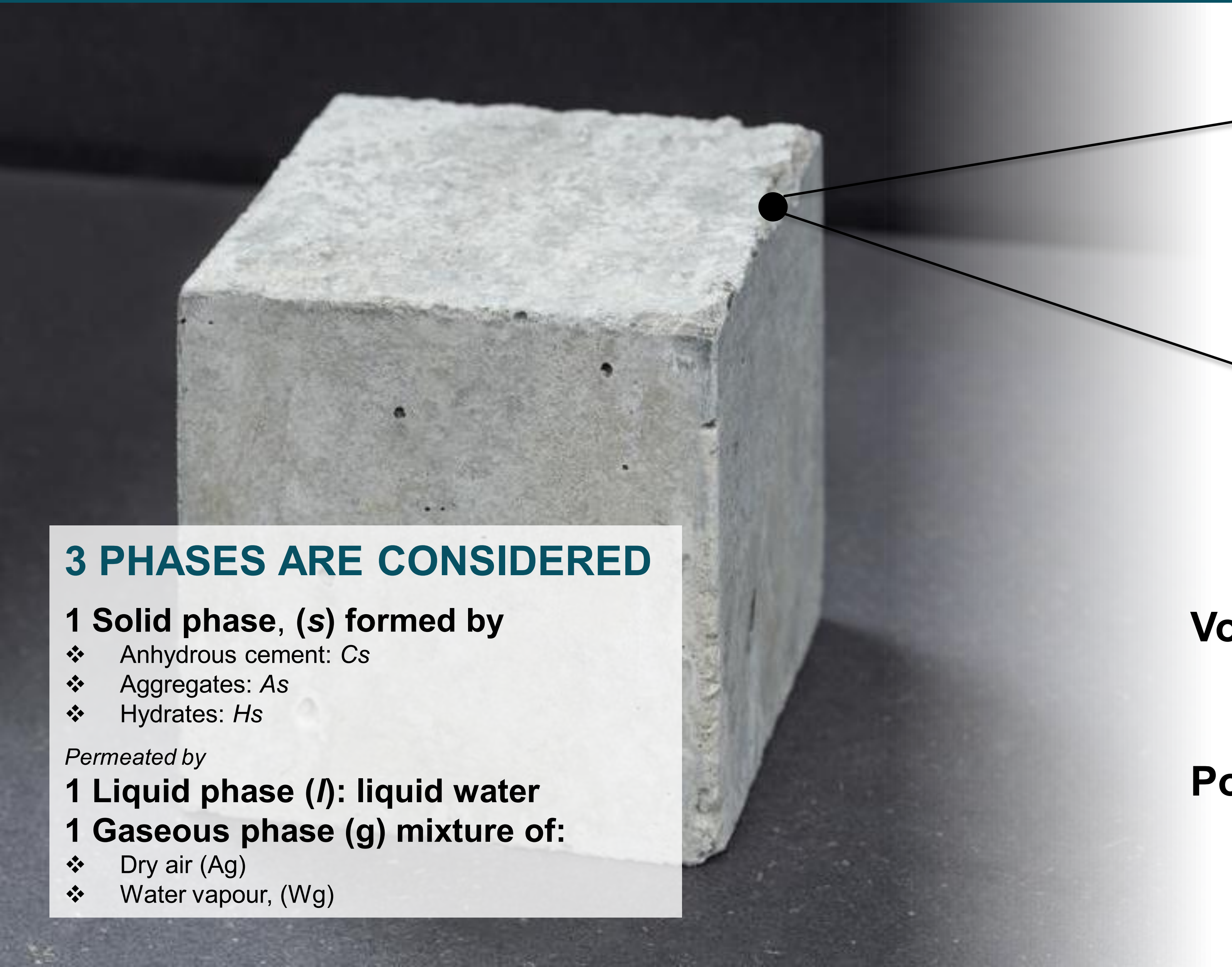
1 Gaseous phase (g) mixture of:

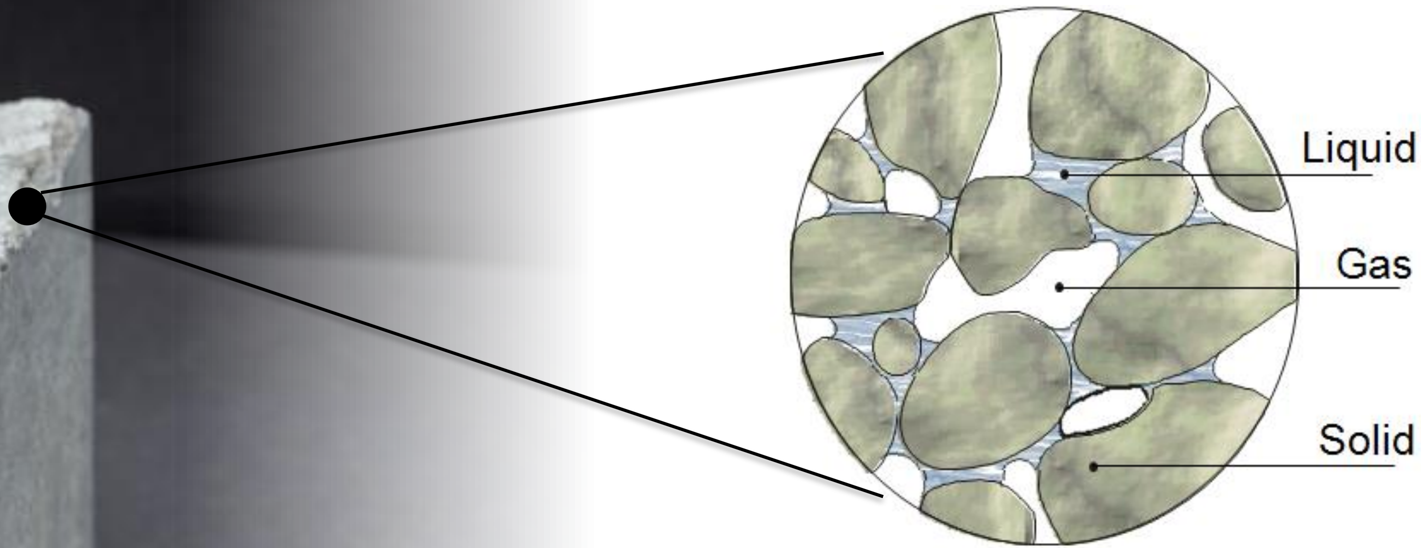
- Dry air (Ag)
- Water vapour, (Wg)

Reference approach of

Gawin, Pesavento & Schrefler

Micro → Macro approach *via* averaging theories





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Volume Fractions **occupied by the three phases:**

$$\varepsilon^s + \varepsilon^g + \varepsilon^l = 1$$

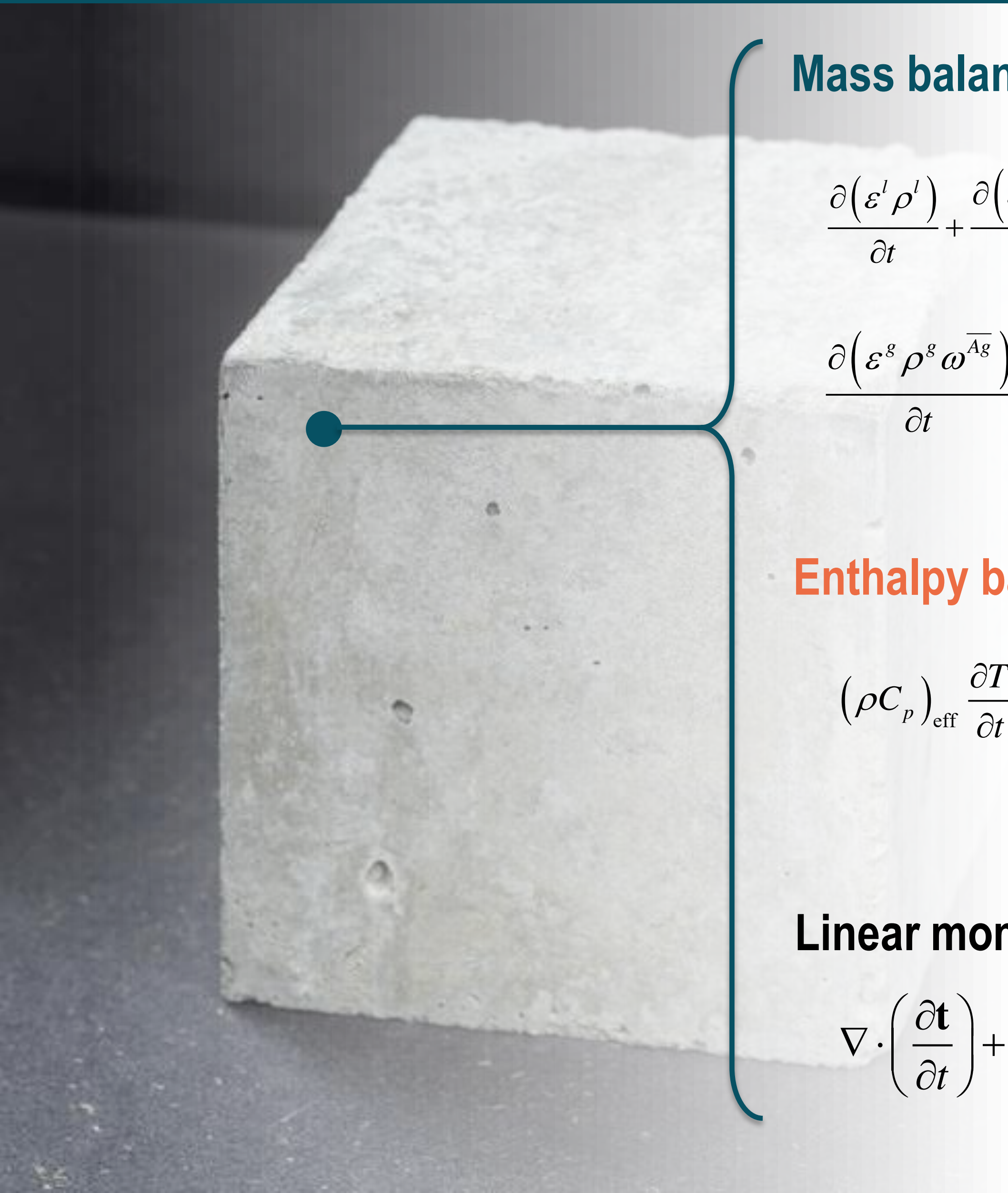
Porosity & Saturation: $S^g + S^l = 1$

$$\varepsilon^s = 1 - \varepsilon \qquad \varepsilon^l = \varepsilon S^l \qquad \varepsilon^g = \varepsilon S^g$$

Hypotheses and adopted physical laws

- **Gaseous phase** is a **binary mixture of vapour and dry air ;**
- The gaseous phase, vapour and dry air are **perfect gazes** ;
- **Dalton's law** is assumed valid: $p^{gA} + p^{gW} = p^{g}$;
- **Clapeyron law** is used (Kelvin's eqn not suitable due to fluctuations of p^{g})

Governing equations



Mass balance eqs (water species, dry air)

$$\frac{\partial(\varepsilon^l\rho^l)}{\partial t}+\frac{\partial(\varepsilon^g\rho^g\omega^{\overline{Wg}})}{\partial t}-\nabla\cdot\left[\rho^l\frac{k^l_{rel}\mathbf{k}}{\mu^l}\nabla(p^g-p^c)\right]-\nabla\cdot\left(\rho^{gW}\frac{k^g_{rel}\mathbf{k}}{\mu^g}\nabla p^g\right)-\nabla\cdot\left[\rho^g\frac{M_AM_W}{M_g^2}D^{\overline{Wg}}\nabla\left(\frac{p^{gW}}{p^g}\right)\right]=-\overset{l\to Hs}{M}$$

$$\frac{\partial(\varepsilon^g\rho^g\omega^{\overline{Ag}})}{\partial t}-\nabla\cdot\left(\rho^{gA}\frac{k^g_{rel}\mathbf{k}}{\mu^g}\nabla p^g\right)+\nabla\cdot\left[\rho^g\frac{M_AM_W}{M_g^2}D^{\overline{Wg}}\nabla\left(\frac{p^{gW}}{p^g}\right)\right]=0$$

Sink/source term due to cement hydration/dehydration

Enthalpy balance eqn

$$(\rho C_p)_{\mathrm{eff}}\frac{\partial T}{\partial t}-\nabla\cdot(\chi_{\mathrm{eff}}\nabla T)=L_{hydr}\frac{\mathrm{d}\Gamma}{\mathrm{d}t}+H_{vap}\frac{\partial(\varepsilon^l\rho^l)}{\partial t}+H_{vap}\overset{l\to Hs}{M}-H_{vap}\nabla\cdot\left[\rho^l\frac{k^l_{rel}\mathbf{k}}{\mu^l}\nabla(p^g-p^c)\right]$$

Heat released/absorbed

Terms related to evaporation/condensation

Linear momentum balance equation:

$$\nabla\cdot\left(\frac{\partial\mathbf{t}}{\partial t}\right)+\frac{\partial\rho}{\partial t}\mathbf{g}=0$$

Primary variables: p^g p^c T $\mathbf{u}$
Int. variables: Γ D

Originalities *with respect to the reference model of Gawin et al.*

- Unified model for hydration / fire dehydration;
- Explicit introduction of Powers model. This reduce model complexity and parameters;
- New retention curve accounting for changes of microstructure and water surface tension;
- Autogenous and drying shrinkage finely computed with a sole constitutive model based on effective stress principle;
- Mechanical viscoelastic-damage model

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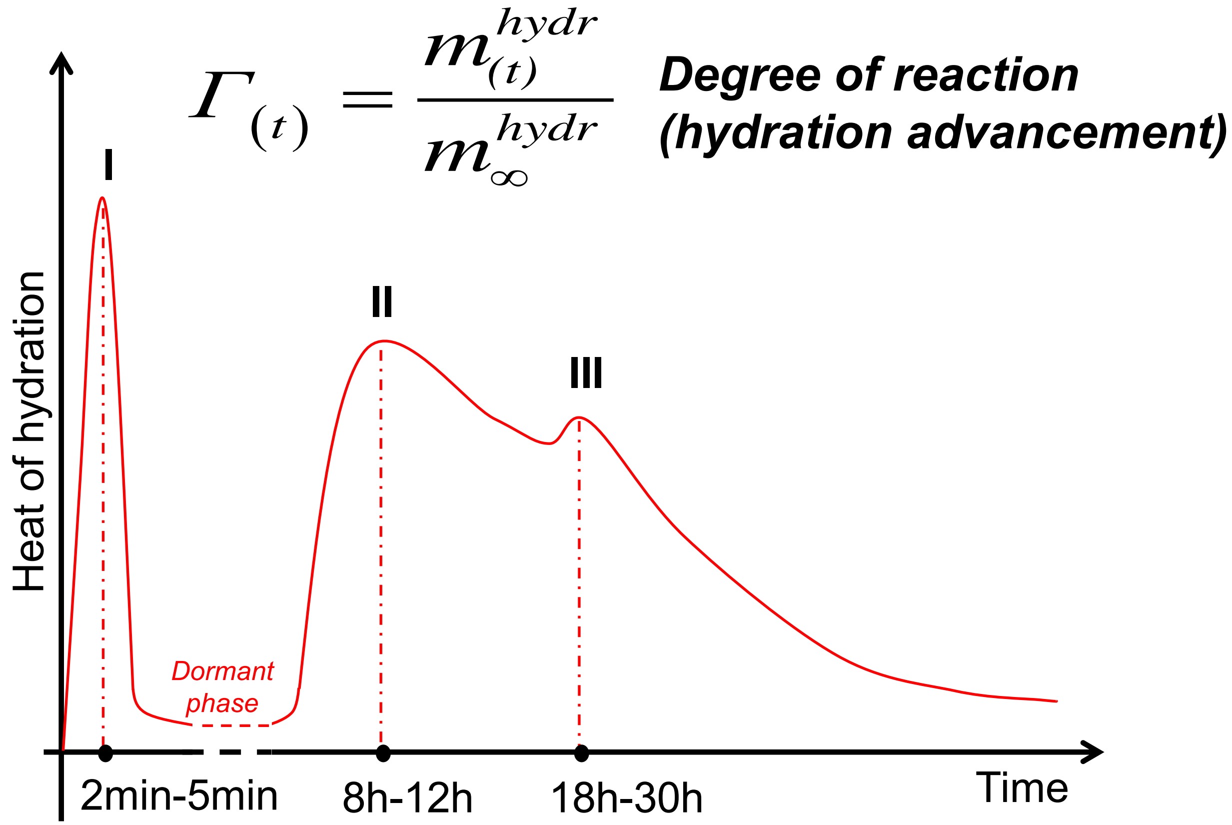


Unified model for hydration / fire dehydration

- The hydration degree is an internal variable of the model

The hydration & dehydration model

$$\tilde{\Gamma} = (1 - \mathrm{F})\Gamma$$

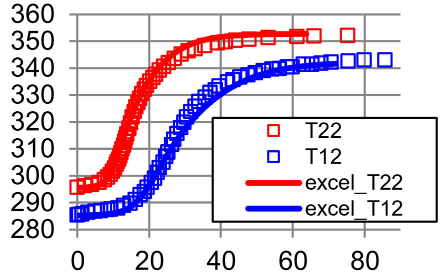
Hydration: Arrhenius type eqn

$$\frac{\mathrm{D}^s \Gamma}{\mathrm{D}t} = A_{(\Gamma)} \beta_{(h)} \exp\left(-\frac{E_a}{RT}\right)$$

Fire dehydration: Gawin et al. 2011

$$F(T) = \begin{cases} 0 & \text{for } T \leq T_d = 378.15 \ K \\ a_3 (T - T_d)^3 + a_2 (T - T_d)^2 + a_1 (T - T_d) & \text{for } T > T_d \end{cases}$$

Adiabatic Calorimetry



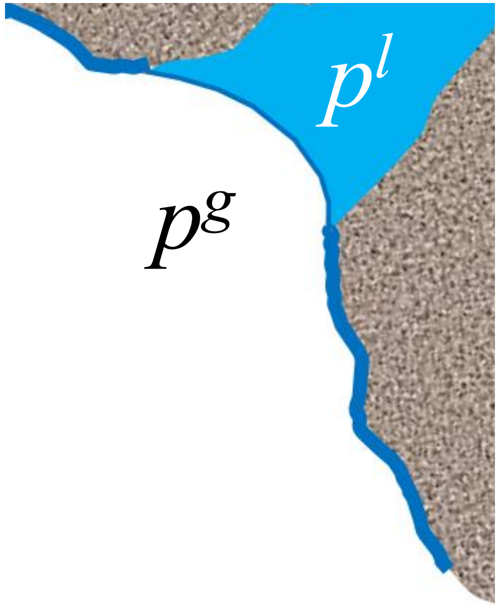
Coupled evolution model

(equivalent hydr. degree) :

$$\frac{\mathrm{D}^s \tilde{\Gamma}}{\mathrm{D}t} = \underbrace{(1 - F)\frac{\mathrm{D}^s \Gamma}{\mathrm{D}t}}_{\text{Hydration}} - \underbrace{\Gamma \frac{\mathrm{D}^s F}{\mathrm{D}t}}_{\text{Fire dehydration}}$$

Irreversibility of fire dehydration:

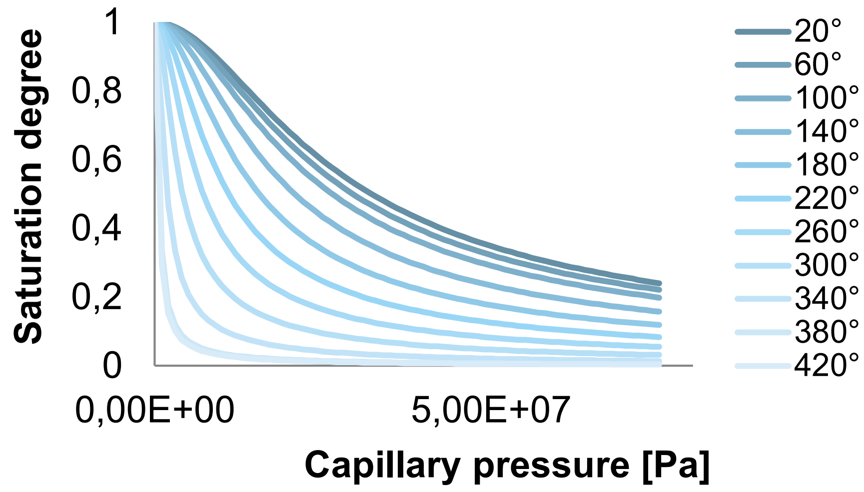
$$\frac{\mathrm{D}^s F}{\mathrm{D}t} = \begin{cases} \frac{\partial F(T)}{\partial T} \left\langle \frac{\mathrm{D}^s T}{\mathrm{D}t} \right\rangle_+ & \text{for } T(t) \geq T_{\max}(t) \\ 0 & \text{for } T(t) < T_{\max}(t) \end{cases}$$

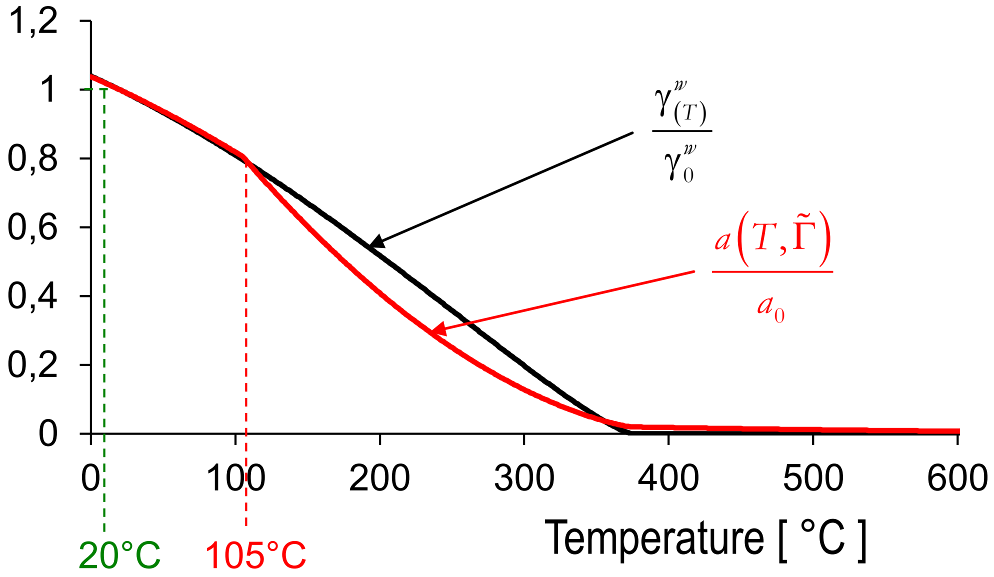


$p^c - S^l$ relationship

- An unified eqn for a reliable coupling between hydrates formation/degradation & water physics

$p^c - S^l$ relationship: the dehydration process





$$S^l = \left[\left(\frac{p^c}{a\left(T, \tilde{\Gamma}\right)} \right)^{\frac{b}{b-1}} + 1 \right]^{-\frac{1}{b}}$$

$$a\left(T,\tilde{\Gamma}\right) = a_0 \left(\frac{\tilde{\Gamma} + 0.1}{1.1} \right)^c \frac{\gamma^w_{(T)} + 0.05\gamma^w_0}{1.05\gamma^w_0}$$

An unified eqn for a reliable coupling between hydrates formation/degradation & water physics

$p^c - S^l$ relationship: the dehydration process

Previous law

$$S = \left[\left(\frac{E}{a} p^c \right)^{\frac{b}{b-1}} + 1 \right]^{(-1/b)}$$

$$a = \text{constant} \quad \text{if } T \leqslant 100^\circ\text{C},$$
$$a = (Q_3 - Q_2)\left[2\left(\frac{T - T_b}{T_{crit} - T_b}\right)^3 - 3\left(\frac{T - T_b}{T_{crit} - T_b}\right)^2 + 1 \right] + Q_2 \quad \text{if } T > 100^\circ\text{C}$$

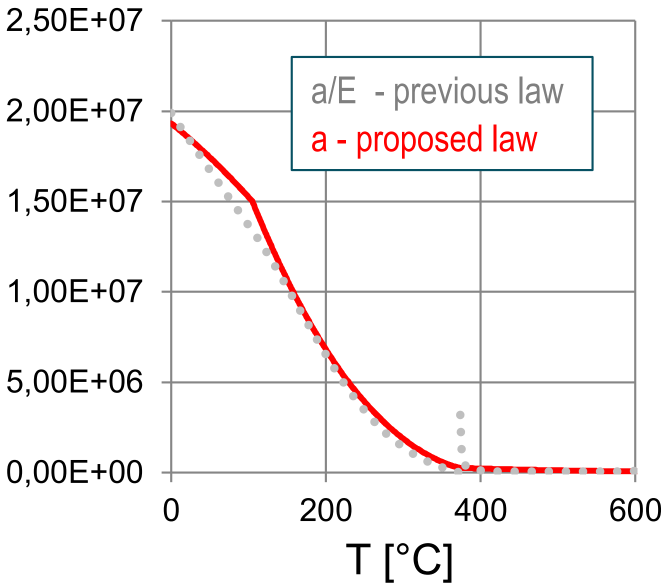
Effect of solid cement matrix dehydration

$$E = \left[\frac{T_{crit} - T_0}{T_{crit} - T}\right]^N \quad \text{if } T < T_{crit},$$
$$E = \frac{N}{z} E_0 T + \left[E_0 - \frac{N}{z} E_0 (T_{crit} - z) \right] \quad \text{if } T \geqslant T_{crit},$$

Effect of temperature on surface tension of water

Extension of Van Genuchten model
(in which E_0 = *1* and *a* = a_0 = *const.*)

Giannuzzi (2000) - ENEA private communication



$$S^l = \left[\left(\frac{p^c}{a(T, \tilde{\Gamma})} \right)^{\frac{b}{b-1}} + 1 \right]^{-\frac{1}{b}}$$

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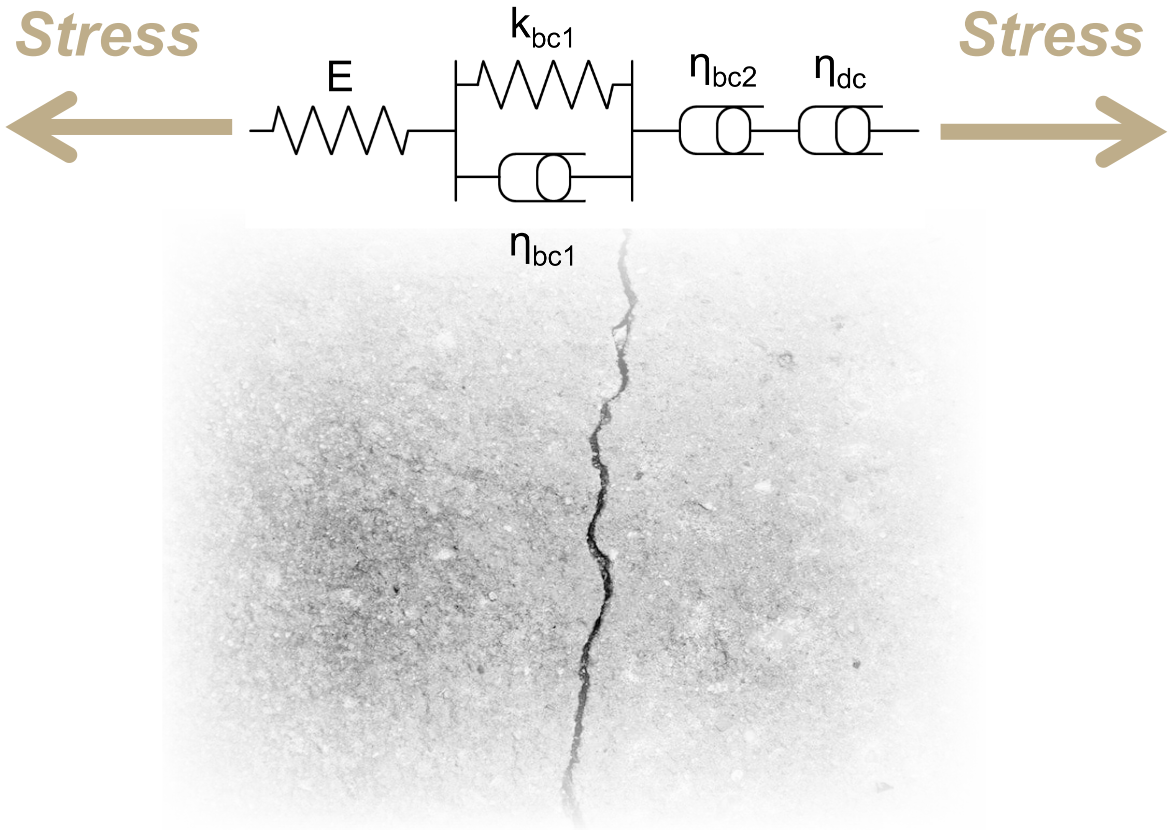
An unified eqn for a reliable coupling between hydrates formation/degradation & water physics

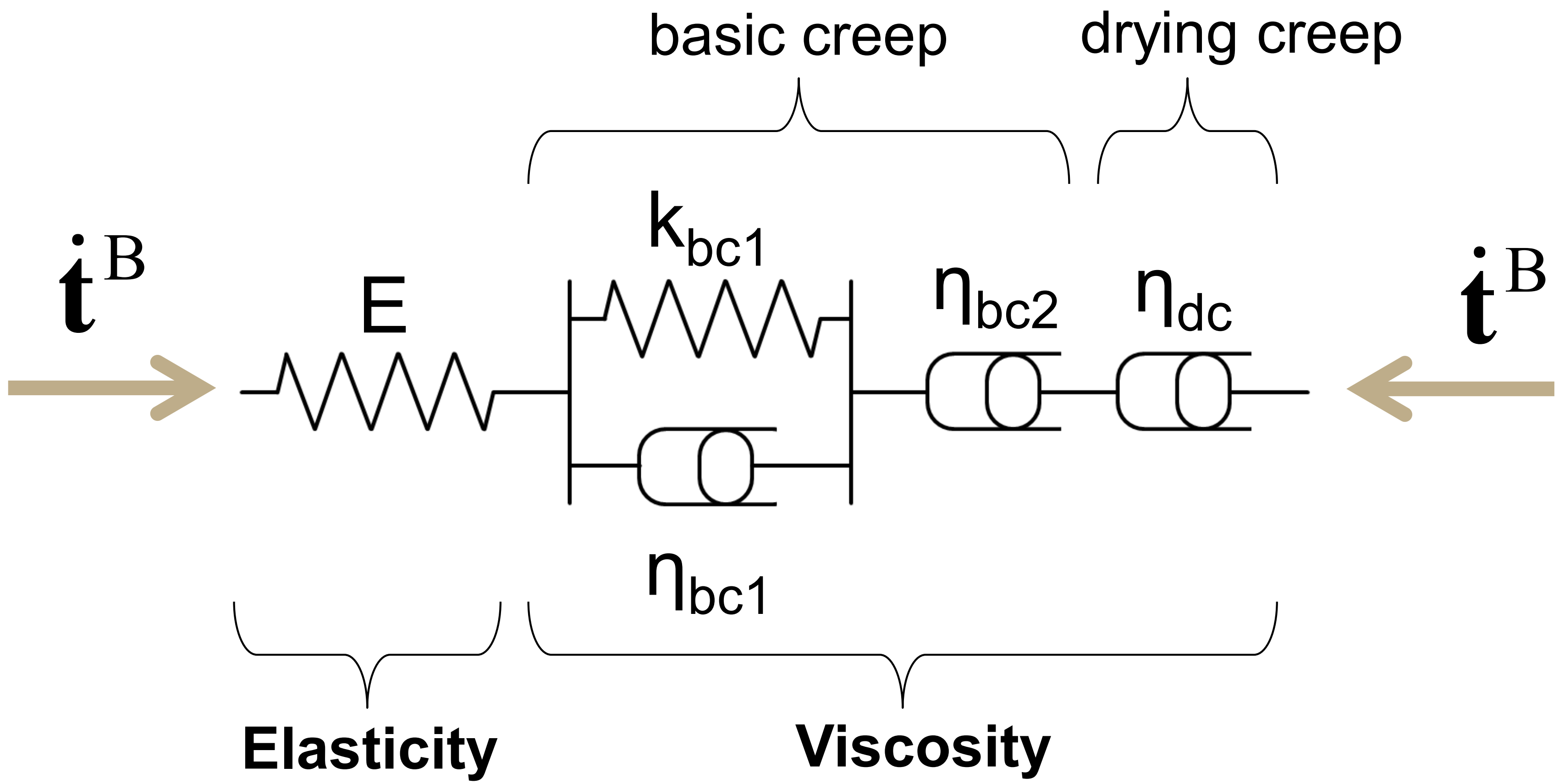
Big advantage:
irreversibility of matrix dehydration properly accounted



Mechanical viscoelastic-damage model

- Accounting for hydration degree and hygro-thermal strains

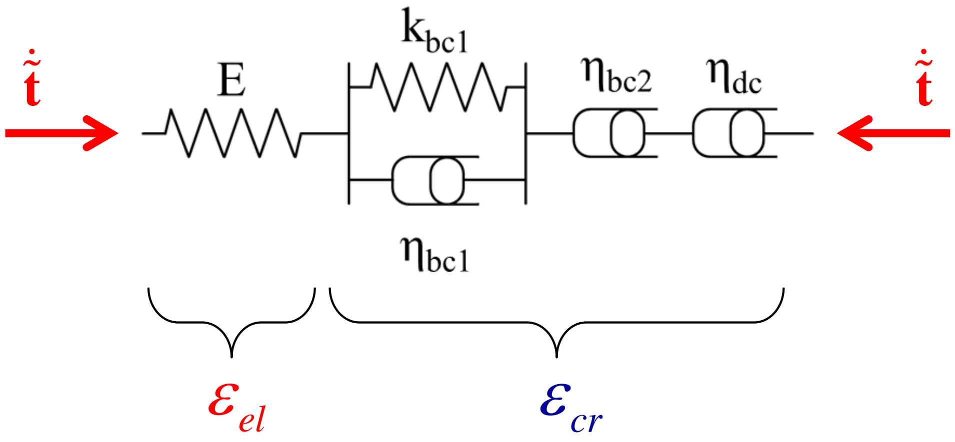
Biot's effective stress: $\dot{\mathbf{t}}^{\mathrm{B}} = \dot{\tilde{\mathbf{t}}} + \alpha\, \dot{p}^{s}\, \mathbf{1}$



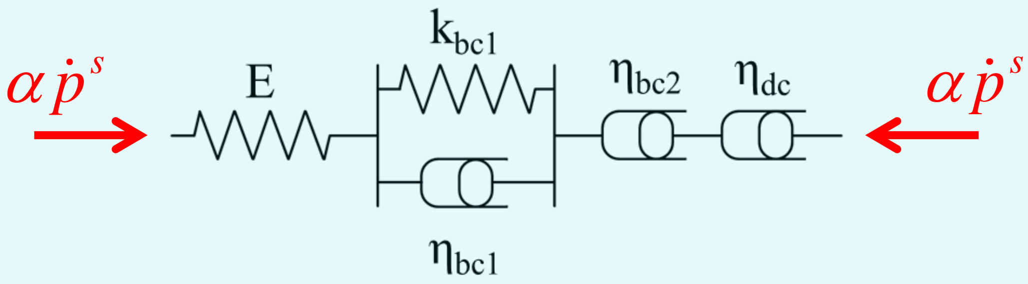
Biot's effective stress: $\dot{\mathbf{t}}^{B} = \dot{\tilde{\mathbf{t}}} + \alpha \dot{p}^{s} \mathbf{1}$

$\tilde{\mathbf{t}}$ is the real stress (in the sense of damage mechanics):

$$\mathbf{t} = (1 - D)\tilde{\mathbf{t}}$$



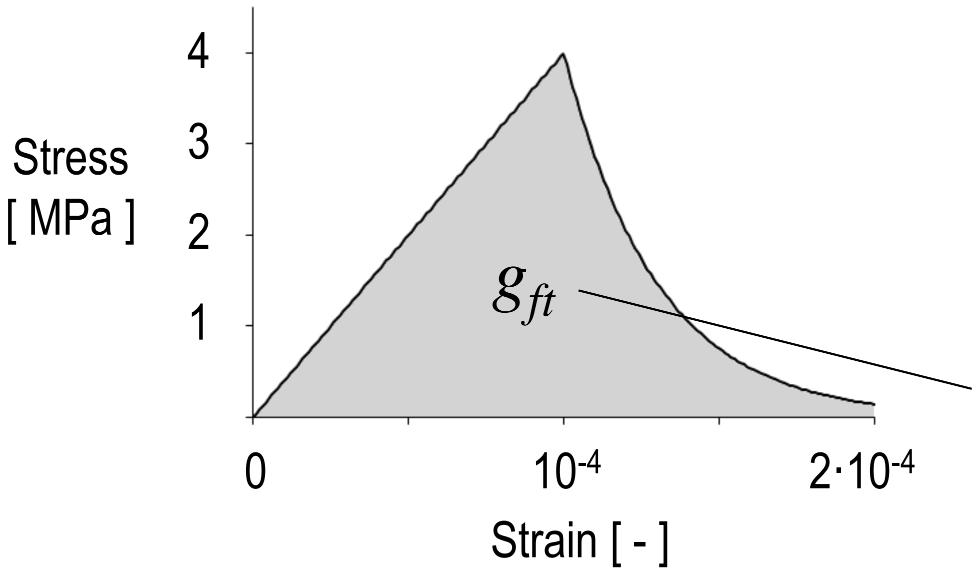
Shrinkage computed consistently with the effective stress principle of porous media mechanics.



$$\dot{\tilde{\mathbf{t}}} = \mathbf{E}_{(\Gamma)} \dot{\boldsymbol{\varepsilon}}_{el} = \mathbf{E}_{(\Gamma)} \left(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}_{th} - \dot{\boldsymbol{\varepsilon}}_{cr} - \dot{\boldsymbol{\varepsilon}}_{sh} \right)$$

The damage model

Tensile branch of the t-e relationship



$$D = 1 - \frac{\varepsilon_0}{\hat{\varepsilon}} \exp\left[-B_t\left(\hat{\varepsilon} - \varepsilon_0\right)\right]$$

$$\mathbf{t} = \left(1 - D\right)\tilde{\mathbf{t}}$$

$$g_{ft} = \int_0^\infty t\,d\varepsilon = f_t\left(\frac{\varepsilon_0}{2} + \frac{1}{B_t}\right) \qquad \left[\frac{\mathrm{N}}{\mathrm{m}^2}\right]$$

Regularization

$$g_{ft} = \frac{G_{ft}}{l_c}$$

G_{ft}: fracture energy

l_c: finite element characteristic length

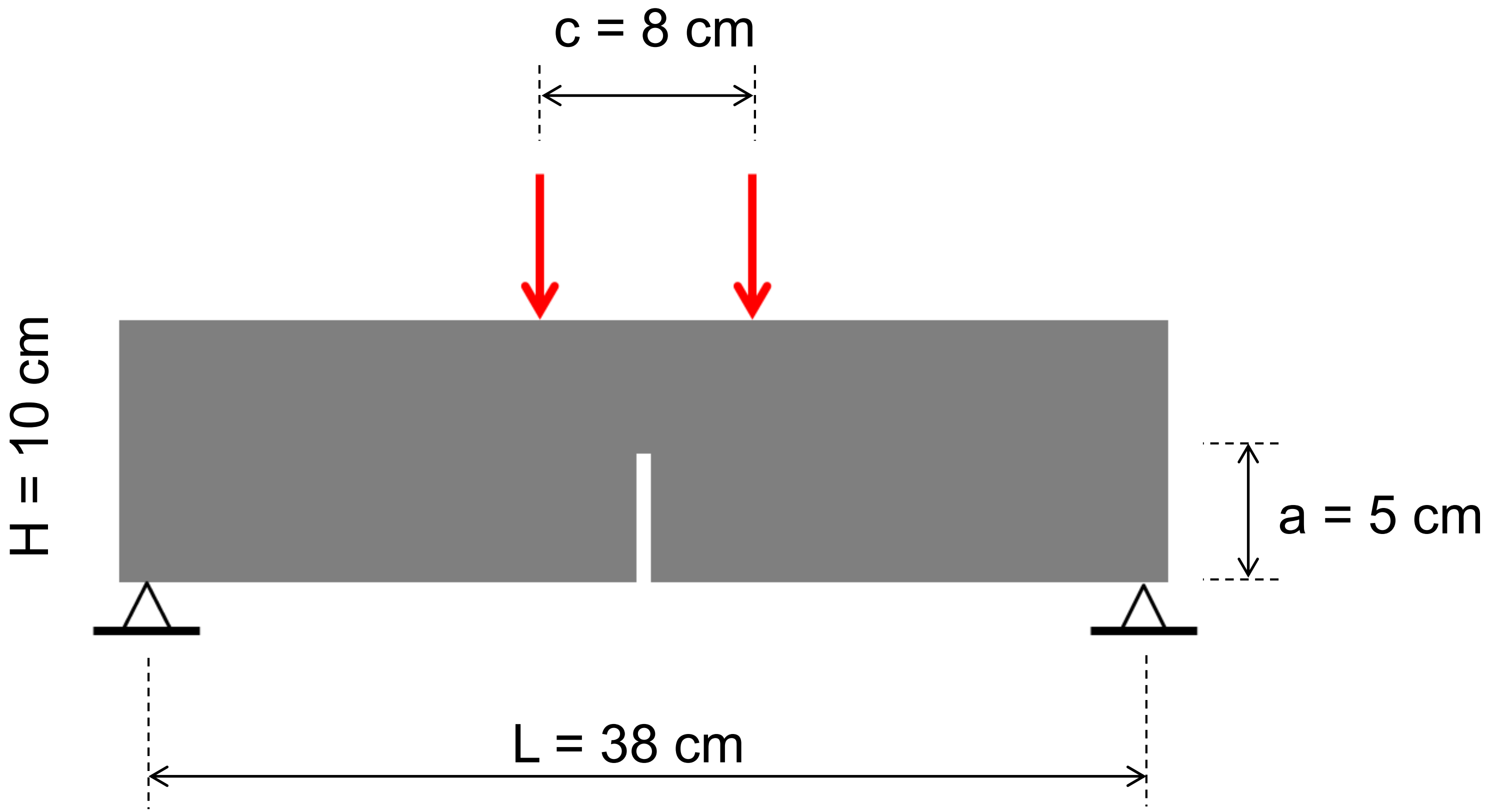
$$B_t = \frac{f_t}{G_{ft} - \frac{f_t^2}{2E} l_c} l_c$$

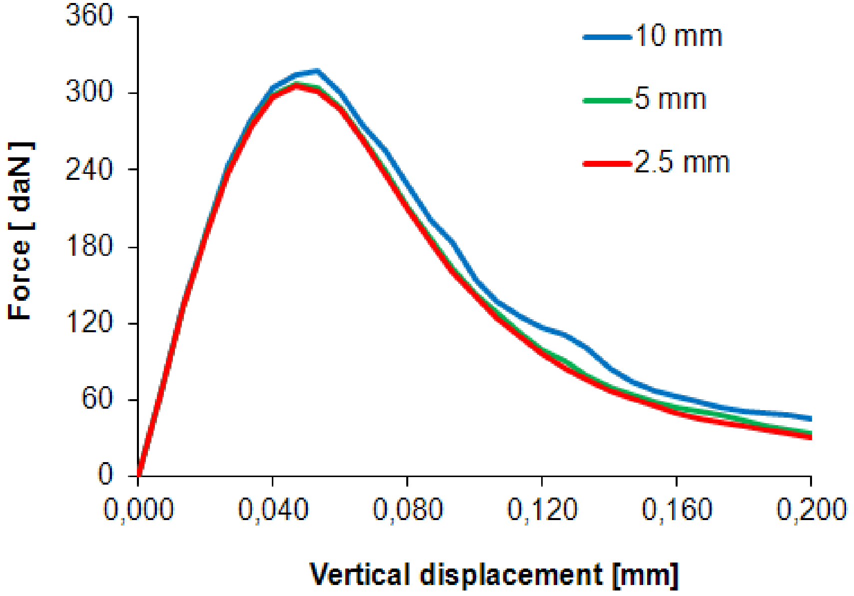
Equivalent strain

$$\hat{\varepsilon} = \sqrt{\left\langle \boldsymbol{\varepsilon}_{el} \right\rangle_+ : \left\langle \boldsymbol{\varepsilon}_{el} \right\rangle_+ + \psi \left\langle \boldsymbol{\varepsilon}_{cr} \right\rangle_+ : \left\langle \boldsymbol{\varepsilon}_{cr} \right\rangle_+}$$

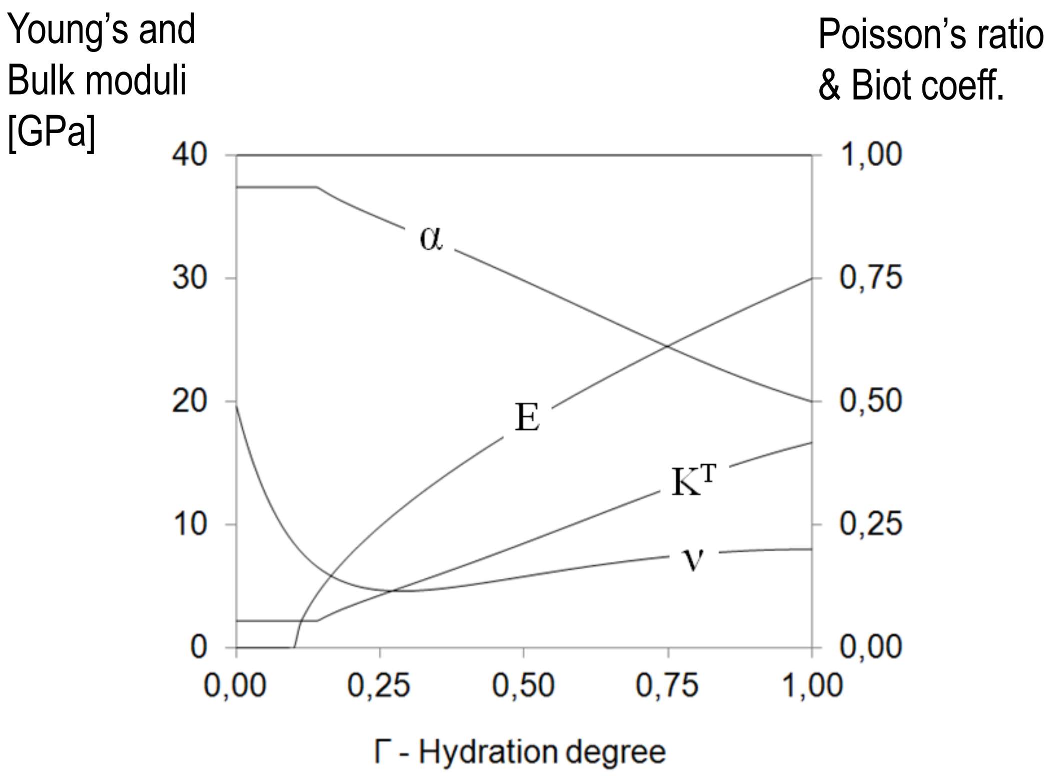
The damage model

Four points bending test



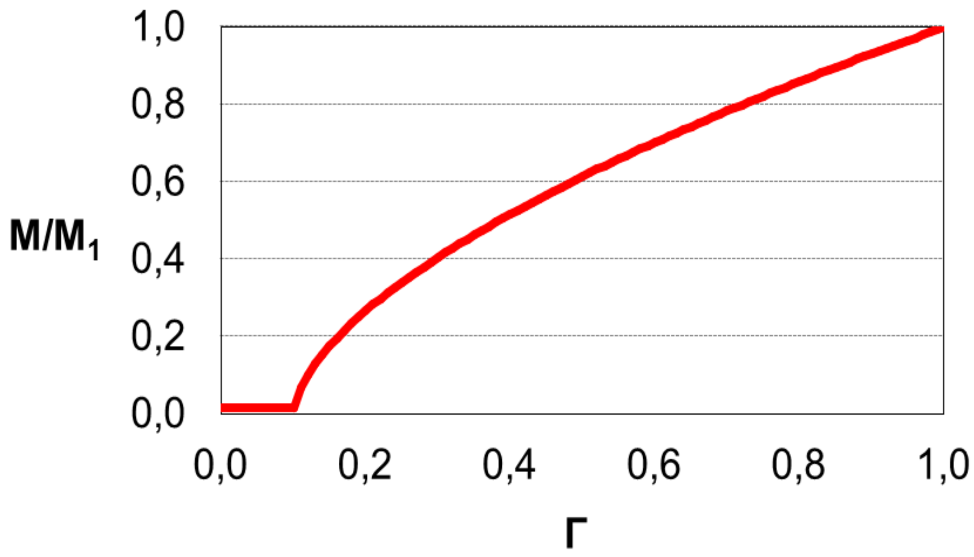


Mechanical properties *vs* hydration degree



De Schutter type equation:

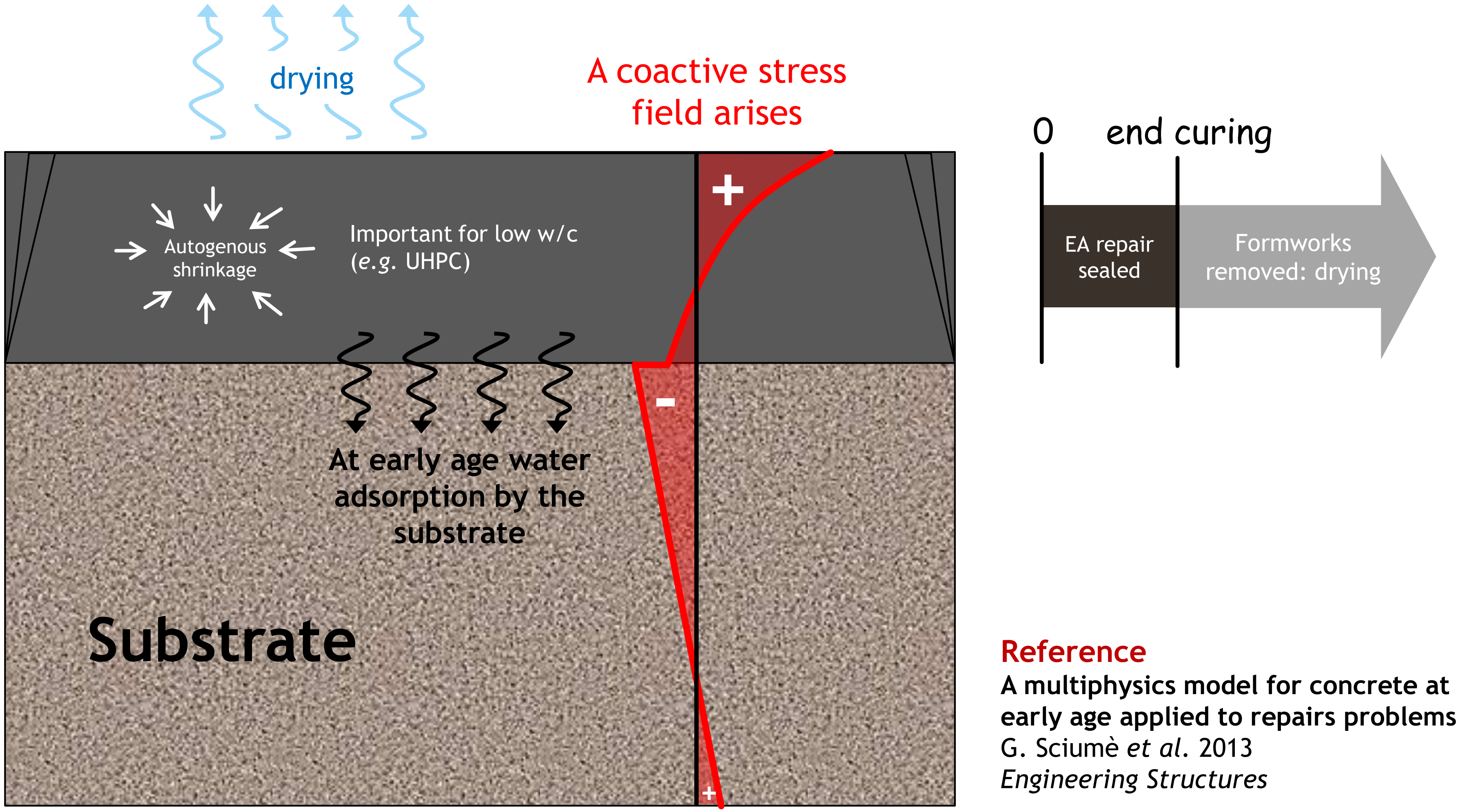
$$\frac{M(\Gamma)}{M_1} = \left\langle \frac{\Gamma - \Gamma_0}{1 - \Gamma_0} \right\rangle_+^{\gamma_M}$$



Applications cases

- Modeling of a repaired beam
- Wall exposed to high temperature

Modeling of a repaired beam



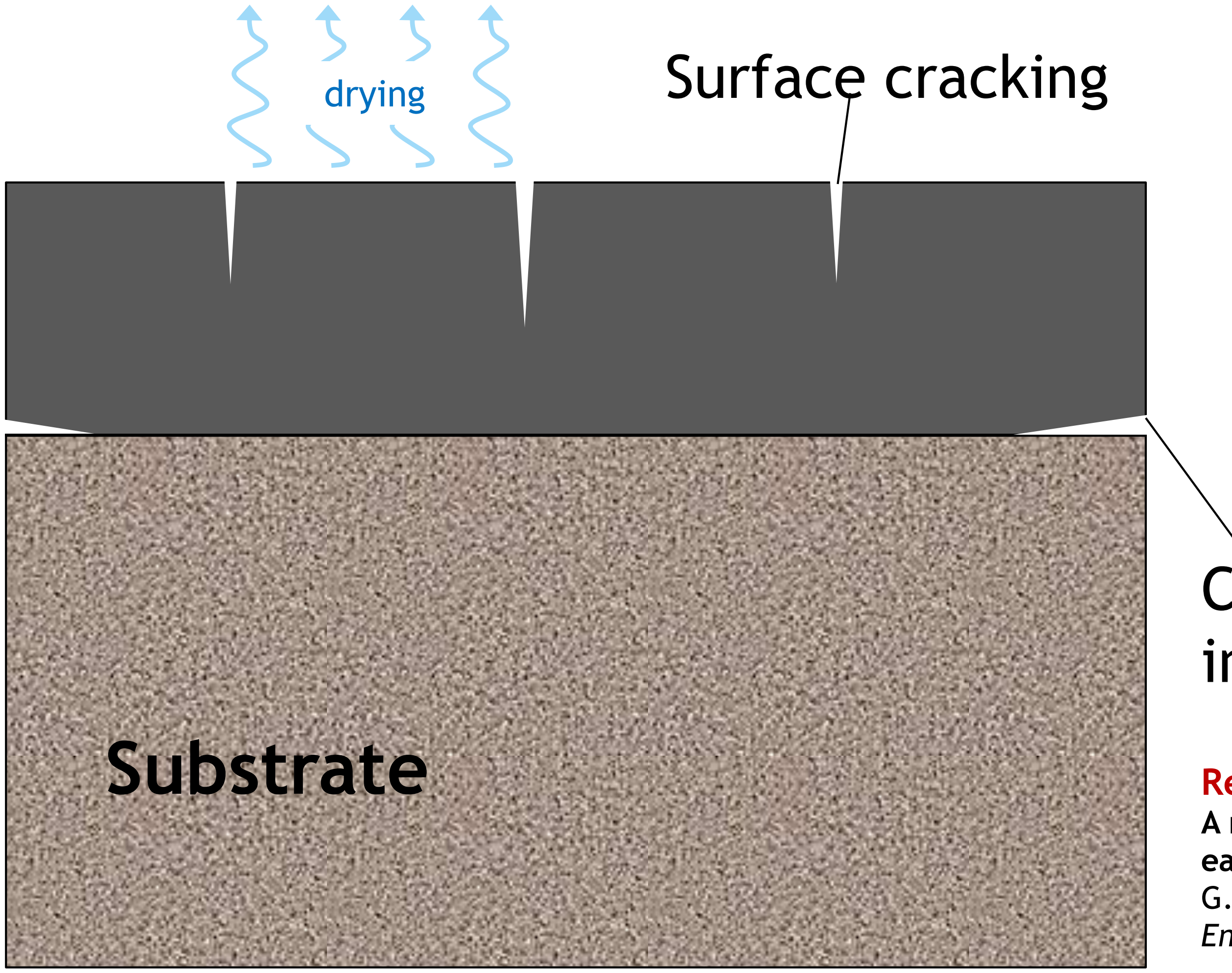
Reference

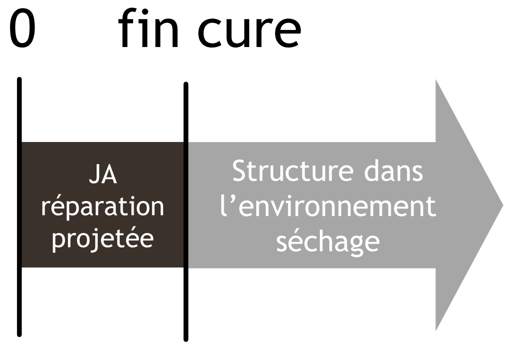
A multiphysics model for concrete at early age applied to repairs problems

G. Sciumè *et al.* 2013

Engineering Structures

Modeling of a repaired beam





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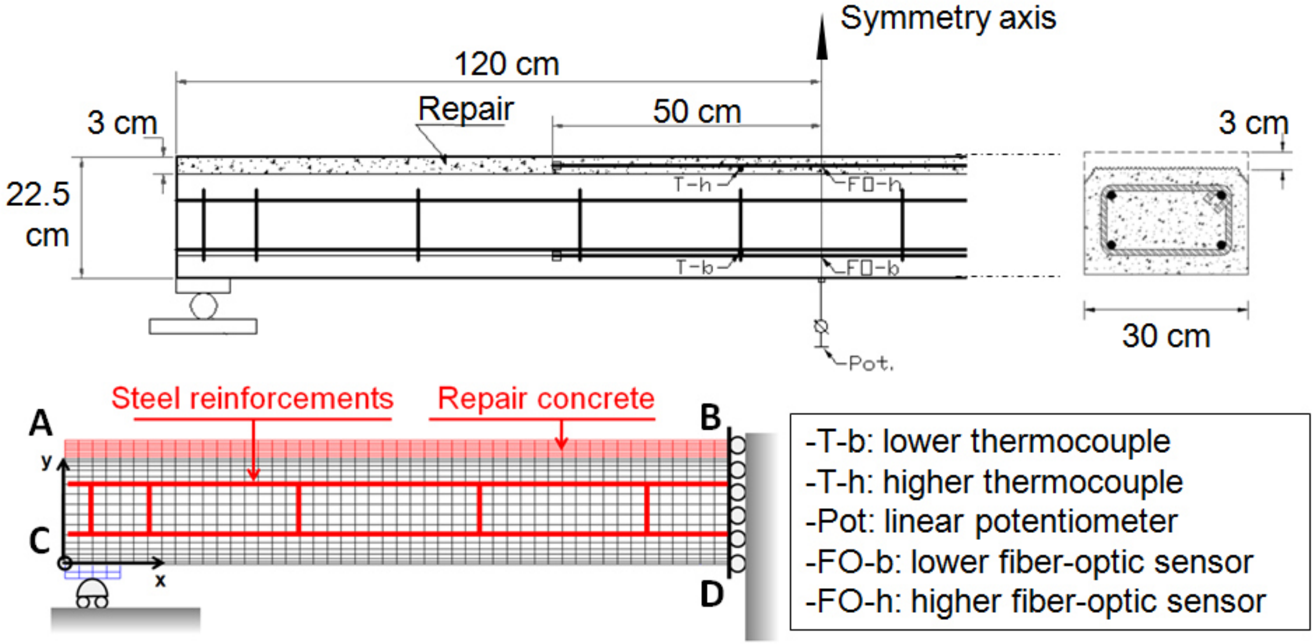


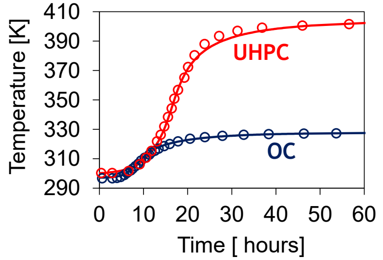
Three identical reinforced beams* are considered. Two of these beams, after the hydrodemolition of 30 mm of the upper part, had been repaired: one using the **ordinary concrete (OC)** and the other using the **ultra-high performance fiber reinforced concrete (UHPC).** The third beam is the reference specimen.

***These repaired beams are real cases analyzed experimentally by Bastien Masse (2010).**

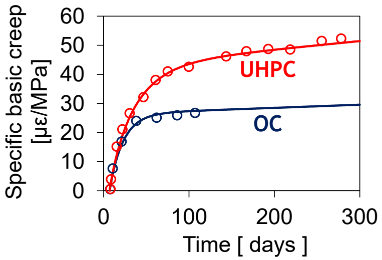
Modeling of a repaired beam

Identification of the input parameters

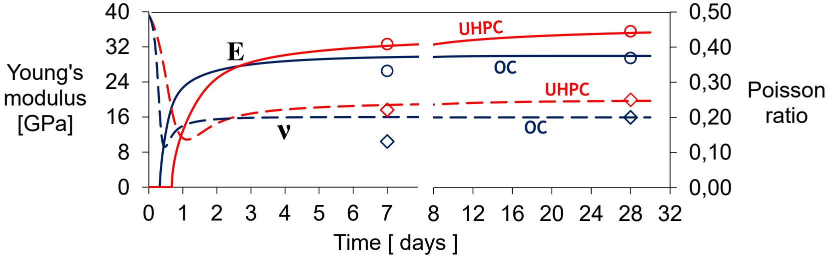
Adiabatic Calorimetry



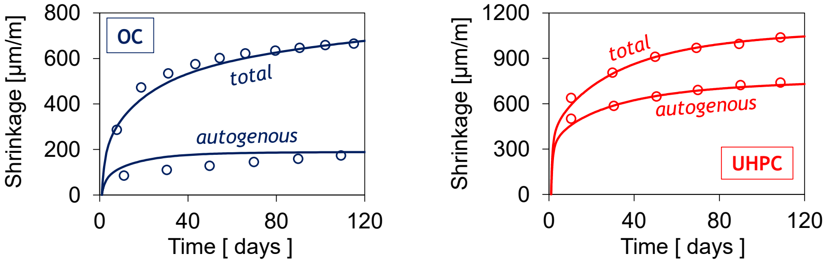
Creep test



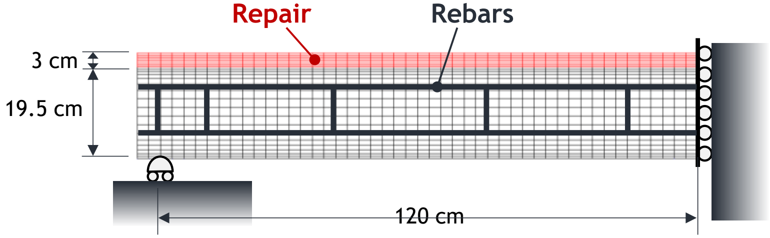
Evolution of the Young's modulus and Poisson's ratio



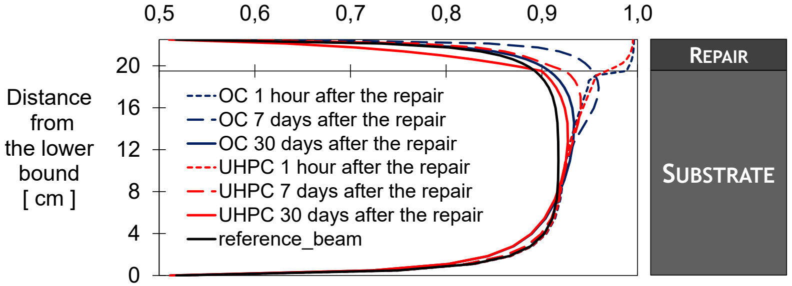
Autogenous and drying shrinkage



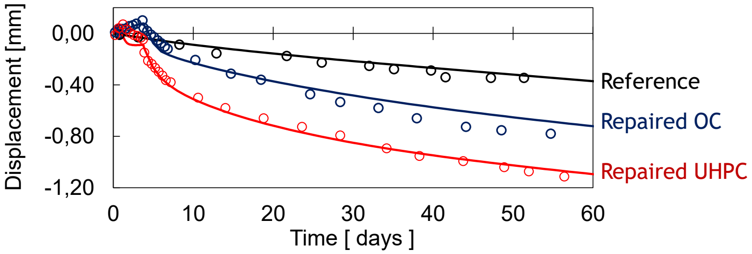
Modeling of the three repaired beams



Evolution of relative humidity



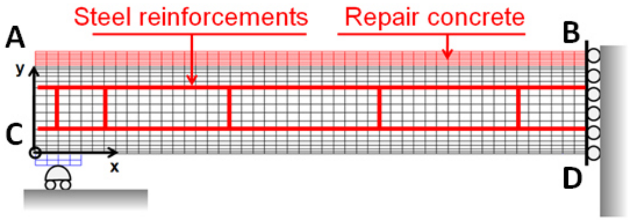
Deflection of the three beams

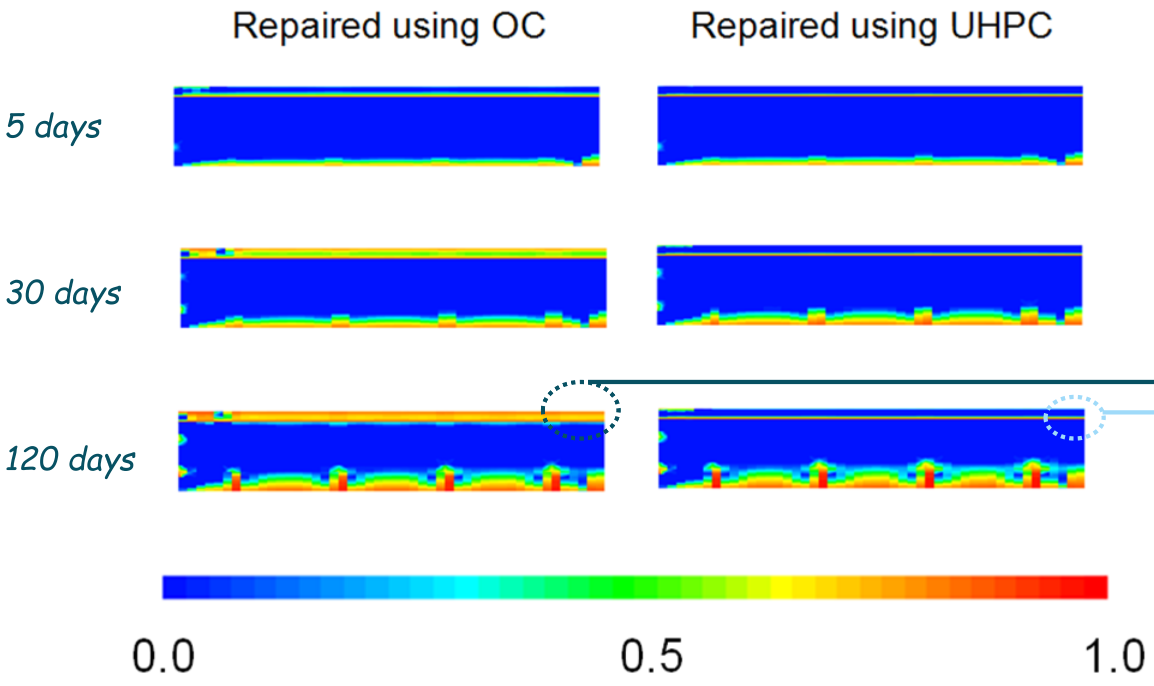


Modeling of a repaired beam

Damage evolution

Damage at 5 days, at 30 days and at 120 days after the repair of two of the beams .





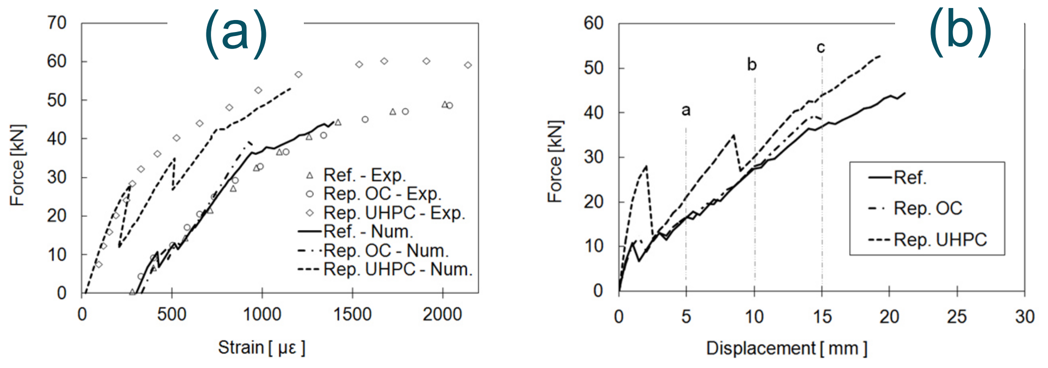
Beam repaired using OC
Diffuse damage
+
localized damage at interface

Beam repaired using UHPC
Damage localized at the interface

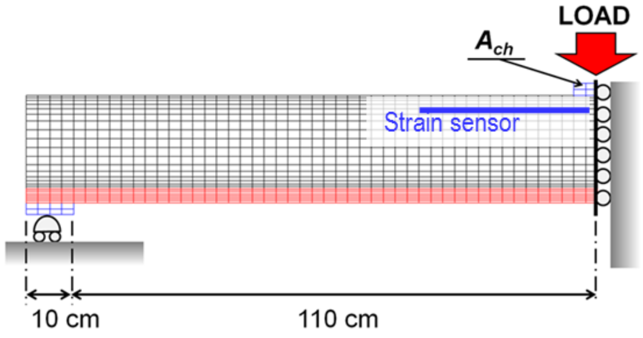
Modeling of a repaired beam

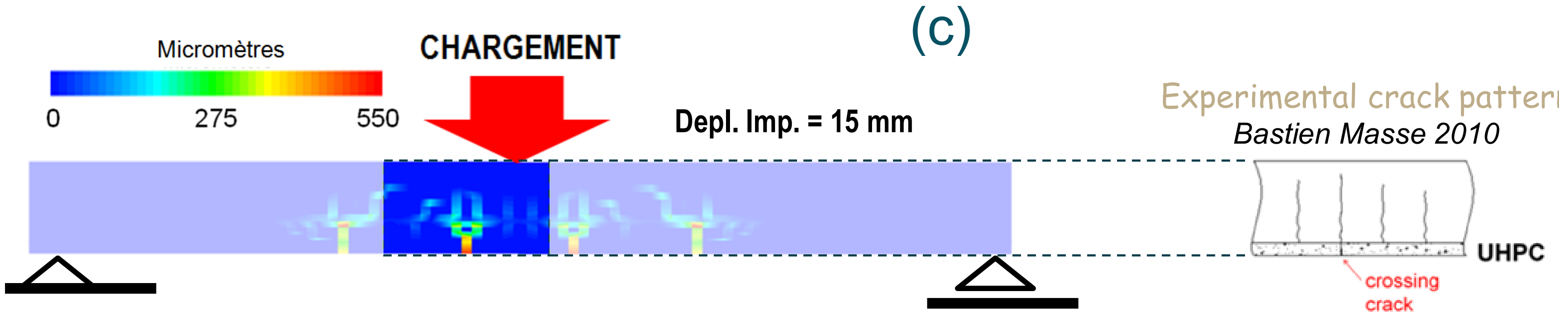
3-points bending test

Force/strain, force/displacement and crack opening.

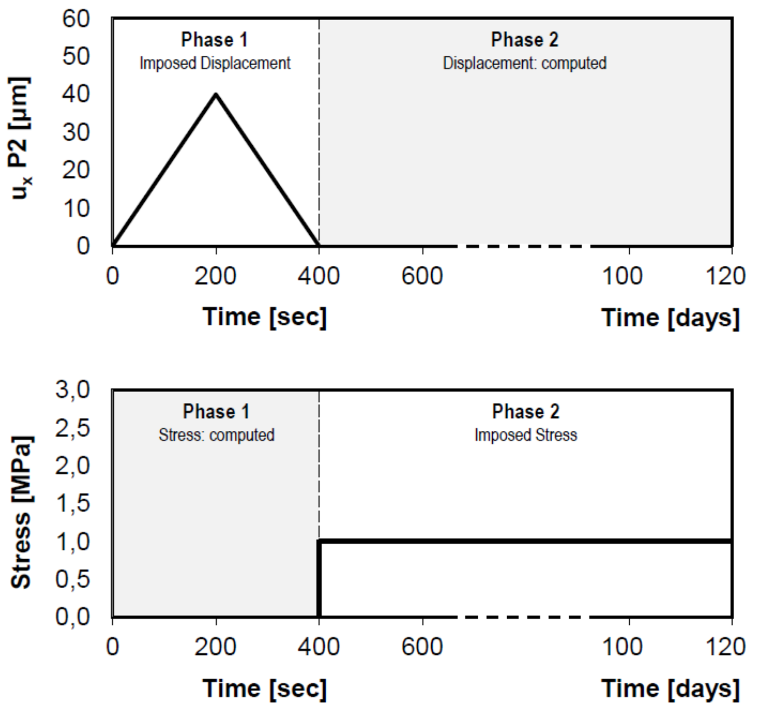


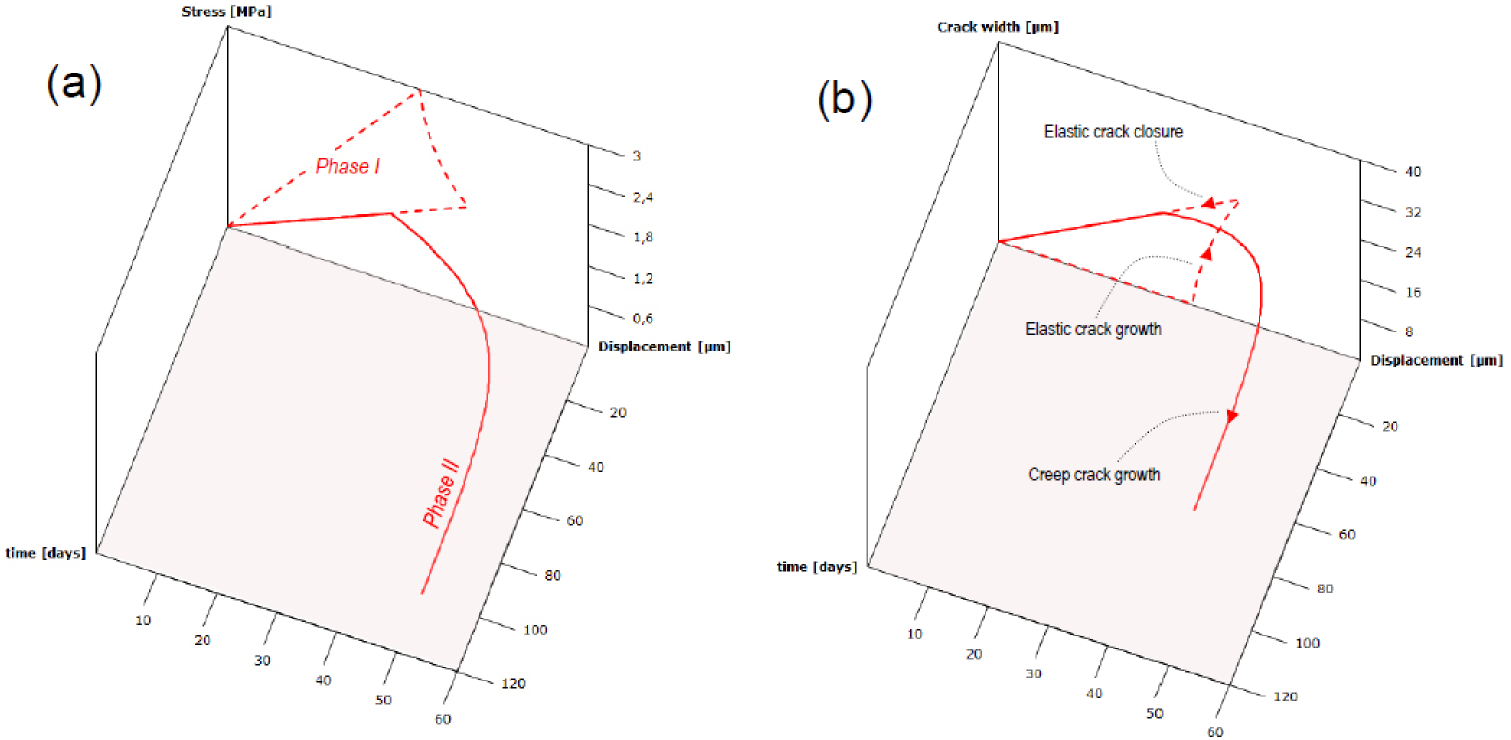
Force versus averaged strain of the compressed fiber **(a)**; force versus displacement curves (numerical results) **(b)**; crack width **(c)**.





Regarding the crack opening (generalization of OUVFISS)





Sciumè G., Benboudjema F. (2017) A viscoelastic Unitary Crack-Opening strain tensor for crack width assessment in fractured concrete structures. MECHANICS OF TIME-DEPENDENT MATERIALS, 21(2): 223–243

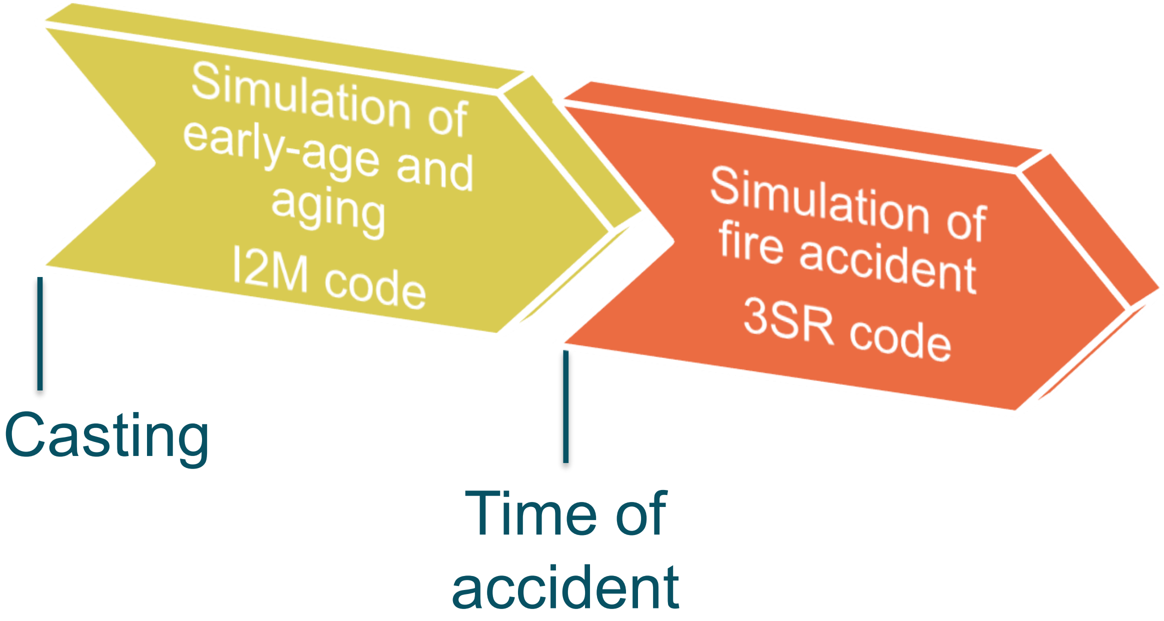
What is the initial HTM state of the specimen?

Initial idea:

Sequential solution

Problems

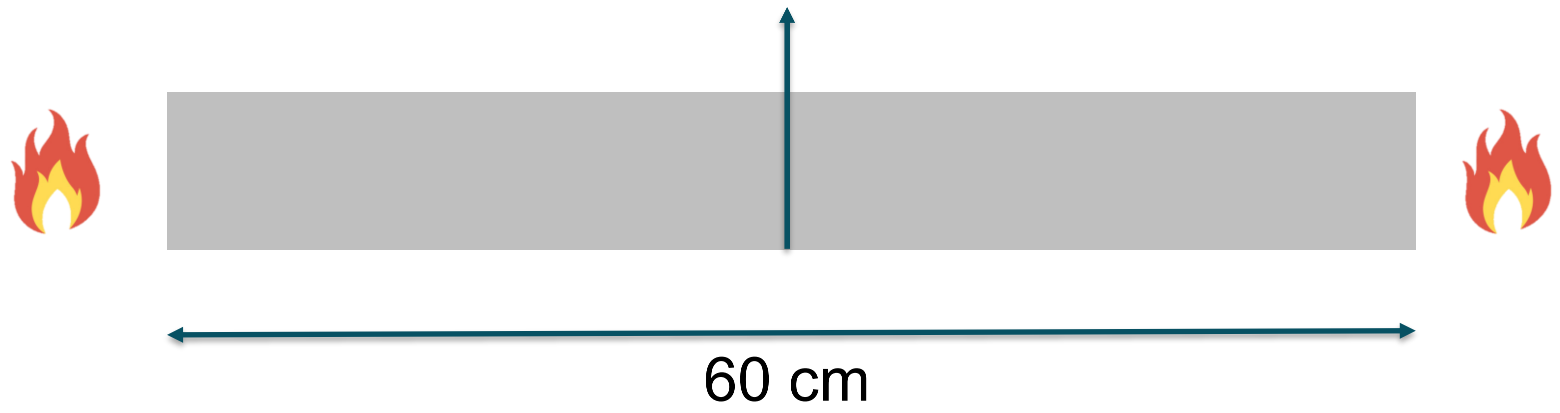
- Early-age / aging solution no totally compatible as initial condition;
- Not practical methodology.



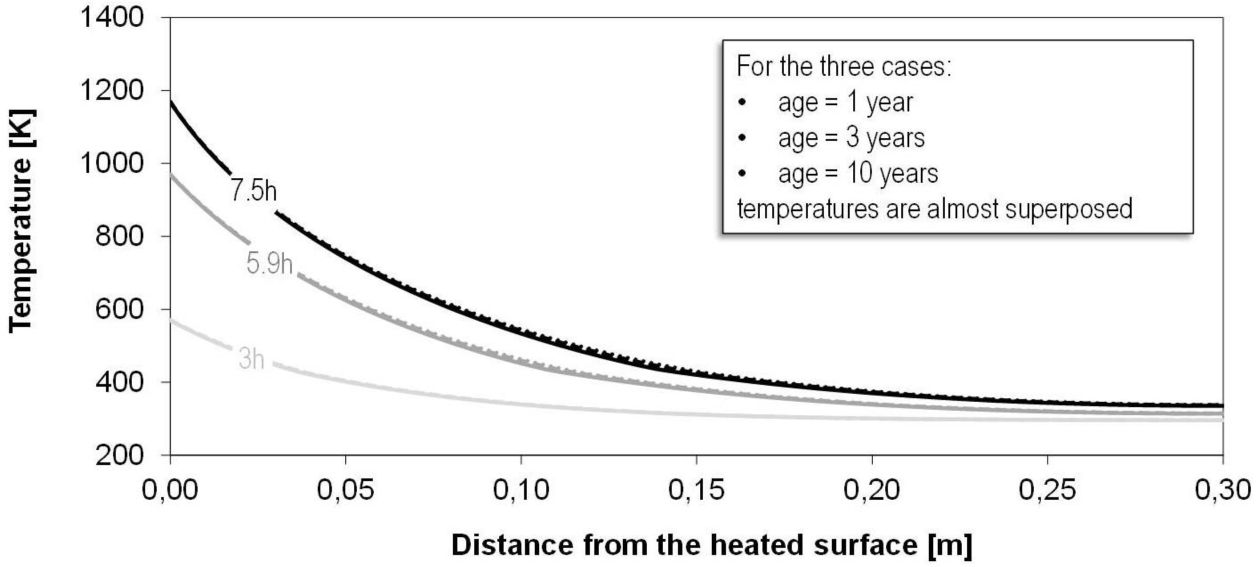
Concrete wall exposed to high temperature

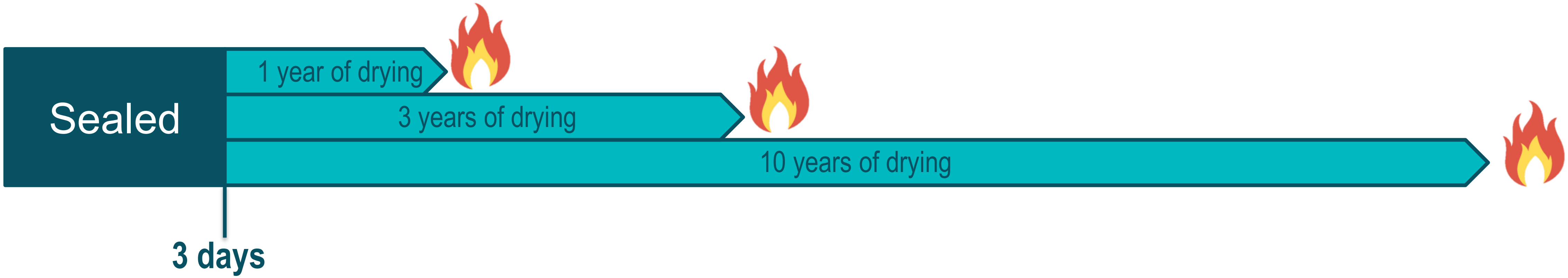
LOW RATE HEATING (2 K/MIN) FOR A 60-CM WALL

- A 1-dimensional case is simulated numerically to analyse and quantify the impact of age on the computed results;
- A 60-cm wall exposed from both sides to heating is modelled;
- The concrete is the OC adopted for the COST Action TU1404 benchmark, its water to cement ratio is of 0.45.

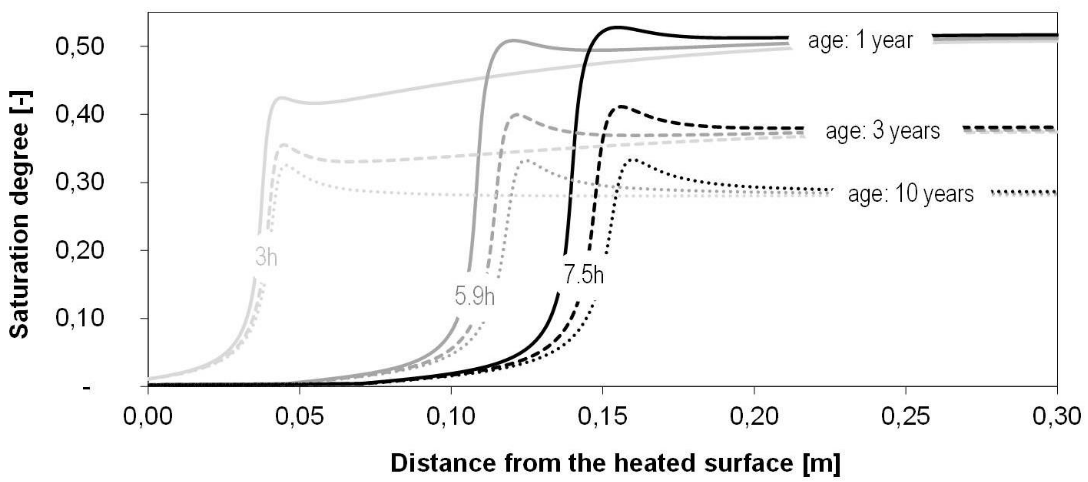


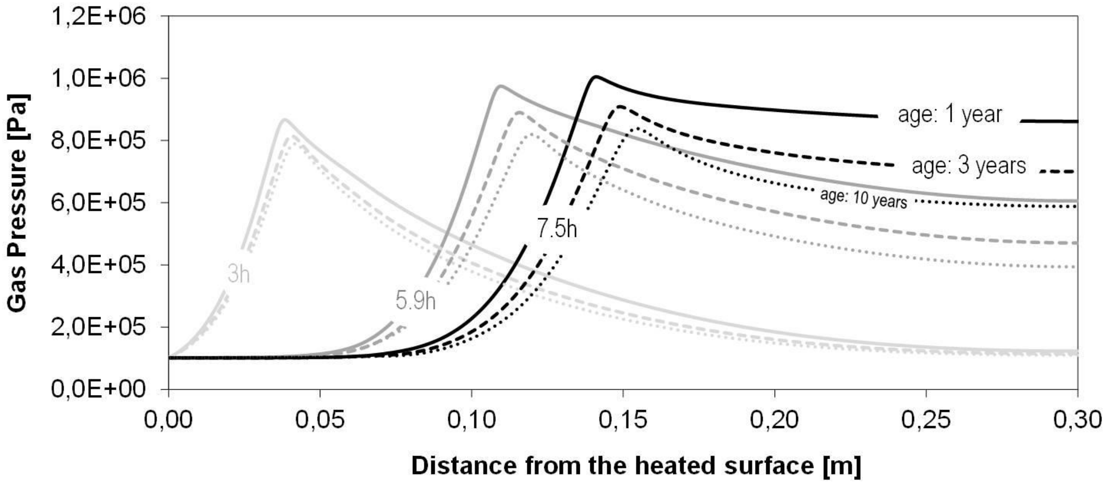
Concrete wall exposed to high temperature

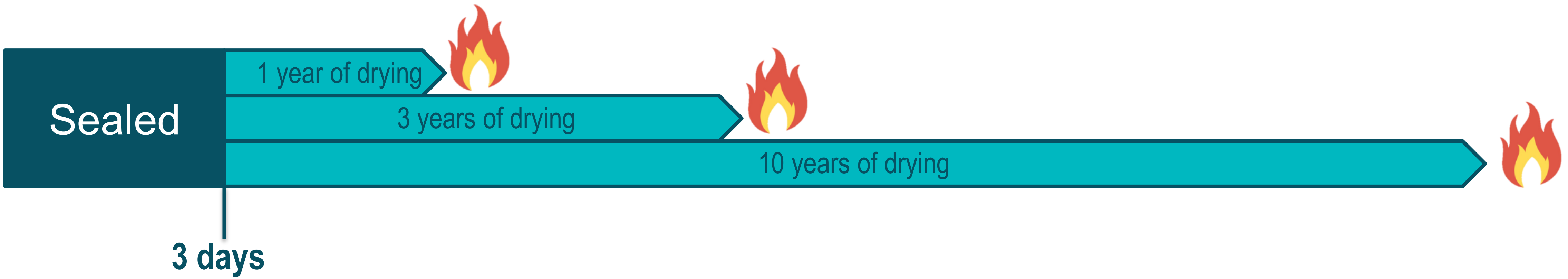




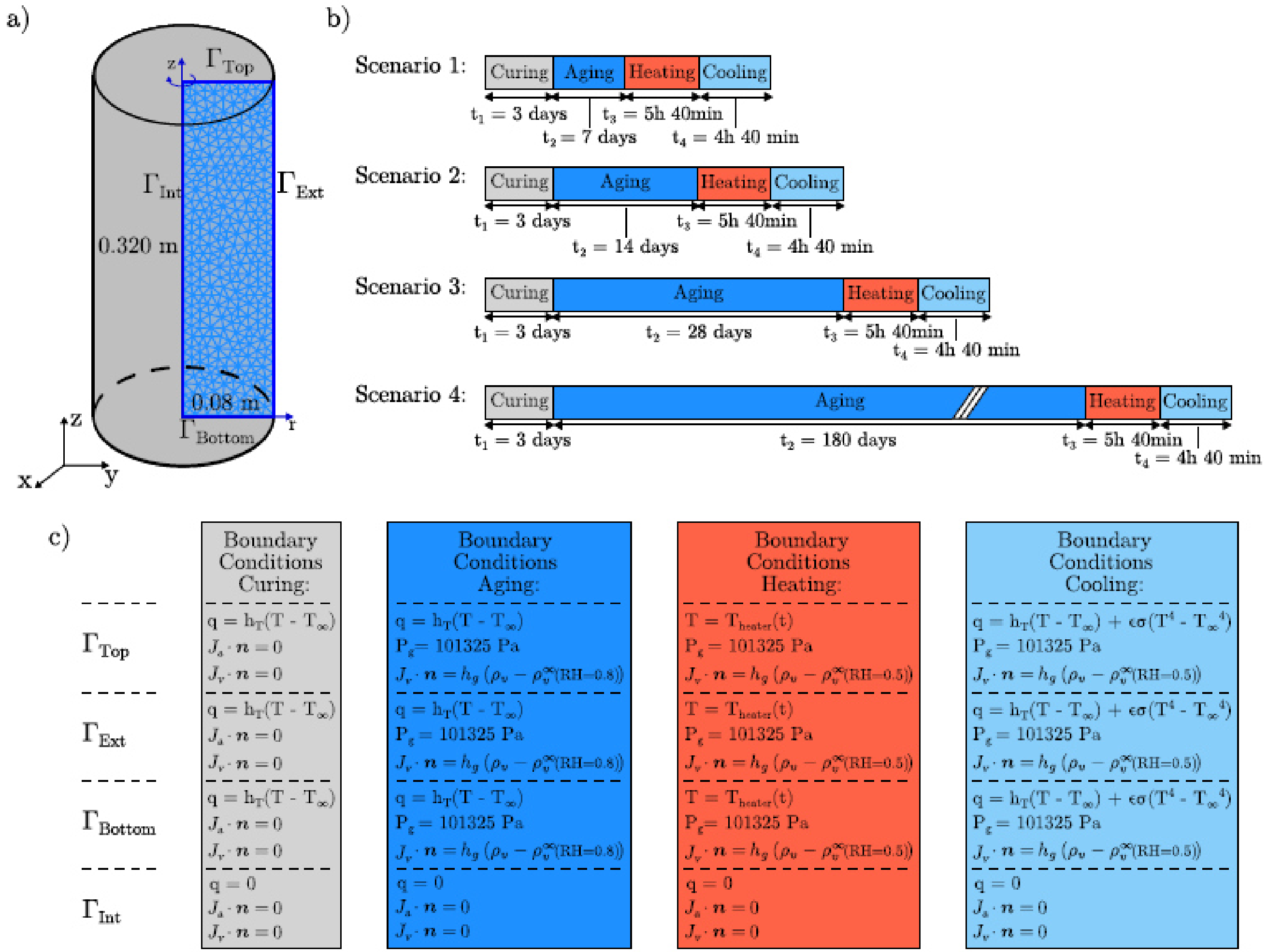
Concrete wall exposed to high temperature

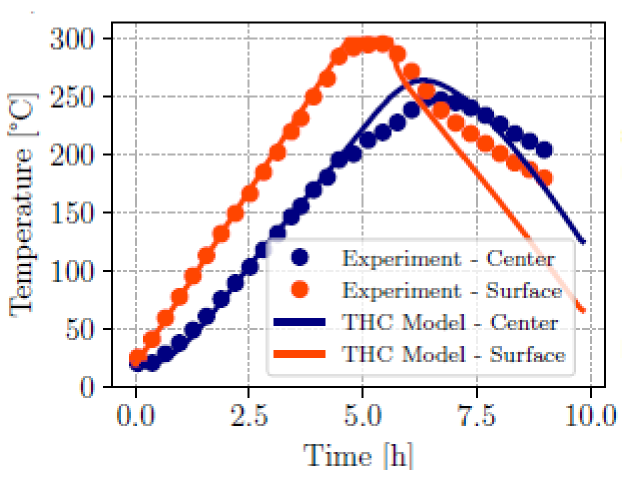


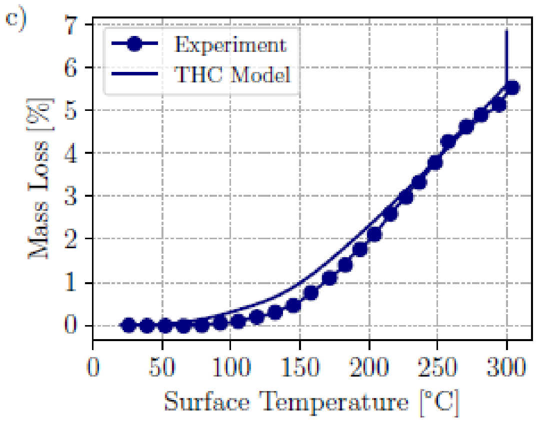




Concrete cylinder exposed to high temperature

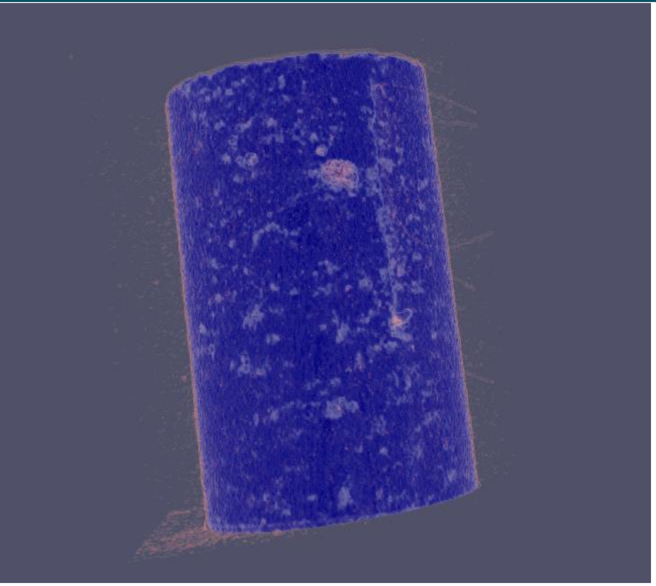






Thermo-hygro-chemical Model of Concrete - From Curing to HighTemperature Behavior
G. Sciumè, M. H. Moreira, S. Dal Pont* (2023) *submitted*

Conclusions



S. Dal Pont

ANR MULTI-FIRE

Modèle bientôt disponible sur Cast3M :

- Partie THC : matériau dans la formulation THERMO-HYDRIQUE
- Partie MEC : évolution de l'actuel FLUTRA;

Thank you for your attention !

Acknowledgements
M. H. Moreira (Brazilian PhD student)