



Study of shrinkage restraint effects at early-age in alkali-activated slag mortars

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DE LA RECHERCHE À L'INDUSTRIE



STUDY OF SHRINKAGE RESTRAINT EFFECTS AT EARLY-AGE IN ALKALI- ACTIVATED SLAG MORTARS



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IC-FraMCoS 9 | Farah RIFAI^{*}

MAY the 31st, 2016

Outline

I. Context, Problems and Strategy

II. Thermo-Chemical Analysis

- **Modelling Strategy**
- **Experimental Tests**
- **Numerical Model and Results**

III. Mechanical Analysis

- **Modelling Approach**
- **Autogenous Shrinkage**
- **Tensile Strength and Young's Modulus**
- **Summary**
- **Behavior law**
- **Elastic Calculations**
- **Damage Model Results**

IV. Conclusions and Perspectives

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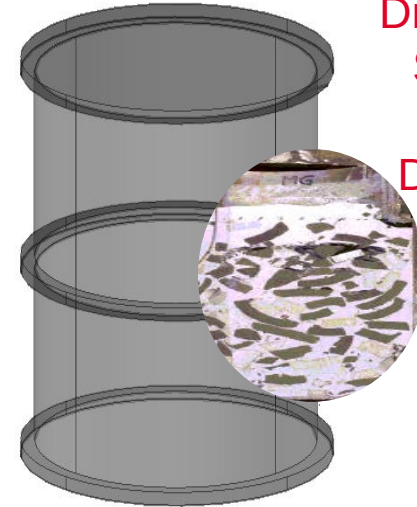
- **Modelling Approach**
- **Autogenous Shrinkage**
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IV. Conclusions and Perspectives

Power Plant reactors dismantling
→ Metallic nuclear waste →
Disposal?



Alkali-activated slag
(AAS) mortar
Chosen with respect to
corrosion behavior



Dimensional
Stability?

Durability?

PhD final objective:

Thermo-chemo-mechanical 3D Model → **cracking** risks during package **lifecycle**
(+ effects of waste corrosion)

(AAS) mortar



Need for experimental data for validation/determination of
Hydration models and Mechanical behavior laws

ECOFRIENDLY MATERIAL

Application of recycled materials in civil engineering

- ❑ **1 ton of cement** produced = **1 ton of CO₂** released → searching for new solutions
- ❑ Volume of cement produced = **555** kilos/person/year (2013)
- ❑ Applications of industrial alkali-activated by-products : Blast furnace slag BFS (steel industry), Fly Ash (Carbon combustion) ..



Construction using alkali-activated materials due to shortage in Portland Cement in USSR

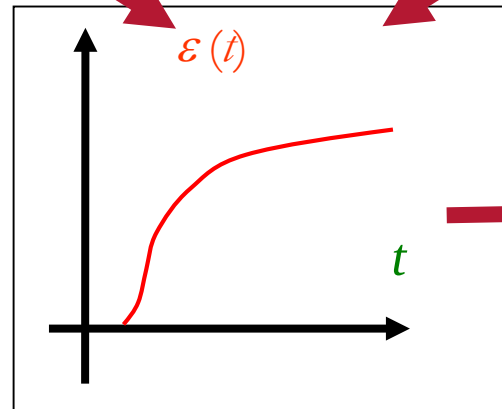
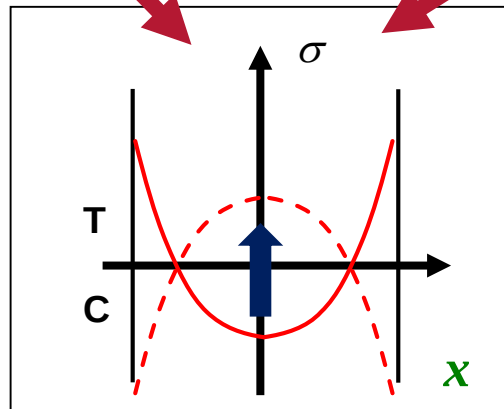
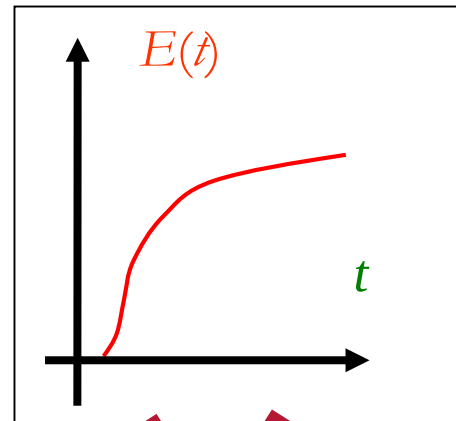
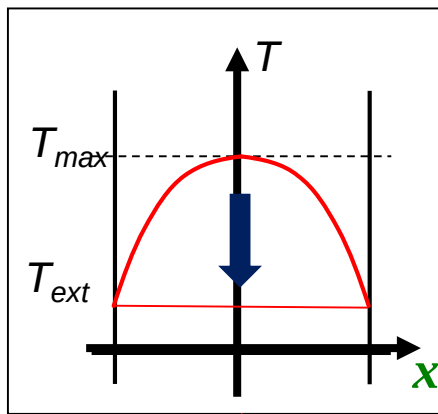
CO ₂ emission (t)	calcination	blending	Silicate sol.	Total	Reduction
Portland Cement	1.000	0.020		1.020	0
Recycled slag	0.140	0.018	0.050	0.208	80%

CO₂ emissions reduction in blast furnace slag binders fabrication
[Davidovids, 2014]

EARLY-AGE CRACKING RISK ORIGINS?

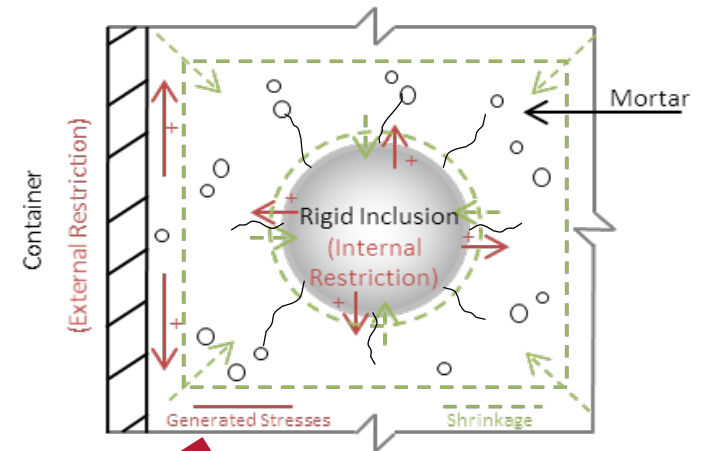
Stresses generated by self-restraint

Thermal Gradient



Stresses generated by internal/external restraints

Shrinkage restriction



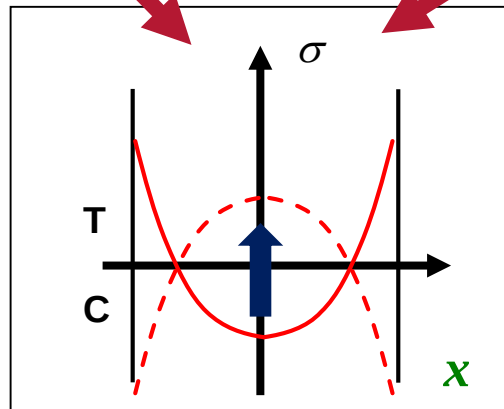
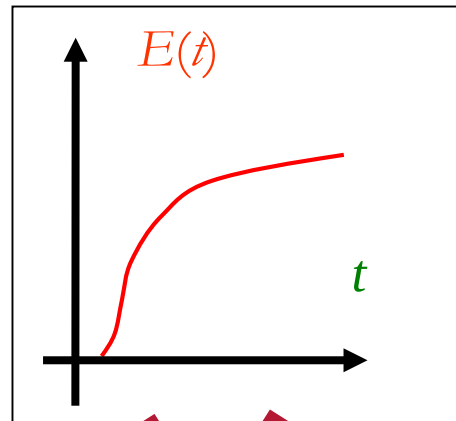
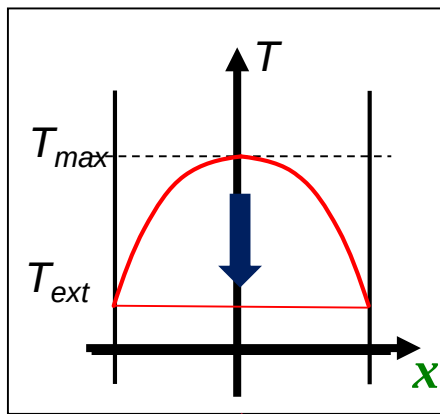
Fully-restricted :

$$\dot{\sigma}(t) = E(t) \dot{\epsilon}(t)$$

EARLY-AGE CRACKING RISK ORIGINS?

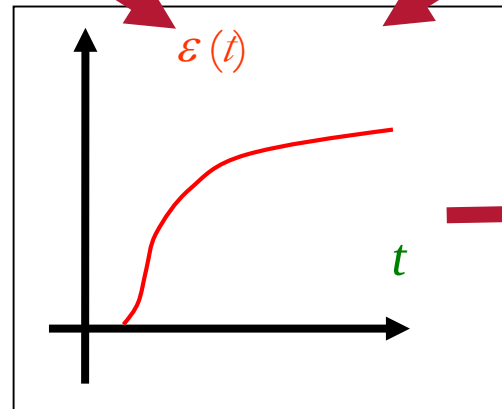
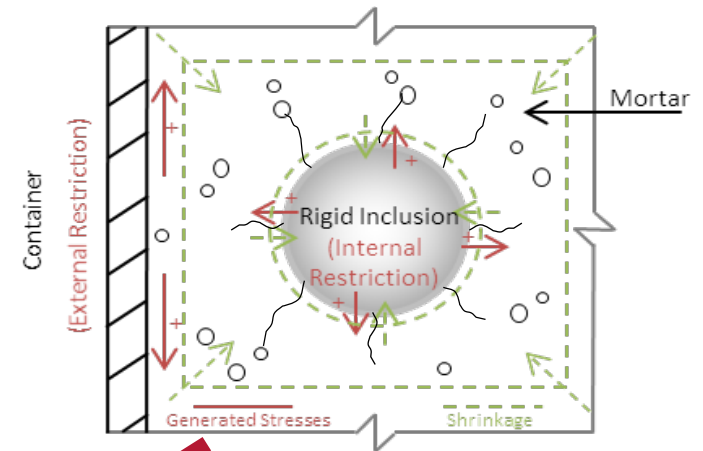
Stresses generated by self-restraint

Thermal Gradient



Stresses generated by internal/external restraints

Shrinkage restriction



Fully-restricted :

$$\dot{\sigma}(t) = E(t) \dot{\epsilon}(t)$$

MODELLING STRATEGY

« Classical » tests
(identification)

« Electro-chemical/mechanical »
coupled tests

Deformations within hydraulic binder matrix

$$\boldsymbol{\varepsilon}(t) = \boldsymbol{\varepsilon}^e(t) + \boldsymbol{\varepsilon}^{th}(t) + \boldsymbol{\varepsilon}^{au}(t) + \boldsymbol{\varepsilon}^{bc}(t) + \boldsymbol{\varepsilon}^{corr}(t)$$

Study in
autogenous
conditions

$E(t) + \text{restrictions}$

Stress generation $\sigma(t)$

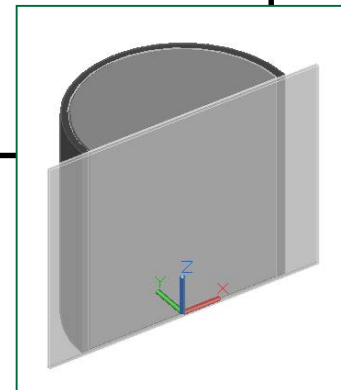
$$\sigma(t) > f(t)??$$

Material cracking??

Thermo-chemo mechanical
modelling

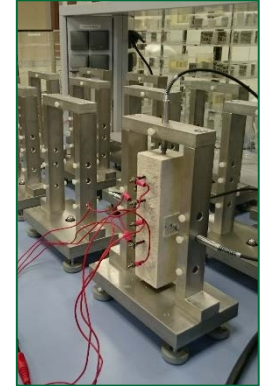


Validation Tests



Instrumented
mock-up (thermo-
couples, DIC,
Strain gauges)

Modelling of Scale 1 packages



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Thermo-Chemical Numerical Model

Heat Balance Equation + Hydration Heat Source

$$\underline{C}\dot{T} = \nabla(\underline{k}\nabla T) + \underline{L}\dot{\xi}$$

C = Volumetric thermal heat capacity [$\text{J} \cdot \text{C}^{-1} \cdot \text{m}^{-3}$] - $C(T, t_e) = C$

k = Thermal conductivity [$\text{W} \cdot \text{C}^{-1} \cdot \text{m}^{-1}$] - $k(T, t_e) = k$

L = hydration latent heat

Hydration (Thermo-activation)

$$\dot{\xi} = \underline{\tilde{A}}(\xi) \exp\left(-\frac{E_a}{RT}\right) \quad [\text{Ulm et Coussy, 1998}]$$

- ✓ Chemical Affinity : polynomial function
- ✓ Thermo-activation : Ahrrenius' law
- ✓ **Time Correction (Maturity equivalent time)**

Hydration Reaction Advancement Degree

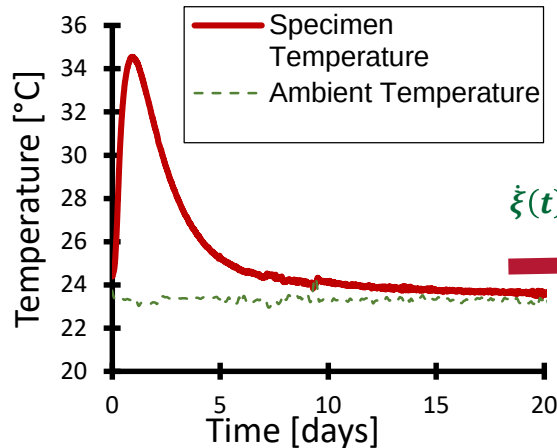
- ✓ Hydration reaction heat release :
proportional to the advancement degree $\xi(t)$

$$\xi(t) = \frac{Q(t)}{Q_\infty}$$

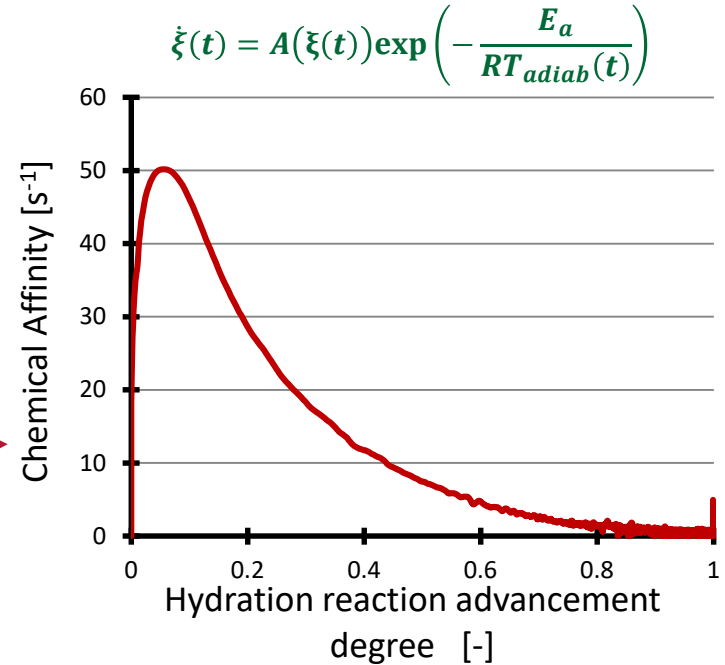
EXPERIMENTAL TESTS

Semi-adiabatic Calorimetry method

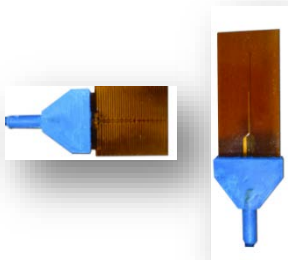
cylindrical specimen ($\Phi = 7 \text{ cm}$; $h = 16 \text{ cm}$)



$$\xi(t) = \frac{\dot{q}(t)}{L}$$



Hot wire/plane method

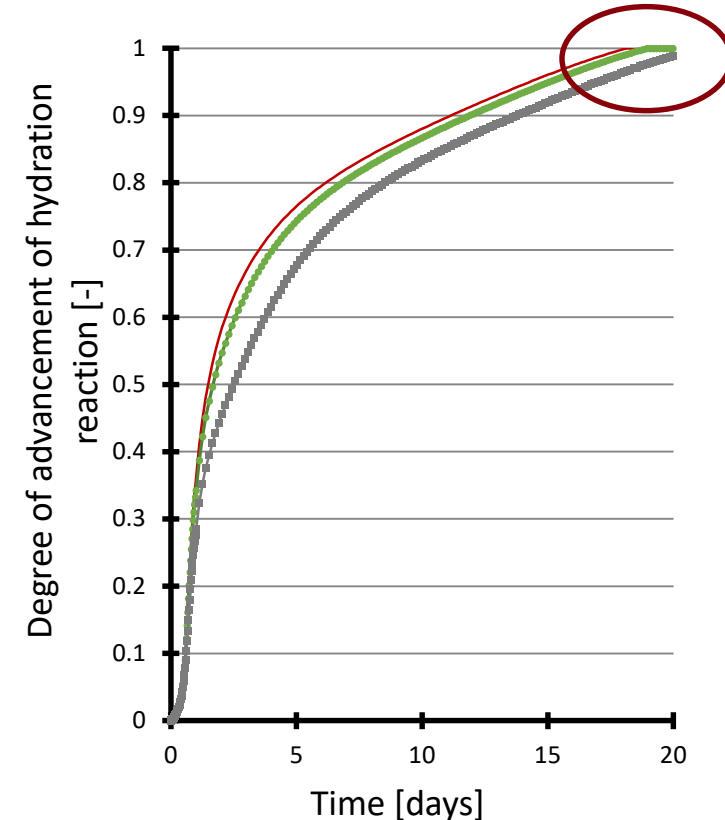
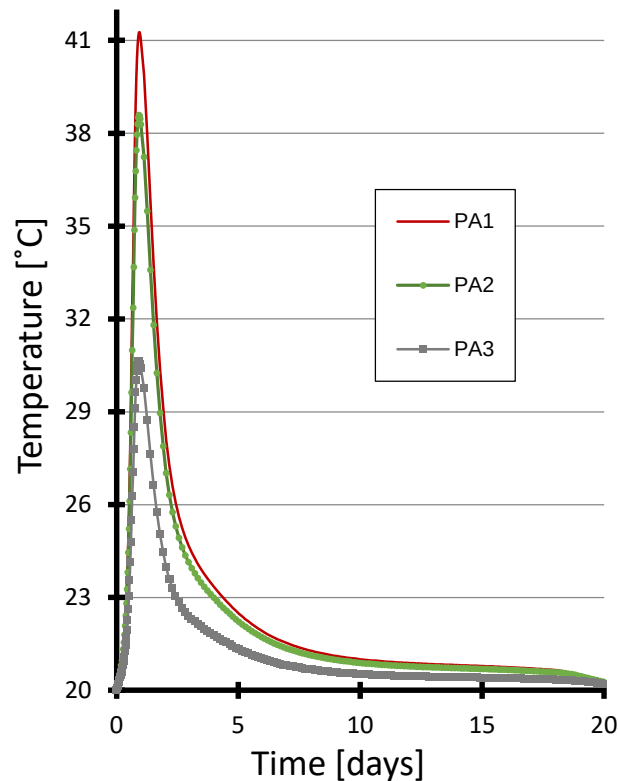
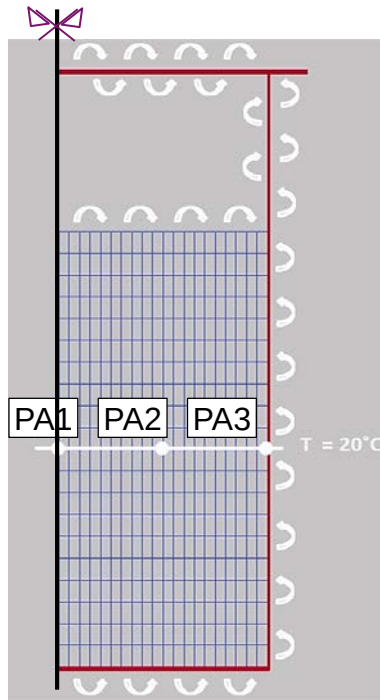


Thermal Conductivity (W/(m.K))	Thermal Effusivity (W.s ^{1/2} /(m ² .K))	Specific Heat (J/(kg.K))
2.642	1623	457

$$E = \sqrt{\lambda \rho C}$$

NUMERICAL MODEL AND RESULTS

$$\varphi = \varphi_{conv} + \varphi_{rad}$$



✓ Rise of 20°C in the center of the package



✓ Low thermal gradient $\rightarrow$ low cracking risk associated to thermal shrinkage self-restraint

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APPROPRIATE MODELLING APPROACH ??

Classical Approach Hydration Reaction advancement degree

$$\bar{\xi} = \left\langle \frac{\xi - \xi_0}{\xi_{\infty} - \xi_0} \right\rangle_+$$

ξ_0 - Hydration degree at setting time

Eurocode Approach Equivalent Time empirical model

$$t_e(t, T) = \int_0^t \exp \left[-\frac{E_a}{R} \left(\frac{1}{T} - \frac{1}{T_{ref}} \right) \right] dt$$

T_{ref} - Reference temperature

Autogenous Shrinkage Evolution

$$\dot{\varepsilon}_{ij}^{au} = \kappa \dot{\xi} \delta_{ij} \quad \text{For } \xi > \xi_0$$

✓ $\kappa = f$ (binder composition)

$$\varepsilon^{au}(t_e) = [\beta_c]_{\varepsilon^{au}}^{n_{\varepsilon^{au}}} \cdot \varepsilon_{28}^{au}$$

✓ ε_{28}^{au} = shrinkage at the age of 28 days

Mechanical Properties' Evolution

Young's Modulus

$$E(\xi) = E_{\infty} \bar{\xi}^{a_E}$$

Tensile Strength

$$f_t(\xi) = f_{t_{\infty}} \bar{\xi}^{a_{f_t}}$$

$$\beta_c = \exp \left[s \left(1 - \sqrt{\frac{28}{\langle t_e - t_0 \rangle_+}} \right) \right]$$

t_0 - setting time

$$E(t_e) = [\beta_c]_{E}^{n_E} \cdot E_{28}$$

$$f_t(t_e) = [\beta_c]_{f_t}^{n_{f_t}} \cdot f_{t,28}$$

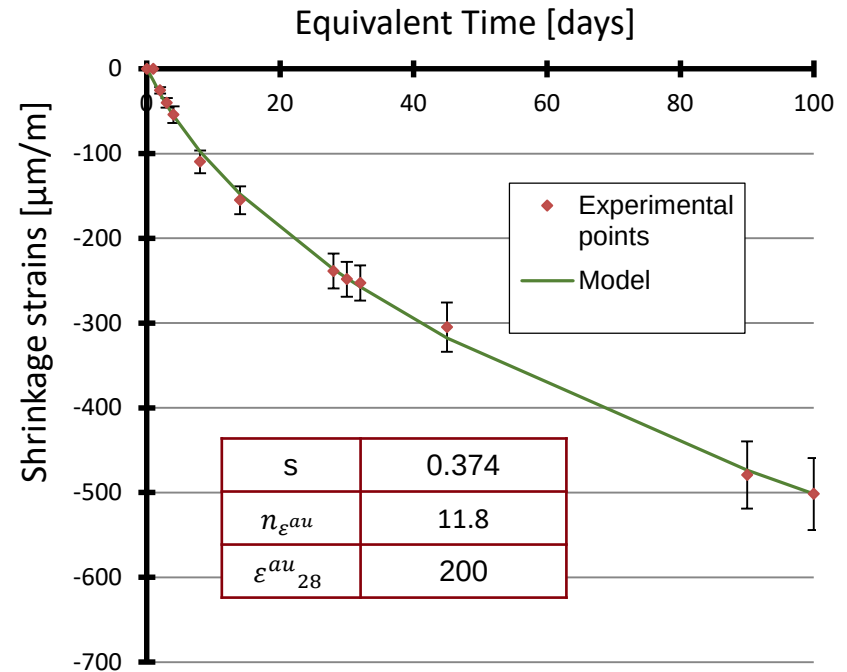
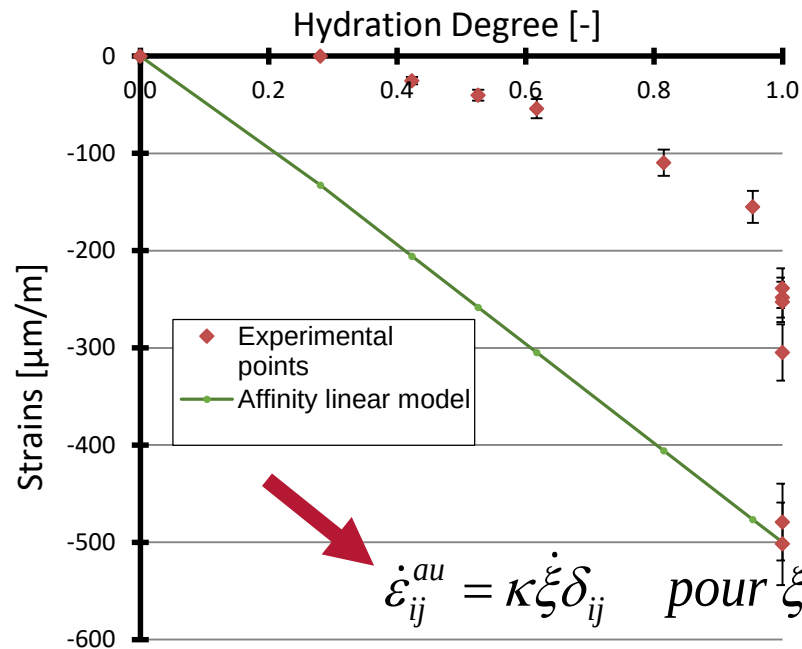
[De Schutter et Taerwe, 1996]

✓ $E_{28}, f_{t,28}$ = properties at the age of 28 days

AUTOGENOUS SHRINKAGE MEASUREMENTS



**LVDT displacement
monitoring on 3
duplicate samples
4x4x16 cm**



$$\epsilon^{au}(t_e) = [\beta_c]^{n_{\epsilon^{au}}} \cdot \epsilon_{28}^{au}$$

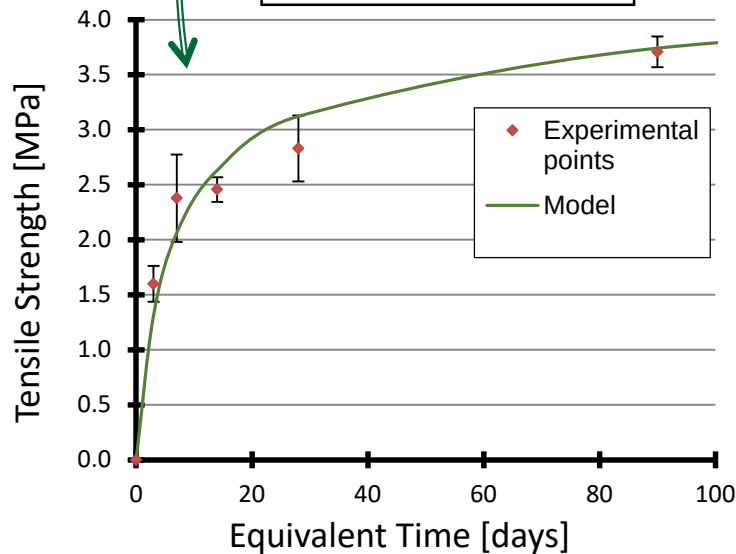
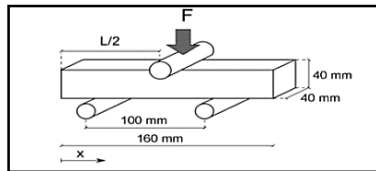
$$\beta_c = \exp \left[s \left(1 - \sqrt{\frac{28}{\langle t_e - t_0 \rangle_+}} \right) \right]$$



3 points flexural test on 3 duplicate samples 4x4x16

$$f_t = \frac{f_{fl}}{1.6}$$

[EC2, 1992]



$$f_t(t_e) = [\beta_c]^{n_f} \cdot f_{t,28}$$

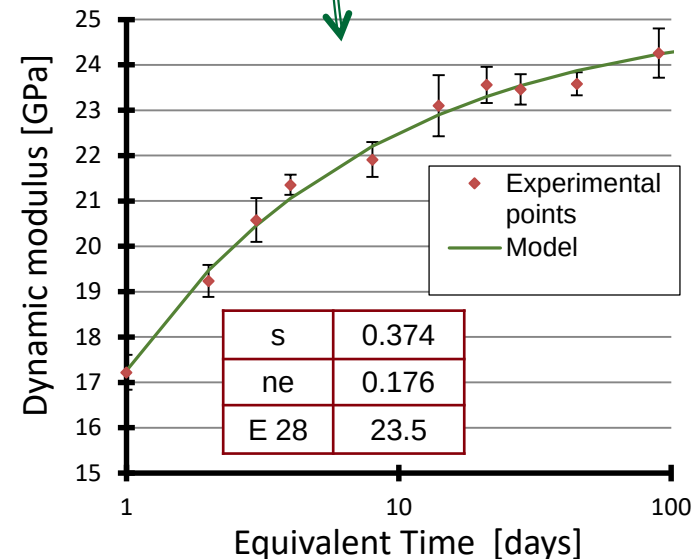
s	0.374
nft	1.09
Ft 28	3.13

Ultrasonic measurements on 3 duplicate samples 4x4x16

$$E_s = \frac{E_d}{1.2}$$



$$E(t_e) = [\beta_c]^{n_E} \cdot E_{28}$$



s	0.374
ne	0.176
E 28	23.5

Elastic strains tensor

$$\boldsymbol{\varepsilon}^e(t) = \boldsymbol{\varepsilon}(t) - (\boldsymbol{\varepsilon}^{th}(t) + \boldsymbol{\varepsilon}^{au}(t) + \boldsymbol{\varepsilon}^{bc}(t))$$

Basic creep relaxation effect taken into account in calculation tensile strength

[EC2, 1992]

$$\dot{\varepsilon}^{th} = \alpha_T \dot{T} \quad \varepsilon^{au}(t_e) = [\beta_c]^{n_{\varepsilon^{au}}} \cdot \varepsilon^{au}_{28}$$

Young Modulus and Tensile strength evolution

$$E(t_e) = [\beta_c]^{n_E} \cdot E_{28}; \quad f_t(t_e) = [\beta_c]^{n_f} \cdot f_{t,28}; \quad n_E = 0.176; \quad n_{f_t} = 1.09$$

Giving the Tensile strain threshold $\kappa_0 = \frac{f_t}{E}$

Effective stresses tensor

$$\dot{\bar{\sigma}} = E \dot{\boldsymbol{\varepsilon}}^e = E (\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{au} - \dot{\boldsymbol{\varepsilon}}^{th} - \dot{\boldsymbol{\varepsilon}}^{bc}) \longrightarrow$$

Isotropic elastic damage model
based on Mazars Model

$$\sigma = (1 - \mathbf{D}) \bar{\sigma}$$

Apparent stresses tensor

MECHANICAL BEHAVIOR DAMAGE LAW

Mazars Damage Criterion

$$f = \hat{\varepsilon} - \kappa_0 ; \quad \hat{\varepsilon} = \sqrt{\langle \varepsilon_{el} \rangle_+ : \langle \varepsilon_{el} \rangle_+}$$

Equivalent tensile strain tensor

Damage Variable in tension $\hat{\varepsilon} \geq \kappa_0$

$$D = 1 - \frac{\kappa_0}{\hat{\varepsilon}} \left[(1 + A_t) \exp(-B_t \hat{\varepsilon}) - A_t \exp(-2B_t \hat{\varepsilon}) \right]$$

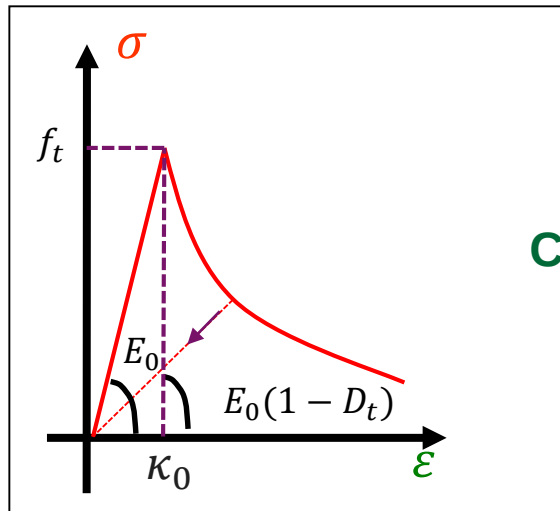
Regularization using
fracture energy

Dissipated energy
density at failure

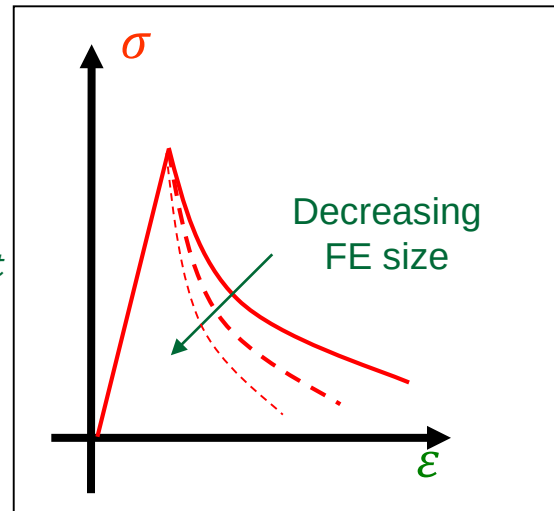
$$g_{ft}(t_e) = \frac{f_t(1 + A_t/2)}{B_t(t_e)}$$

$$g_{ft}(t_e) = \frac{G_{ft}(t_e)}{\textcircled{l_c}}$$

Finite Element
characteristic
length



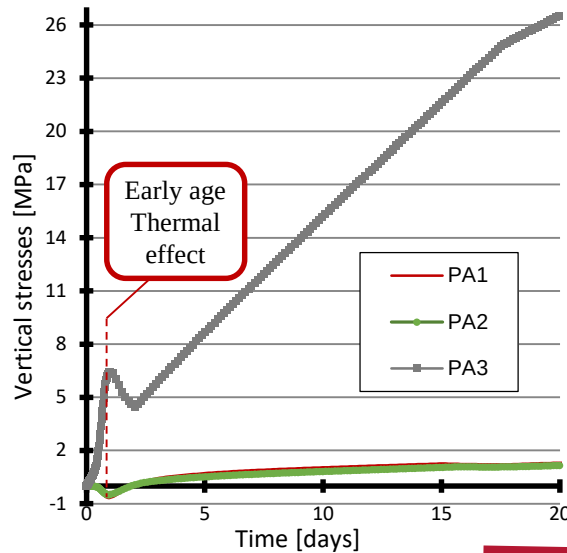
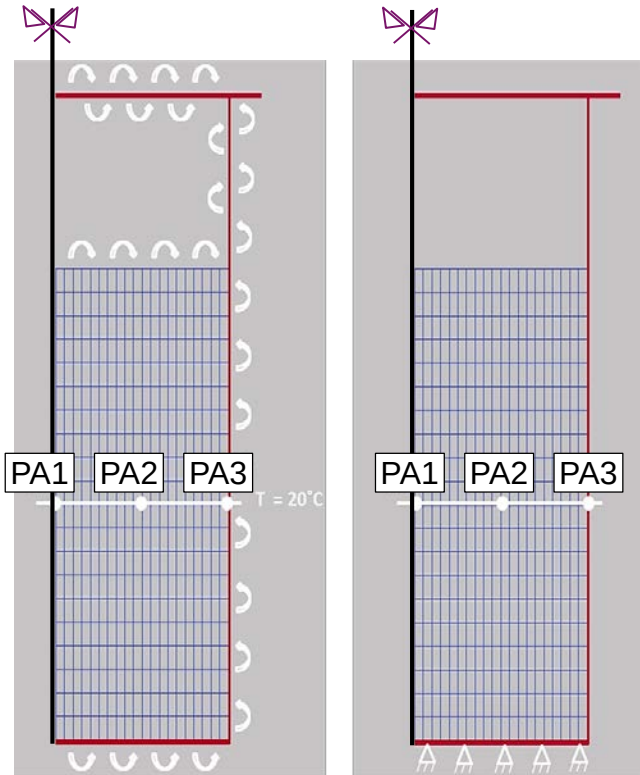
Constant B_t



[Hillerborg et al., 1976]

ELSATIC CALCULATIONS RESULTS

Geometric model with boundary conditions

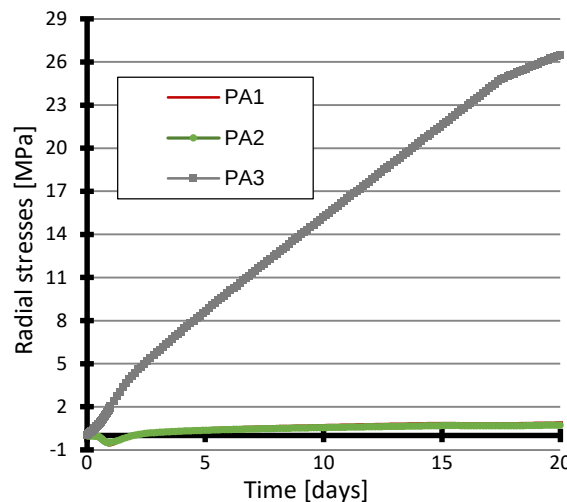


✓ Early age thermal effect results in surface tension, core compression

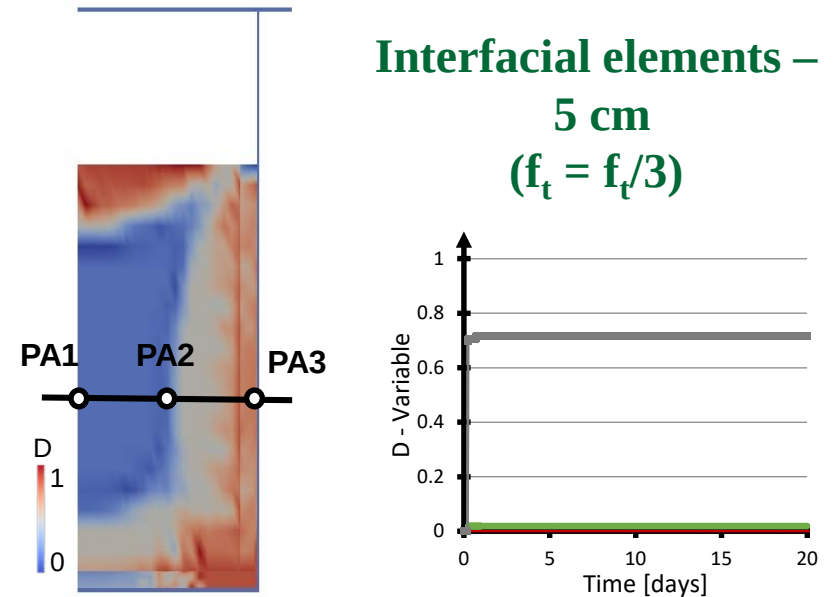
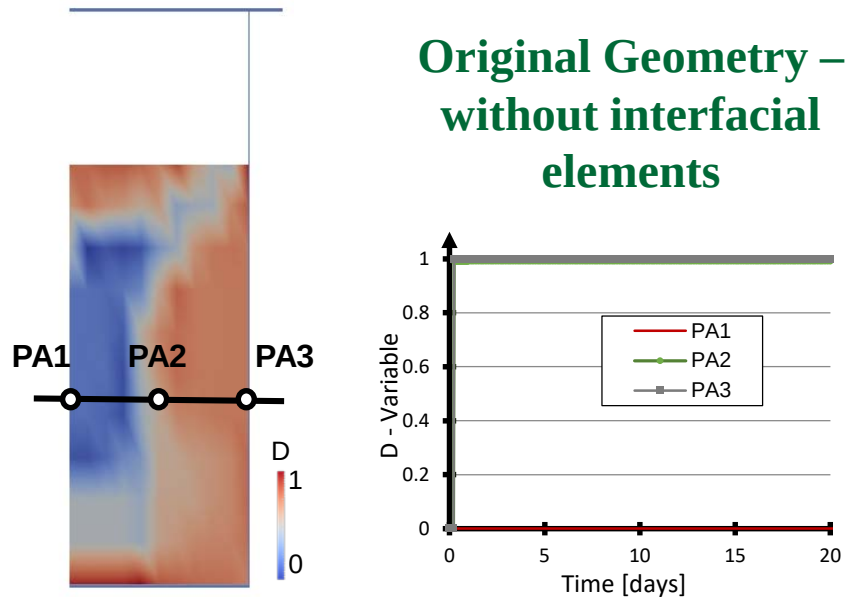
✓ Shrinkage restraint

→ High stresses at advanced ages

?? Steel/binder interface debonding



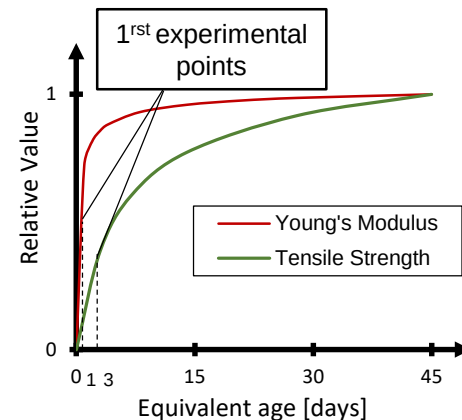
DAMAGE MODEL RESULTS



Damage occurs at very early age – just after setting



Need to refine Tensile Resistance and Young's modulus development laws



$$\frac{n_{ft}}{n_E} \approx 10$$

2-3 OPC binders

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CONCLUSIONS AND PERSPECTIVES

- ❑ Waste package : more sensitive to proper **deformations restriction** than temperature gradient
- ❑ Unexpected **quick** numerical damage →
 - Dynamic to static E conversion
 - Experimental points at early age
 - Mechanical properties evolution
 - Self-Healing??
- ❑ **High radial stresses** at mortar/container interface → Steel/Slag adhesion?
Tensile creep ?
- ❑ **High Autogenous shrinkage** strains + significant evolution after 100 days
 - Internal relative humidity? → Phenomenological models
- ❑ **Meso-scale** Calculations →
 - Rigid inclusion shrinkage restraint
 - Thermal-equivalent corrosion strains
 - Macro Properties → waste % in packages

Thank you for your
attention !

Questions are
Welcome ☺



F. RIFAI

Berkeley, May the 31st 2016



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Radionucléides
LECBA