Numerical Modeling
Strategies for Sustainable Concrete Structures

Nonlinear basic creep and drying creep modeling

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Outline

1- The main concrete creep phenomena to model

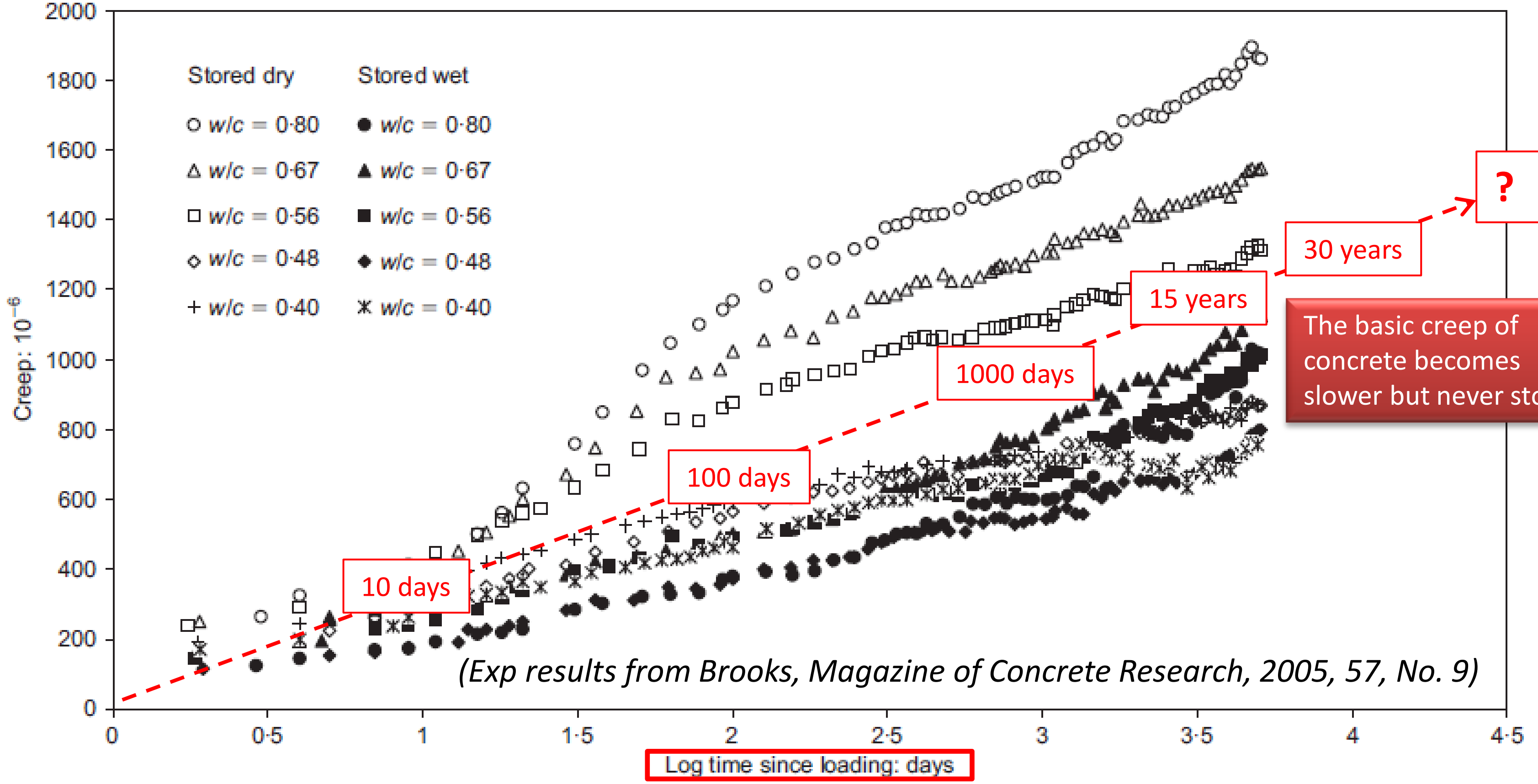
2- The physical origin of creep, the roles of water and temperature

3- The main principles of the proposed model

4- Abilities of the model to simulate non linear creep phenomena

1- The main creep phenomena to understand and model

Basic creep : a non asymptotic phenomena but a decreasing velocity with time



The basic creep of concrete becomes slower but never stops…

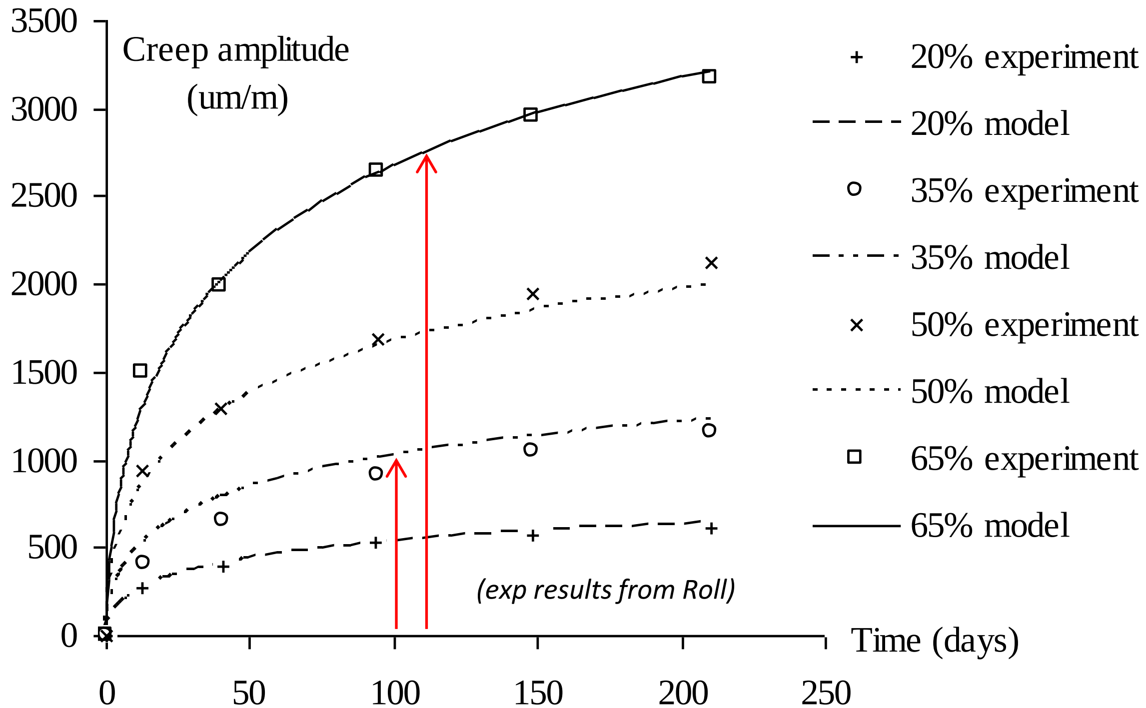
How to model simply this non asymptotic creep ?

1- The main creep phenomena to understand and model

Non linear dependence of the creep amplitude / stress

Basic creep strain X 2.8

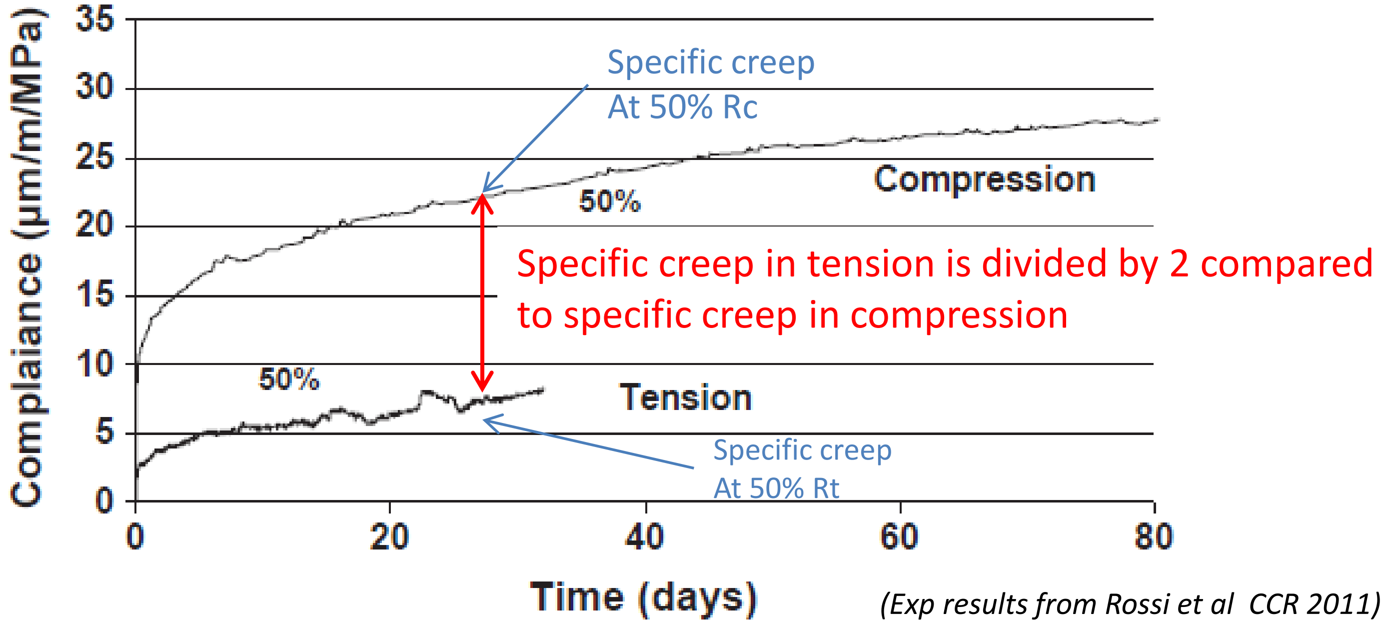
Compressive stress X 1.7



Why the creep amplitude is not proportional to the applied stress ?

1- The main creep phenomena to understand and model

Difference of specific creep between compression and tension



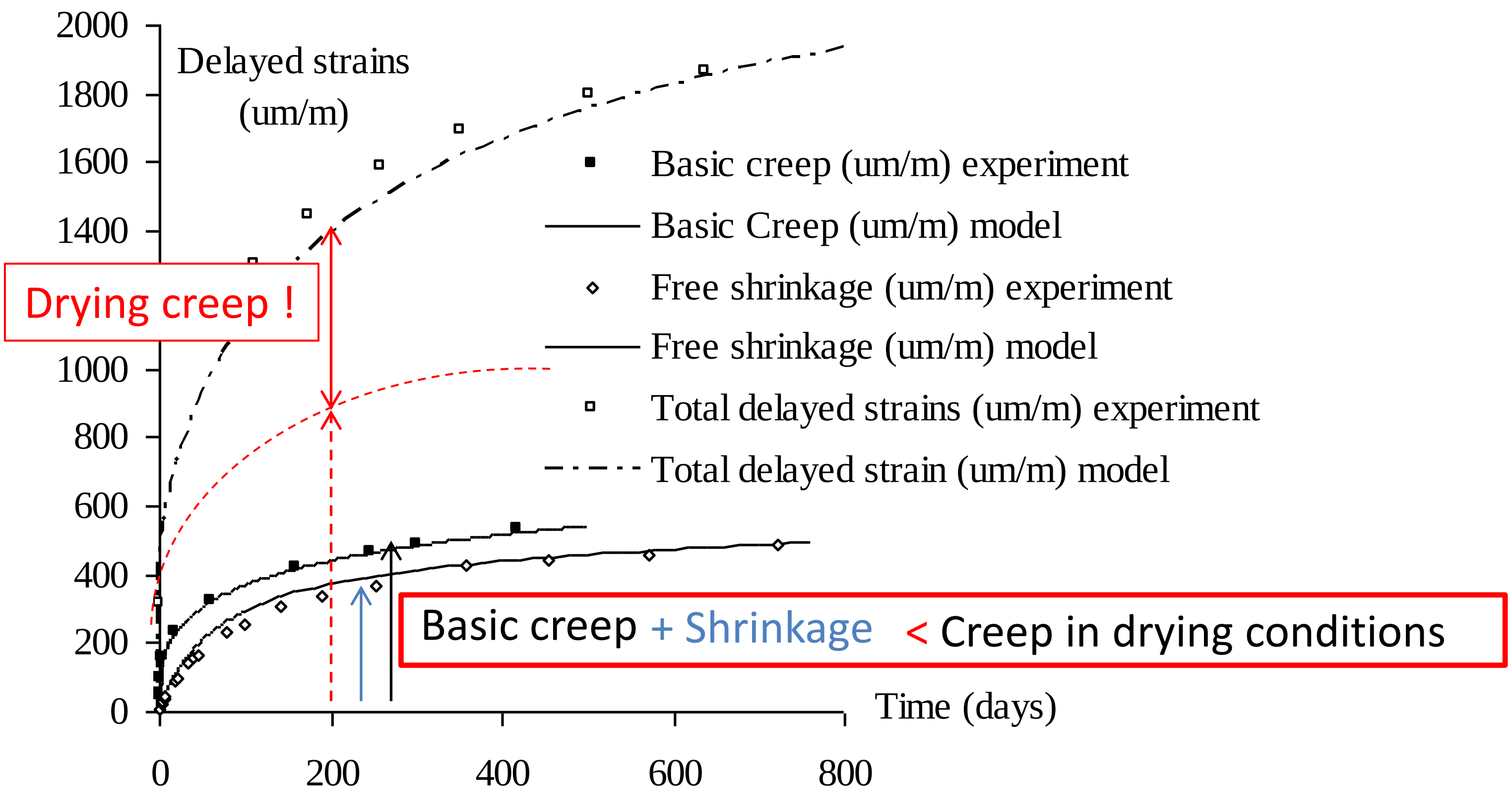
(Exp results from Rossi et al CCR 2011)

Fig. 16. Compliance curves related to the basic creep in compression and in tension (same loading level and same concrete age).

Why the specific creep are different in tension and in compression ?

1- The main creep phenomena to understand and model

Drying creep

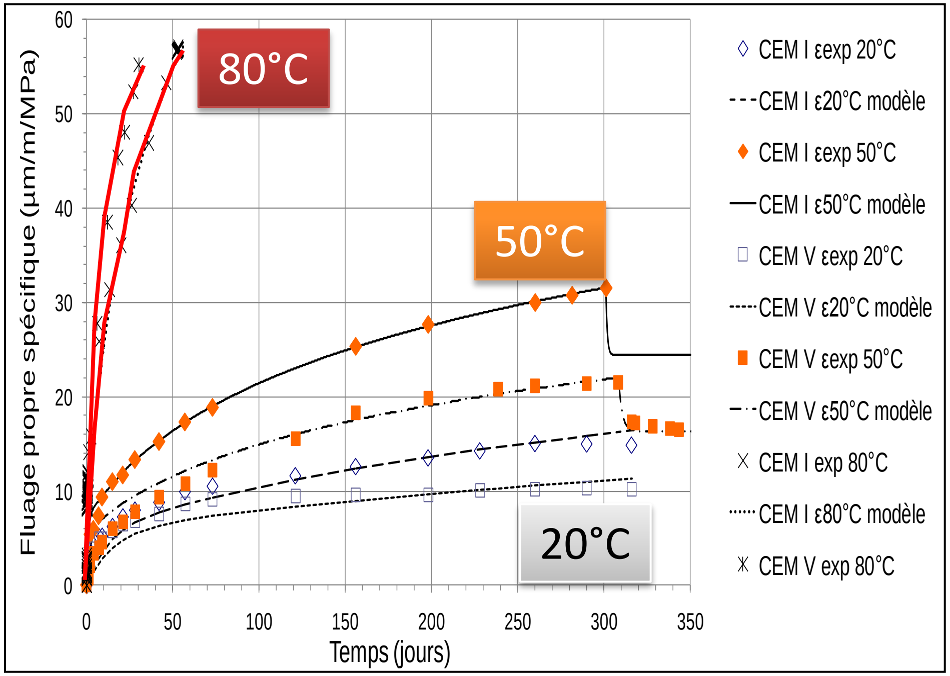


(exp results from Granger)

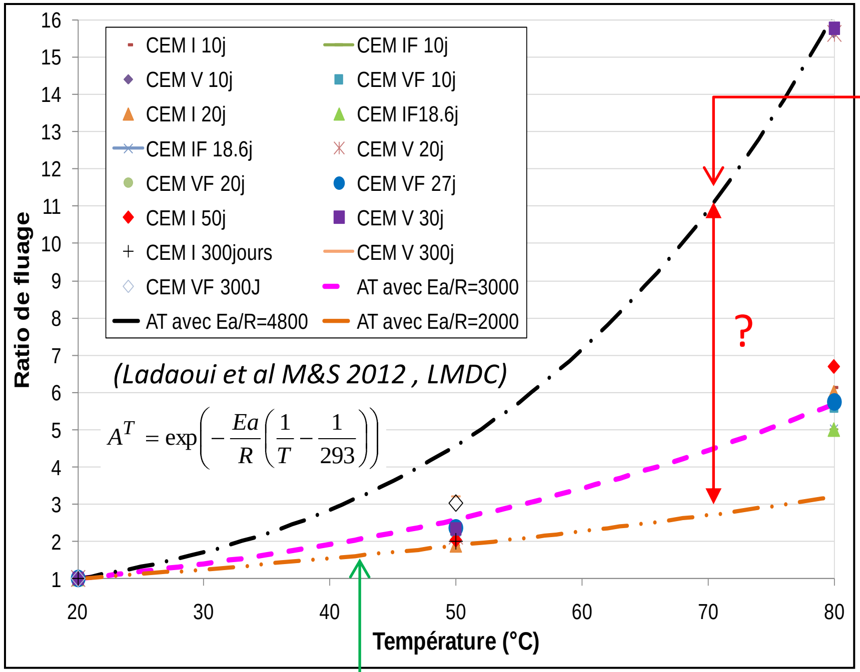
What is the reason for the drying creep (Pickett effect) ?

1- The main creep phenomena to understand and model

Effect of temperature on basic creep



(PhD W. Ladaoui exp results, LMDC 2010, M&S 2012)



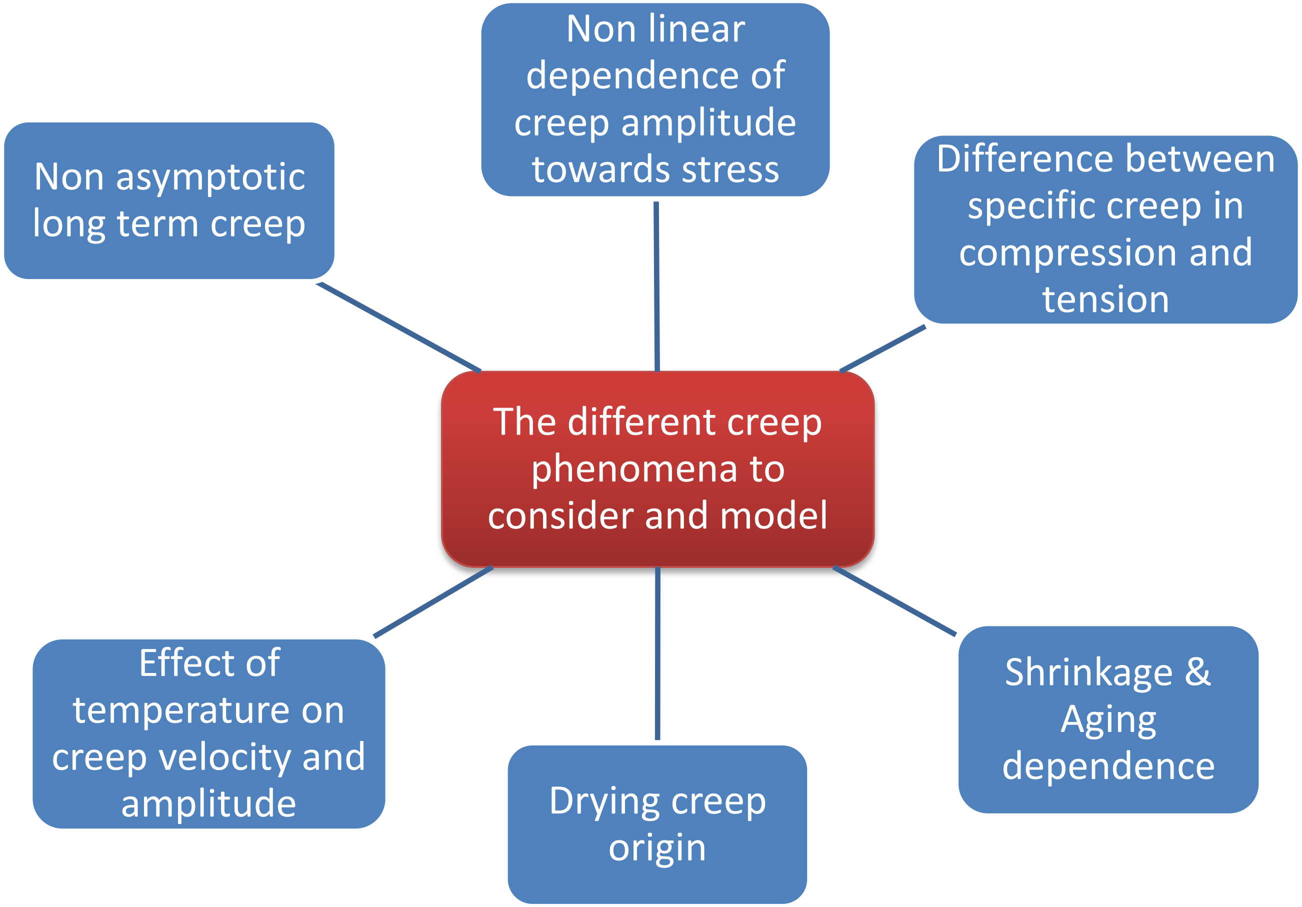
Heating from 20°C to 50°C : Creep X 2

Heating from 20°C to 80°C : creep X 5

Activation energy of water viscosity explains transition from 20 to 50°C but not to 80°C.

What happened above 50°C ?

1- The main creep phenomena to understand and model



Principle to clarify the model : Seeking underlying jointly causes to obtain a unified modeling of these different phenomena

2- The physical origin of creep

The hydrated cement paste : an heterogeneous material

Table 1 - Elastic, plastic and viscous characteristics of the main constituents of a fiber-reinforced UHPC (*Ductal*®), as measured using the nanoindentation technique (n.m. = not measurable).

	YOUNG's modulus (GPa)	Hardness (GPa)	Viscosity ($10^{-9} \cdot s^{-1}$)
Quartz aggregate	73 ± 1.6	10 ± 0.3	n. m.
Limestone aggregate	78 ± 1.4	10 ± 0.4	n. m.
Clinker: C_3S	135 ± 7	8.7 ± 1	n. m.
C_2S	130 ± 20	8.0 ± 2	n. m.
C_3A	145 ± 10	10.8 ± 1.5	n. m.
C_4AF	125 ± 25	9.5 ± 3	n. m.
C-S-H: C/S < 1	20 ± 2	0.8 ± 0.2	> 1
C/S > 1	31 ± 4	0.9 ± 0.3	~ 1
CH	36 ± 3	1.35 ± 0.5	n. m.

(From Acker ACI 2004)

Other phases are elastic and are able to limit the viscous strain of CSH

At the nanoscale level, the viscous phenomena are observable only in CSH

Damage induced by the heterogeneity nature of the material

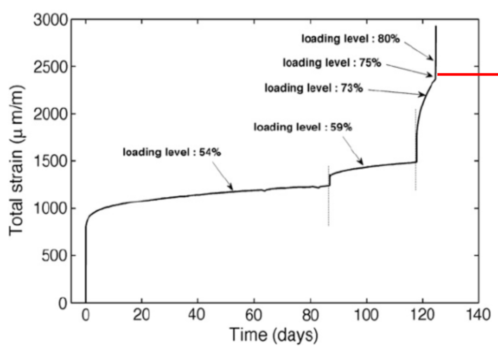


Fig. 2. Total strain versus time.

(Exp res from Rossi et al 2011)

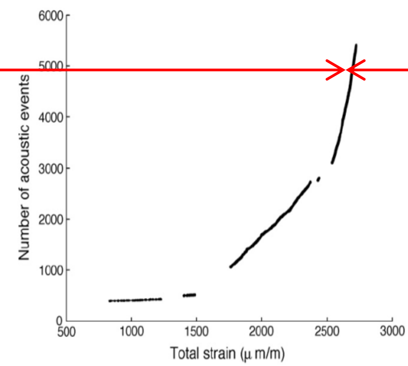


Fig. 3. Total number of acoustic events versus total strain for all the duration of the creep test.

Acoustic emission increases with creep amplitude and creep velocity

The creep is due to the visco-plastic behaviour of CSH (*)

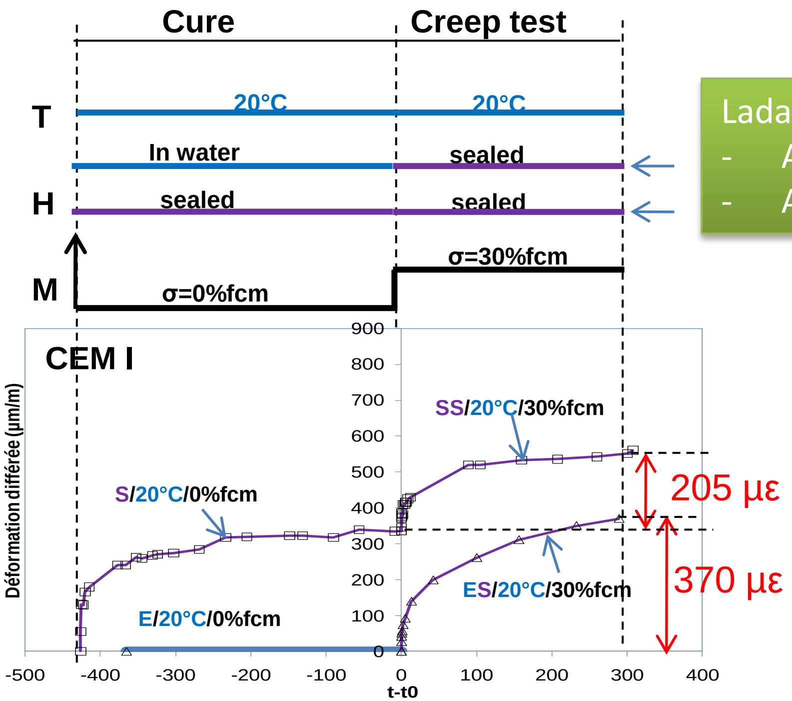
The other elastic phases limit creep

The stress redistribution induced at the micro-scale riles damage

Damage unblocks CSH sites to allows new creep…

2- The physical origin of creep

Link between basic creep strain and shrinkage, the importance of hydric history of concrete



THM creep test performed at LMDC Toulouse (Ladaoui et al 2011)

Ladaoui & al performed two simultaneous tests (LMDC Toulouse 2010):
- A specimen stored in water before basic creep test
- Another one stored in sealed condition before basic creep test

Basic creep is reduced if shrinkage occurs before the creep test

Basic creep capability is larger if autogenous shrincakge is limited before the creep test

Concrete presents a delayed strain potential which can be consumed either by shrinkage or by creep

It is not possible to predict properly the creep amplitude without considering the complete thermo-hydro-mechanical history of concrete !

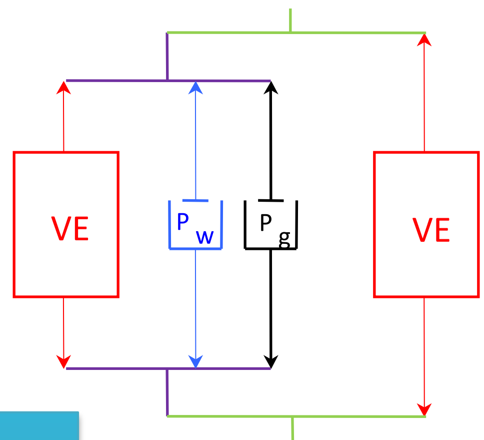
3- The main principles of the proposed model

A classical poro mechanical framework

Total stress

Spherical part of the total stress

Effective stress on Visco Elastic solid skeleton (spherical part)



Deviatoric part of the stress applied on Visco Elastic solid skeleton

$$\sigma = \sigma' - b_w S_w P_w \ldots$$

Water pressure
- positive if saturated
- negative for capillary effects

1st objective : understand and model the effect of water to assess *bw Sw Pw*

Other interstitial pressure (Gas, Ice, AAR, DEF, …)

2nd objective : Understand and model the behavior of the solid skeleton to assess the effective stress

3- The main principles of the proposed model

The water effect for non saturated concrete

- Capillary pressure acts on the solid to compress it

- Drying changes the interlayer distance for CSH riling a CSH shrinkage

→ The cement paste volume decreases

↓ Aggregates constrain the paste shrinkage

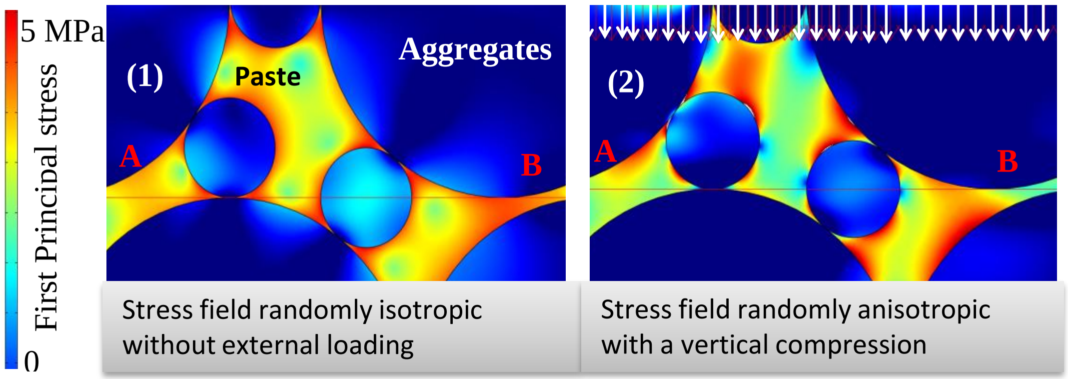
↓ An heterogeneous stress field appears

↓ Cracking induced by positive stresses in the paste

↓

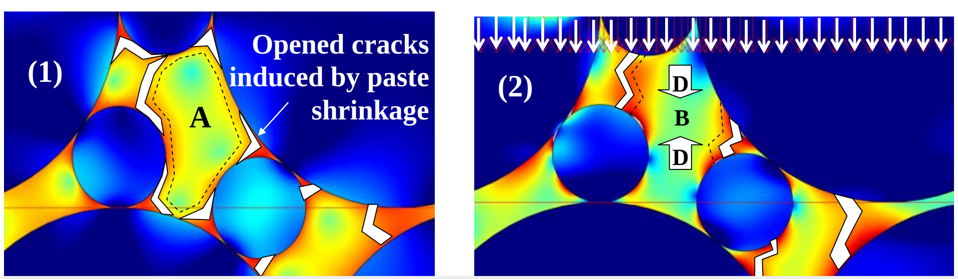
$$\sigma_I = \sigma_I' - b^0 (1 - \sigma_I / \sigma^{dc}) S_w P_w$$

↑ The transmission of water pressure in the poro-mechanical formulation becomes "anisotropicaly stress dependent"



Stress field randomly isotropic without external loading

Stress field randomly anisotropic with a vertical compression

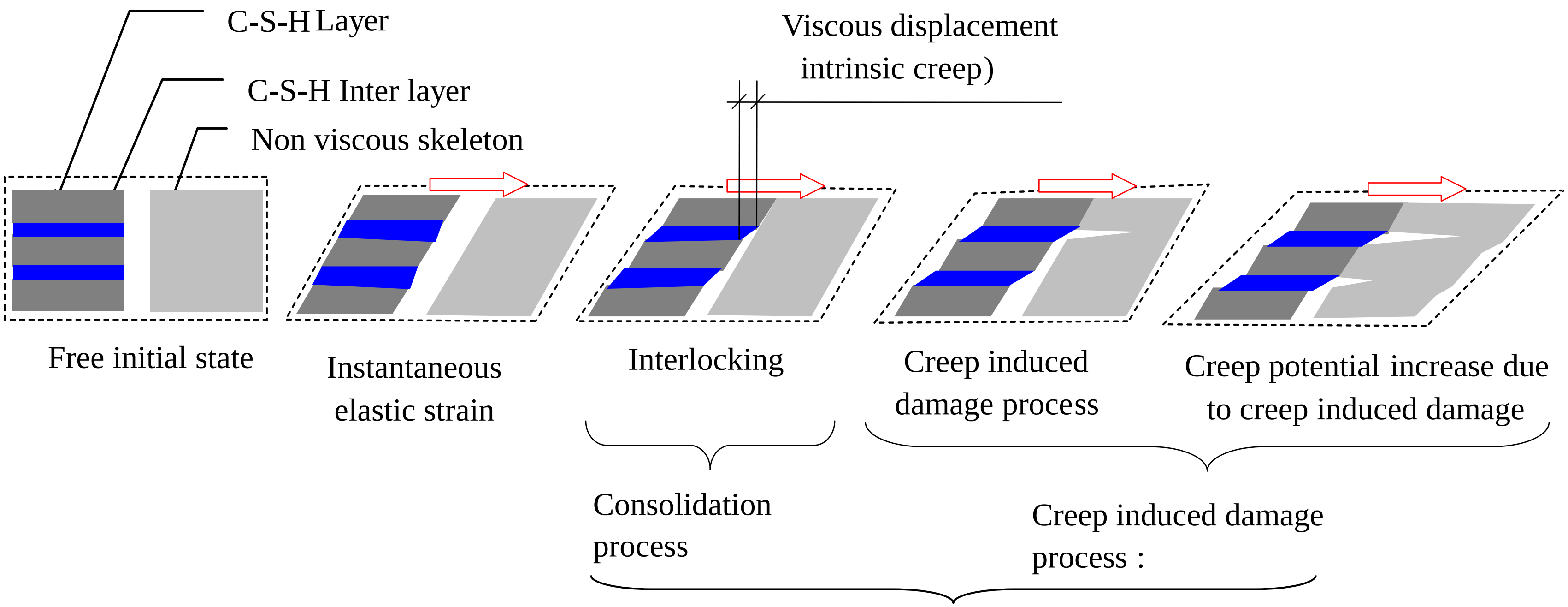


Paste clusters become isotropicaly unable to transmit their shrinkage to the macro level

Cracks are oriented : shrinkage continues to have an anisotropic effect only in the compression direction

3- The main principles of the proposed model

Solid skeleton behavior : main phenomena to consider non asymptotic creep and damage

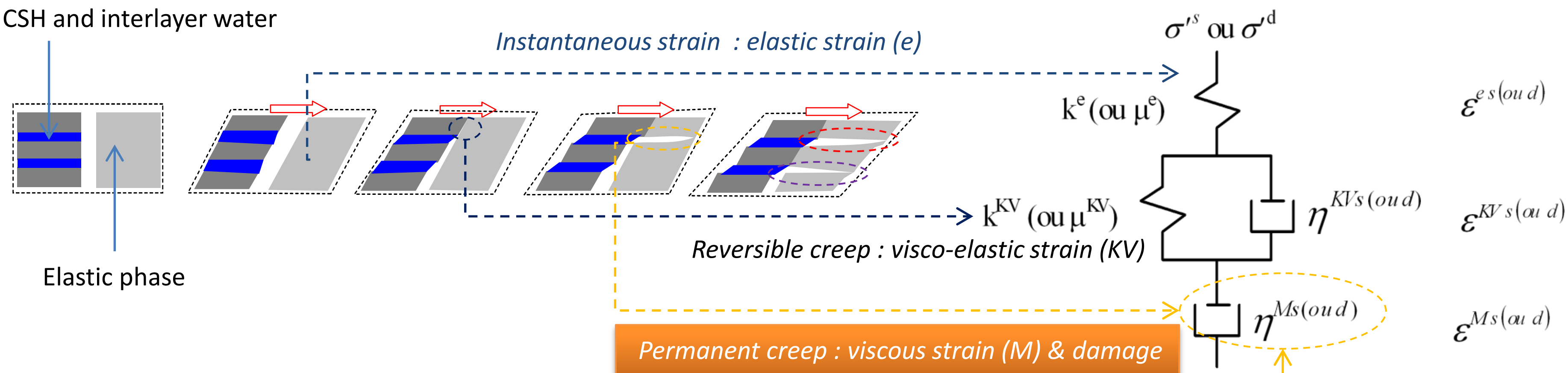


Two antagonist mechanisms coexist during creep phenomena :

- Interlocking decreases creep velocity and is responsible for the “strain creep potential” and the non asymptotic behavior at long term
- Damage allows news delayed strains, it increases the “strain creep potential” and explains the non linear dependence of creep amplitude towards the stress level

3- The main principles of the proposed model

Corresponding rheological scheme and associated equations



Permanent creep : viscous strain (M) & damage

Interlocking by elastic component increases apparent viscosity : i.e. consolidation phenomenon

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=−

The consolidation depends on viscous strain and creep strain potential

The stress redistribution between viscous & non viscous phases induces damage (acoustic emission evidences)

=

Damage increases creep strain potential and effective stresses (non linearity /)

3- The main principles of the proposed model

Equation forms for 3D incremental formulation

1- To compute the stress increment in the solid , strain increment splitted in elastic, visco-elastic and viscous strains

$$
\begin{cases}
\dot{\tilde{\sigma}}_{(s)} = k^0 \dot{\varepsilon}^0_{(s)} + \left\langle \dot{k}^0 \right\rangle^- \varepsilon^0_{(s)} \\
\dot{\tilde{\sigma}}_{(s)} = k^{KV} \dot{\varepsilon}^{KV}_{(s)} + \left\langle \dot{k}^{KV} \right\rangle \varepsilon^{KV}_{(s)} + \dot{\eta}^{KV}_{(s)} \dot{\varepsilon}^{KV}_{(s)} + \eta^{KV}_{(s)} \ddot{\varepsilon}^{KV}_{(s)} \\
\dot{\tilde{\sigma}}_{(s)} = (\dot{\eta}^M_{(s)} \cdot Cc + \eta^M_{(s)} \cdot \dot{C}c)\, \dot{\varepsilon}^M_{(s)} + (\eta^M_{(s)} \cdot Cc)\, \ddot{\varepsilon}^M_{(s)} \\
\dot{\varepsilon}_{(s)} = \dot{\varepsilon}^H_{(s)} + \dot{\varepsilon}^{KV}_{(s)} + \dot{\varepsilon}^M_{(s)} + \beta \cdot \dot{T}
\end{cases}
$$

In 3D Equivalent viscous strain is computed with viscous dissipation at a reference temperature

$$\varepsilon^{eq} = \frac{6\beta}{Rc(1+2\beta)} \Phi^v \qquad \Phi^v = \int \left(\varphi^d + \varphi^s \right) \left(\exp\left(-\frac{Ea}{R}\left(\frac{1}{T} - \frac{1}{T_O} \right) \right) \right) dt$$

Creep strain potential depends on loading level via the asymptotic damage and on temperature

$$\varepsilon_k = \varepsilon_0 \frac{d^{bc}_\infty}{d^{bc}_{\max}} \exp\left(-\frac{Ea}{R}\left(\frac{1}{T} - \frac{1}{\inf(T_2, T)} \right) \right)$$

Viscosity depends on temperature and consolidation state

Consolidation state depends on equivalent viscous strain and creep potential

$$\eta^M = C_c \cdot \frac{\eta^{M0}}{\exp\left(-\frac{Ea}{R}\left(\frac{1}{T} - \frac{1}{T_O} \right) \right)} \qquad C_c = \exp\left(\frac{\varepsilon^{eq}}{\varepsilon^k} \right)$$

Asymptotic damage depend on the energy restitution rate in elastic phases

Creep damage tends to the asymptotic damage according to the consolidation coefficient evolution

$$\dot{d}^{bc} = \frac{d^{bc}_{\max}}{\varepsilon_0 C_c} \dot{\varepsilon}^{eq} \qquad \frac{d^{bc}_\infty}{d^{bc}_{\max}} = \frac{Y^{bc(e)}}{Y^{bc(\max)}}$$

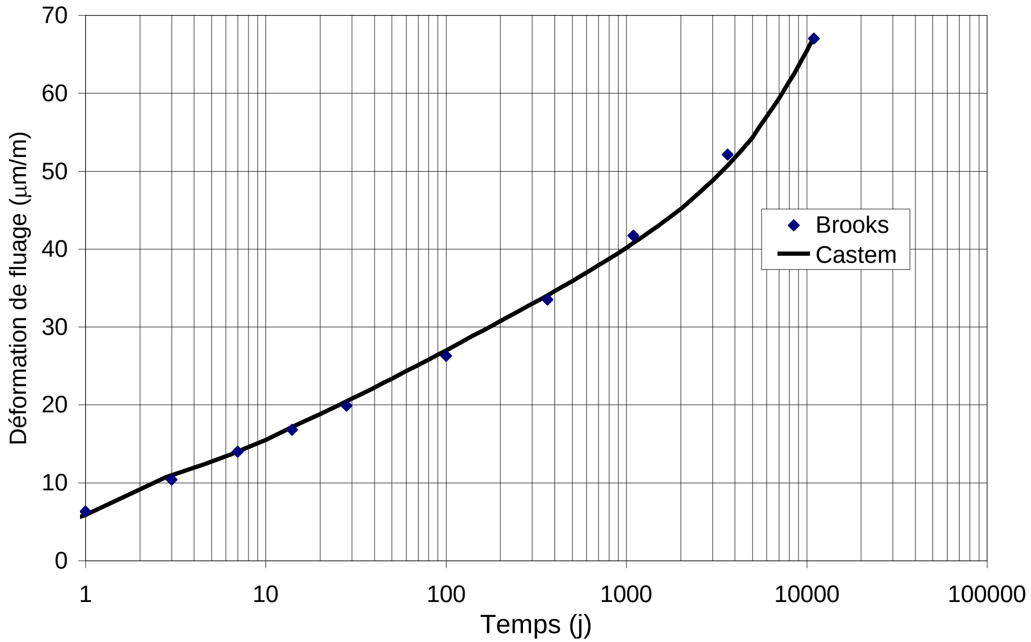
2- The poro damage theory merges creep damage and pore pressure to achieve the model

Once effective stress and damage are assessed the poro-mechanical formulation with the modified transmission of capillary pressure merges the different phenomena

$$\vec{\sigma} = (1 - d^{bc}) \vec{\sigma}' - b^0 (1 - \vec{\sigma} / \sigma^{dc}) \pi$$

4- Abilities of the model to simulate non linear creep phenomena

Non asymptotic creep phenomena induced by progressive consolidation of concrete

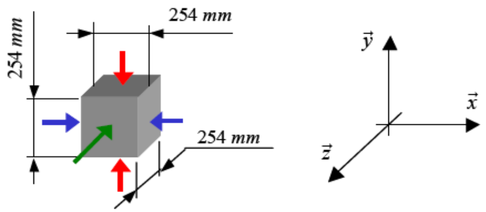


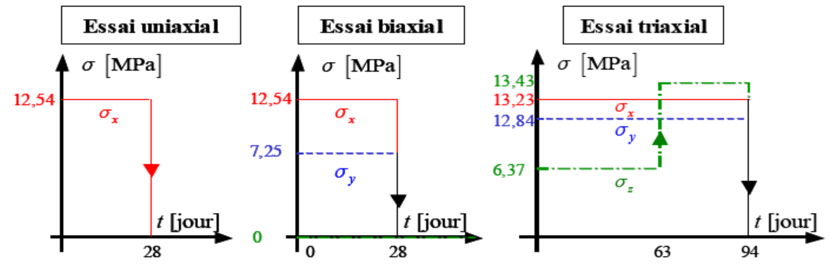
(Fitting on 30 years uniaxial basic creep test performed by Brooks)

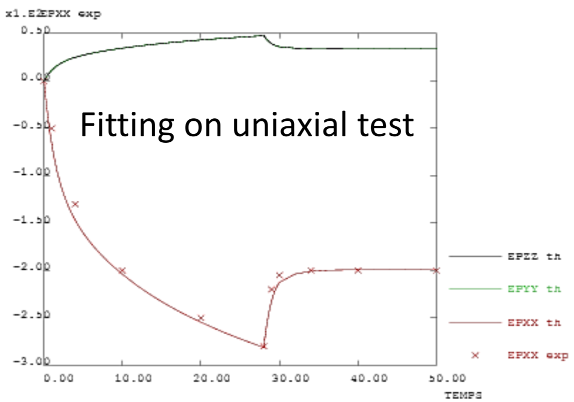
The exponential form chosen for the consolidation function allows to simulate non asymptotic long term basic creep, fitting only two parameters (initial viscosity and creep strain potential)

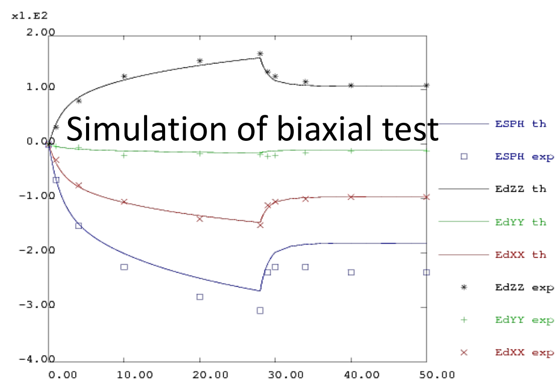
4- Abilities of the model to simulate non linear creep phenomena

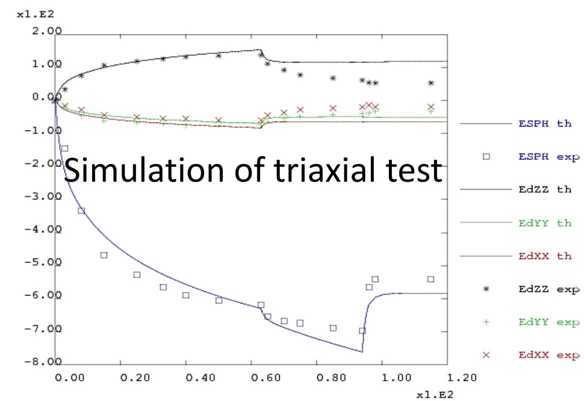
Consolidation under multiaxial loading











(Exp results from Gopalakrishnan et al., 1969)

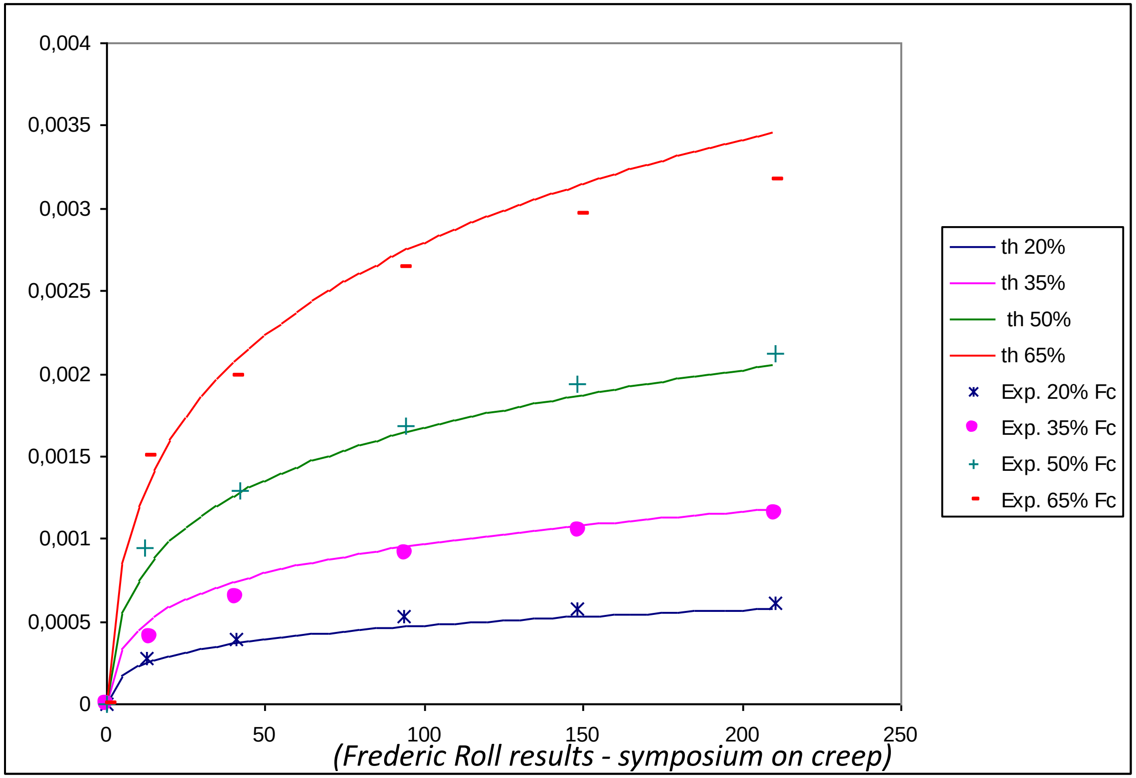
The equivalent strain (computed from the total viscous dissipation) is able to consider consolidation phenomenon under multi axial loading

4- Abilities of the model to simulate non linear creep phenomena

Non linear dependence of creep amplitude on stress

Basic creep strain X 2.8

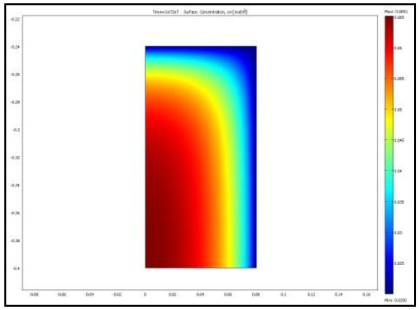
Compressive stress X 1.7



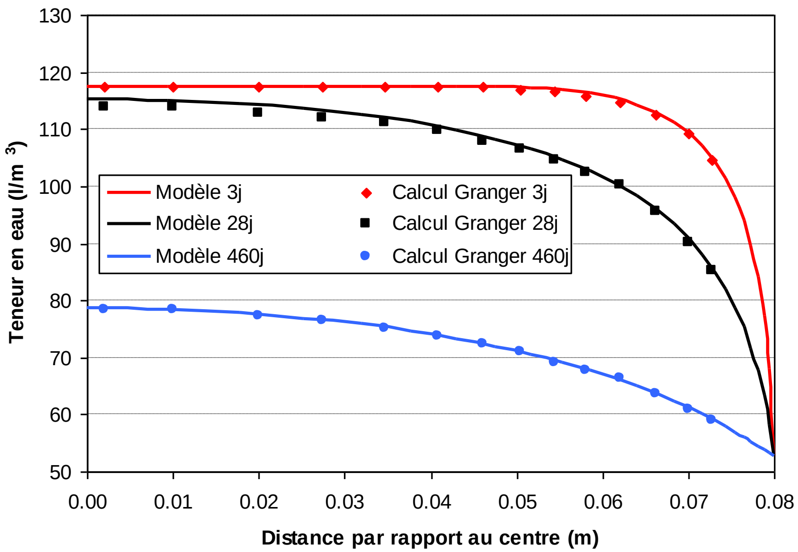
The elastic energy restitution rates used to asses damage and its coupling with consolidation leads to a non linear dependence of creep amplitude towards the stress

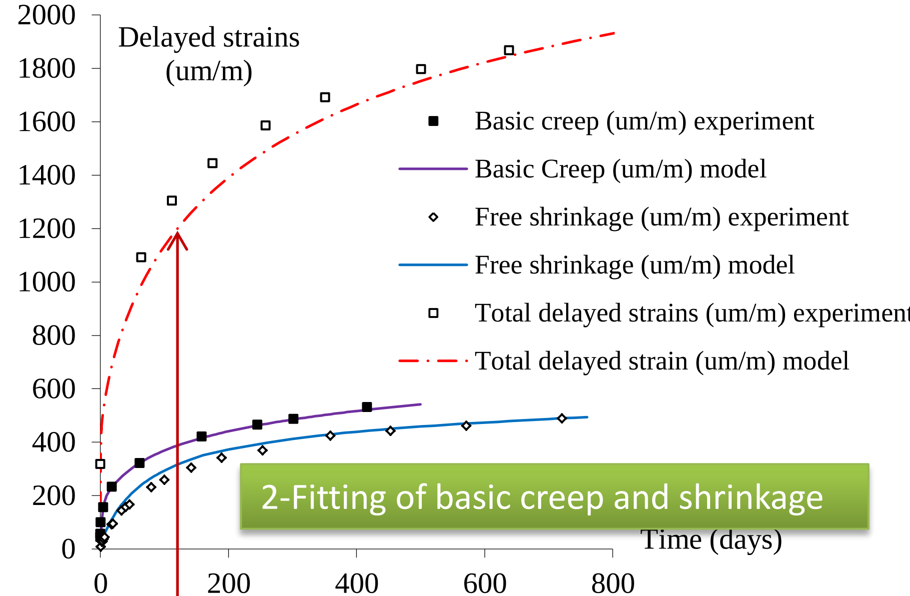
4- Abilities of the model to simulate non linear creep phenomena

Pickett effect (drying creep)



1- Water mass loss simulation





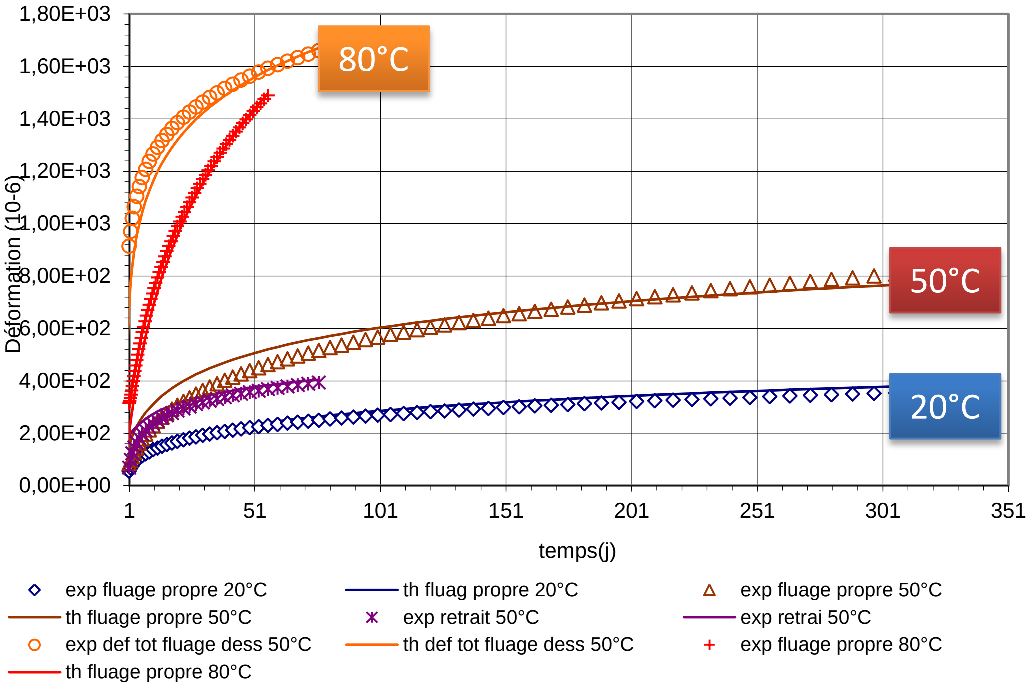
2-Fitting of basic creep and shrinkage

3- The non linear poro-mechanical formulation allows to simulate the Pickett effect

4- Abilities of the model to simulate non linear creep phenomena

Pickett effect (drying creep)

(Fitting on Ladaoui et al. 2012 results)

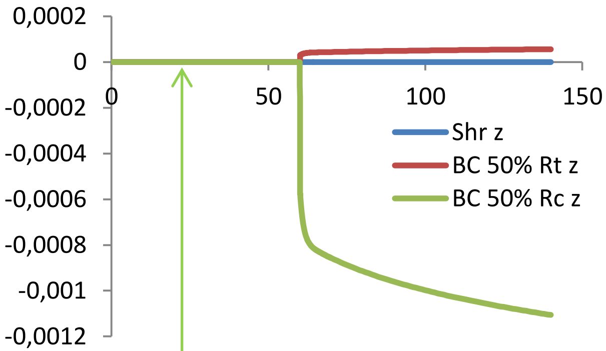


Dependence of damage on temperature allows to reach exp results at 80°C

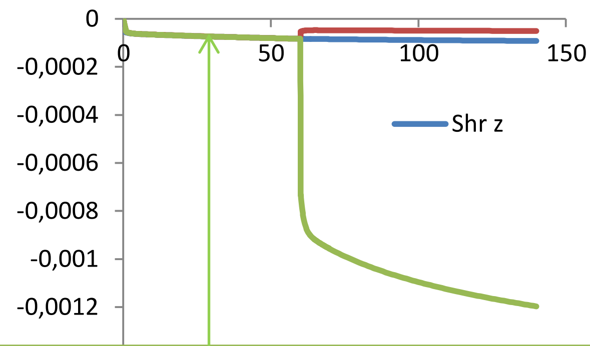
Dependence of viscosity on temperature allows to simulate effect of temperature until 50°C

4- Abilities of the model to simulate non linear creep phenomena

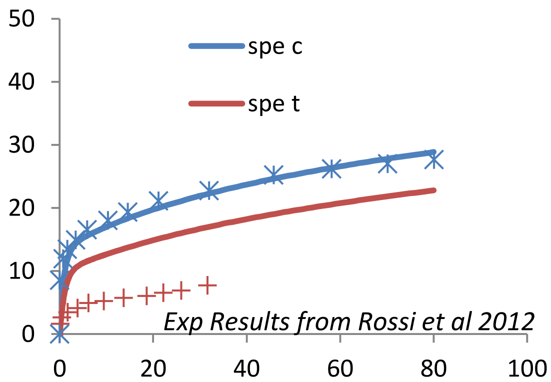
Difference of specific creep in tension and in compression

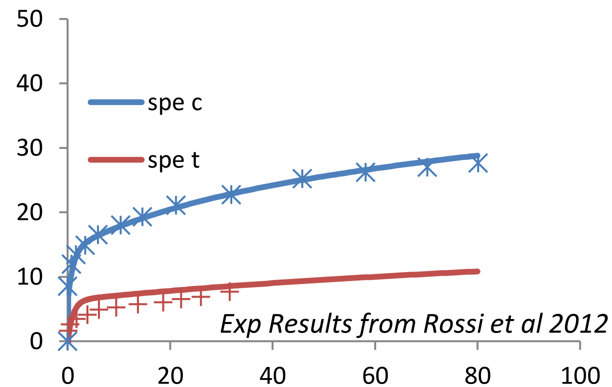


Creep without previous autogenous shrinkage



Creep with previous autogenous shrinkage





Specific creep in tension over estimated if hydric historu of specimen neglected

Specific creep in tension lesser than in compression <u>if hydric history correctly considered in the simulation</u>

Conclusion

Four basic phenomena allows to simulate the main experimental observations

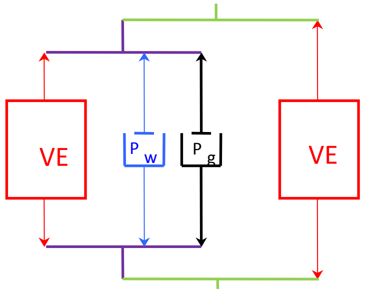
Most of them are the direct consequences of the heterogeneous nature of the material

1- The Pickett effect is due to a modification of the water pressure transmission in the poro-mechanical scheme

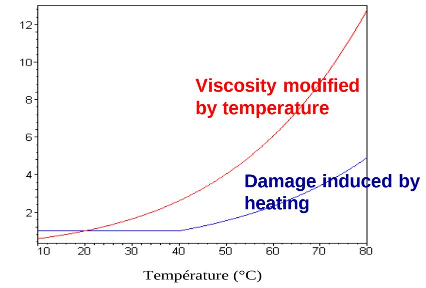
Temperature reduces the viscosity, and
2- temperature >50°C modifies the creep strain potential (damaging the cement paste)

3- The non asymptotic shape of the creep curve id due to the consolidation process induced by interlocking of CSH by elastic inclusion

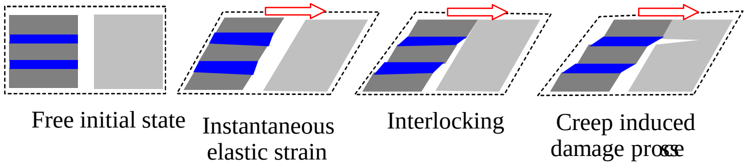
4- The dependence of the creep amplitude towards the stress is a consequence of damage due to the redistribution of stress between viscous and non viscous inclusions



Thermal activation of creep



All the other observations (effect of multi-axiality or effect of the sign of stresses on the specific creep) can be simulated provided the hydric history of the specimen is correctly considered



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Thank you for your attention

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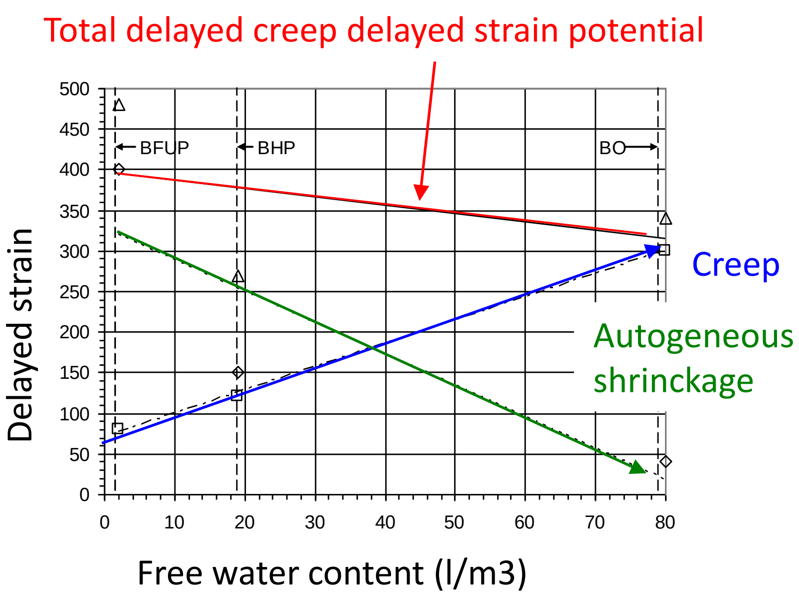
2- The physical origin of creep

Experimental evidence of link between basic creep strain and shrinkage



(A.Sellier & L.Buffo Lacarriere EJECE 2009)
(Exp Results from REGC P.Acker 2003)

Larger the initial shrinkage, lesser the creep

Basic creep is reduced by previous autogeneous shrinckage

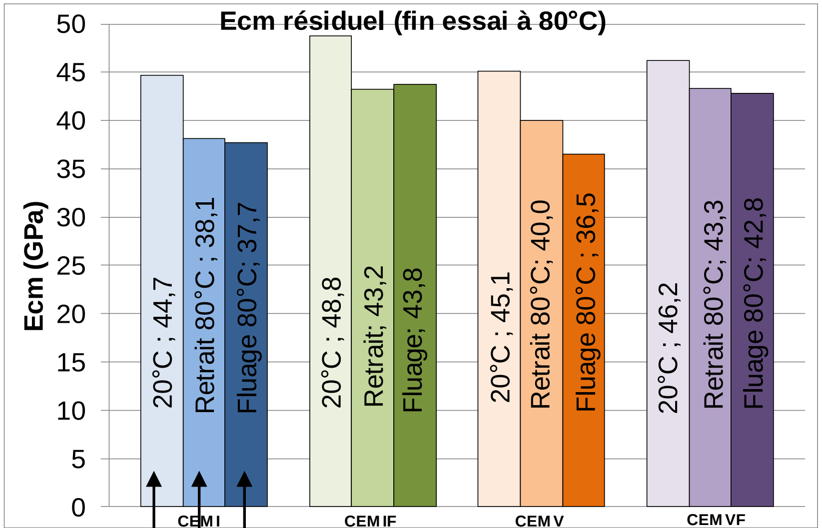
Need to consider effect of capillary pressure as a loading superposed to the external loading : the both loading consumes simultaneously the "creep delayed strain capabilty of concrete"

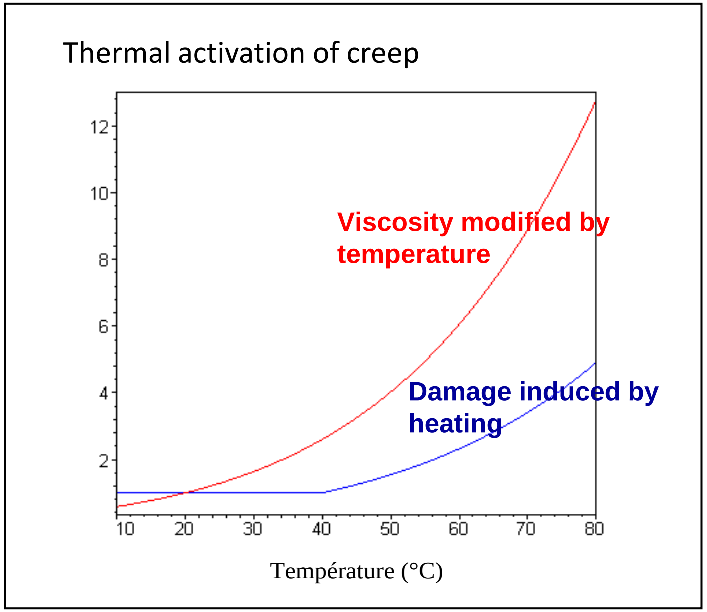
The poro mechanics framework must be used to merge internal and external loading

3- The main principles of the proposed model

The effect of temperature on creep velocity and amplitude

(LMDC results PhD work of W.Ladaoui 2010)





Effect of temperature can be devided in viscosity effect and thermal damage effect

Young modulus after creep

Young modulus after heating

Young Modulus before heating

At 80°C damage mainly due to heating, not to creep

Temperature effect on viscosity acts on viscosity

Thermal damage changes the creep strain potential