

# **Fatigue THM-C des bâtiments historiques : entre les mythes et les réalités**

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# Plan

1 – Motivation

2 – Investigation de quelques mécanismes de dégradation des pierres :

- Contrainte thermo-hydro-mécanique
- Hétérogénéité et variabilité des propriétés physiques
- Interaction hydro-mécano-chimique avec l'environnement

3- Conclusions

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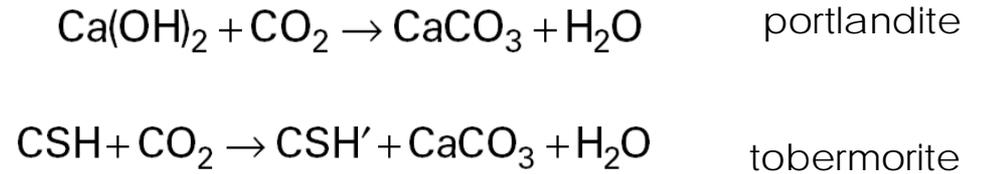
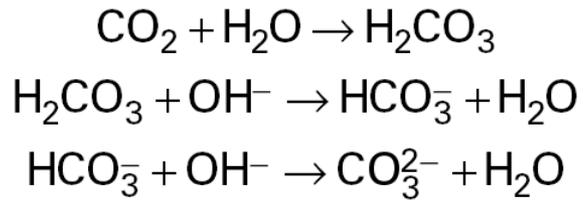


# 1- MOTIVATION





# 1- MOTIVATION



pH > 10



8.3 < pH < 10



pH < 8.3

From Ph.D. Huet B. (2005)

# What is the role of natural factors on degradation process ?



-Pas de sources locales anthropologiques connues ni de conditions particulières pour expliquer la dégradation ,

Credits : <http://www.crmd-sa>



# 1- MOTIVATION



**CRACK & DEFORMATION**  
FISSURE & DÉFORMATION

**CRACK** . FISSURE

**Fracture** . Fracture

**Star crack** . Fissuration en étoile

**Hair crack** . Microfissure

**Craquele** . Craquellement

**Splitting** . Clivage

**DEFORMATION** . DÉFORMATION



**DETACHMENT**  
DÉTACHEMENT

**BLISTERING** . BOURSOULFURE

**BURSTING** . ECLATEMENT

**DELAMINATION** . DÉLITAGE

**Exfoliation** . Exfoliation

**DISINTEGRATION** .  
DÉSAGRÉGATION

**Crumbling** . Emiettement

**Granular disintegration** .  
Désagrégation granulaire

■ **Powdering, Chalking** . Pulvéulence,  
Farinage

■ **Sanding** . Désagrégation sableuse

■ **Sugaring** . Désagrégation saccharoïde

**FRAGMENTATION** .  
FRAGMENTATION

**Splintering** . Fragmentation en esquilles

**Chipping** . Epaufrure

**PEELING** . PELAGE

**SCALING** . DESQUAMATION

**Flaking** . Ecaillage

**Contour scaling** . Desquamation en plaque



**FEATURES INDUCED BY MATERIAL LOSS**  
FIGURES INDUITES PAR UNE PERTE DE MATIÈRE

**ALVEOLIZATION** . ALVÉOLISATION

**Coving** . Creusement

**EROSION** . ÉROSION

**Differential erosion** . Erosion différentielle

**Loss** . Perte :

■ **of components** . de constituants

■ **of matrix** . de matrice

**Rounding** . Erosion en boule

**Roughening** . Augmentation de rugosité

**MECHANICAL DAMAGE** .  
DÉGÂT MÉCANIQUE

**Impact damage** . Trace d'impact

**Cut** . Incision

**Scratch** . Rayure

**Abrasion** . Abrasion

**Keying** . Bûchage

**MICROKARST** . MICROKARST

**MISSING PART** .  
PARTIE MANQUANTE

**Gap** . Trou



**DISCOLORATION & DEPOSIT**  
ALTÉRATION CHROMATIQUE ET DÉPÔT

**CRUST** . CROÛTE

**Black crust** . Croûte noire

**Salt crust** . Croûte saline

**DEPOSIT** . DÉPÔT

**DISCOLOURATION** .  
ALTÉRATION CHROMATIQUE

**Colouration** . Coloration

**Bleaching** . Décoloration

**Moist area** . Assombrissement dû à l'humidité

**Staining** . Tache

**EFFLORESCENCE** . EFFLORESCENCE

**ENCRUSTATION** . ENCRÔTEMENT

**Concretion** . Concrétion

**FILM** . FILM

**GLOSSY ASPECT** . ASPECT LUISANT

**GRAFFITI** . GRAFFITI

**PATINA** . PATINE

**Iron rich patina** . Patine ferrugineuse

**Oxalate patina** . Patine d'oxalates



**BIOLOGICAL COLONIZATION**  
COLONISATION BIOLOGIQUE

**BIOLOGICAL COLONIZATION** .  
COLONISATION BIOLOGIQUE

**ALGA** . ALGUE

**LICHEN** . LICHEN

**MOSS** . MOUSSE

**MOULD** . MOISSISURE

**PLANT** . PLANTE

Desquamation en feuillets : rambardes



Desquamation en feuillets : partie inférieure du stylobate



Chambord : Desquamation en feuillets et en plaques

Thèse S. Badoso 2012



Quels mécanismes pour quelle dégradation ?

Quelles évidences des mécanismes supposés ?

Comment vérifier ces hypothèses ?

Comment quantifier l'impact de ces mécanismes ?

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## 3- Conclusions

## 2-INVESTIGATION : Contrainte THM

Usually derived from a rigorous thermodynamic framework:

- state functions
- state variables
- thermodynamic principles

### Principal hypothese

*H-M-T-C additif potentials*

*H-M-T-C additif potentials*



## 2-INVESTIGATION : Contrainte THM

Coussy (2005)

H-M mixed potential of a **fully saturated** porous elasto-plastic material

$$W^\# = W^0 + \frac{1}{2} \underline{\underline{(\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}^p)}} : \underline{\underline{C_0}} : (\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}^p) - (p - p_0) \underline{\underline{B}} : (\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}^p) - \frac{1}{2M} \underline{\underline{(p - p_0)}} + \psi^p(V_k)$$

State equations (isothermal conditions)

$$\underline{\underline{\sigma}} = \frac{\partial W^\#}{\partial \underline{\underline{\varepsilon}}} = \underline{\underline{C_0}} : (\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}^p) - \underline{\underline{B}}(p - p_0)$$

$$\frac{m}{\rho_{fl}^0} \phi^p = \frac{\partial W^\#}{\partial p} = -\underline{\underline{B}} : (\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}^p) - \frac{1}{M}(p - p_0)$$

$$\underline{\underline{\sigma'}} = \underline{\underline{\sigma}} + \underline{\underline{B}}(p - p_0)$$



Terzaghi effective stress

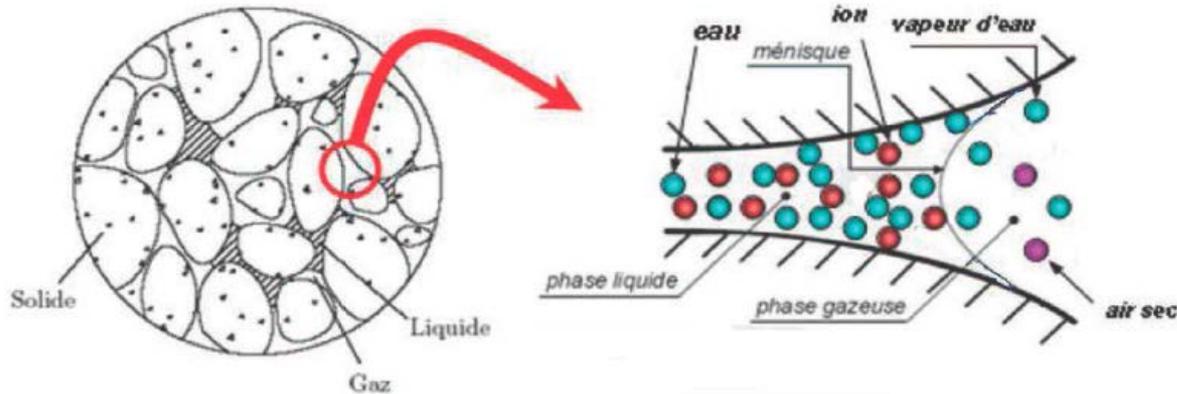
$$\underline{\underline{\sigma'}} = \underline{\underline{\sigma}} - u$$

Purely rheological concepts

$$\underline{\underline{\sigma'}} = \underline{\underline{\sigma}} + \underline{\underline{\beta}}(p - p_0) \quad \text{Effectif plastic stress}$$

## 2-INVESTIGATION : Contrainte THM

For a **partially saturated** porous material (isothermal conditions)



$$\underline{\underline{\sigma'}} = \underline{\underline{\sigma}} + \underline{\underline{B}}(p - p_0)$$



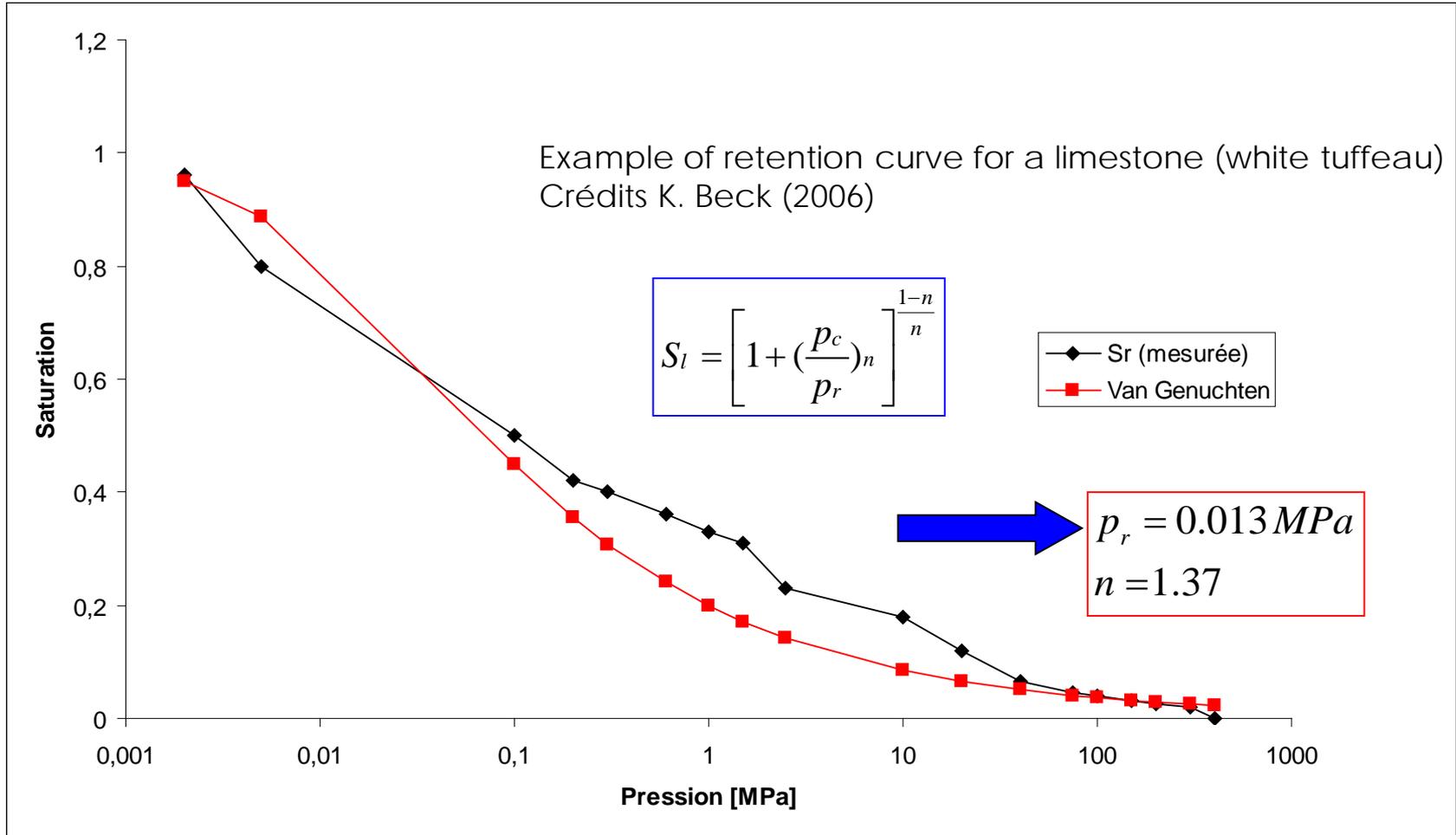
$$\underline{\underline{\sigma'}} = \underline{\underline{\sigma}} + \underline{\underline{B}}(\pi - \pi_0)$$

With

$$\pi = \begin{cases} \int_{S_{lq}}^1 S_{lq}(P_C) dP_C & \text{si } S_{lq} < 1 \\ P_{lq} & \text{si } S_{lq} = 1 \end{cases}$$

$$P_c = P_g - P_{lq}$$

Capillary pressure  $\leftrightarrow$  suction



## - Multiphase flow

## 2-INVESTIGATION : Contrainte THM

$$\frac{\underline{M}_j}{\rho_j} = \lambda_j (-\underline{\nabla}P_j + \rho_j \underline{F}) \quad j = \begin{cases} \text{w} \rightarrow \text{water liquid,} \\ \text{gz} \rightarrow \text{gaz} \end{cases}$$

$$\lambda_j = \frac{k_{in} \cdot k_j^{rel}(S_{lq})}{\mu_j}$$

$$k_l^{rel}(S_{lq}) = S_{lq}^m$$

**Darcy law for unsaturated media**

$$C_{vp} = \frac{p_{vp}}{p_{gz}} \quad \frac{\underline{M}_{vp}}{\rho_{vp}} - \frac{\underline{M}_{as}}{\rho_{as}} = -F \underline{\nabla} C_{vp}$$

**Fick diffusion**

+ *masse conservation law*

Multiphase equilibrium

✓ *Kelvin law:*

*parfait gases (air and water vapor)*

$$P_C = \frac{\rho_l \cdot R \cdot T}{M_l^{ol}} \ln(Hr)$$

## 2-INVESTIGATION : Contrainte THM

*For non-isothermal conditions*

$$\underline{\underline{\sigma'}} = \underline{\underline{\sigma}} + b \pi \underline{\underline{I}} + 3\alpha K \Delta T \underline{\underline{I}}$$

thermics

hydrics

- **Thermal diffusion**

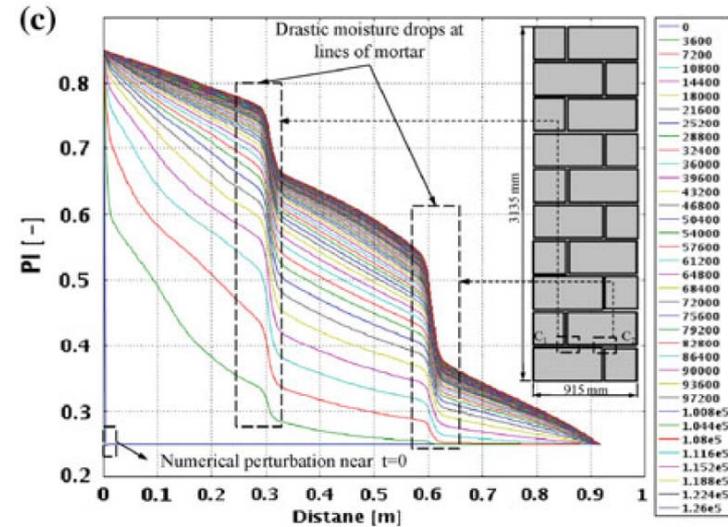
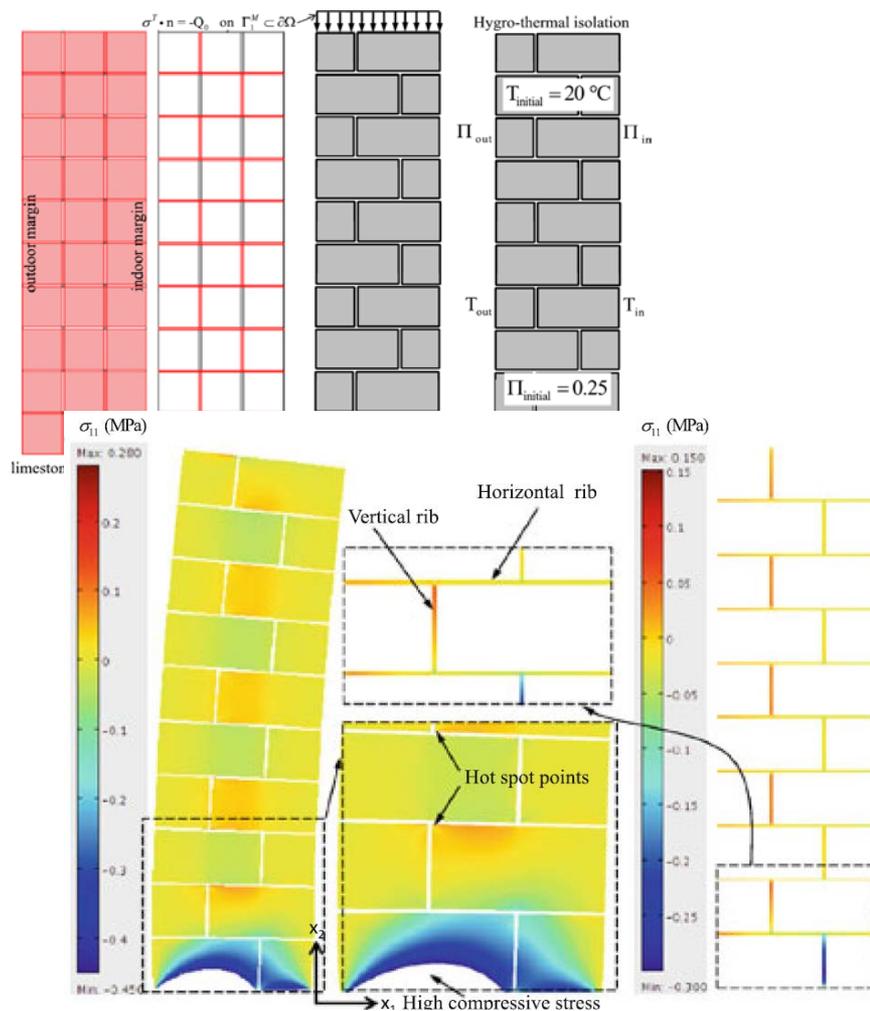
$$\underline{q} = -\lambda_T \nabla (T)$$

**Fourier law**

$$\sum_i h_i^m \dot{m}_i + \sum_i \text{div}(h_i^m \underline{M}_i) + \text{div}(\underline{q}) + Q' = \Theta$$

**Energy conservation**

i = liquid, dry air, vapour, dissolved gas

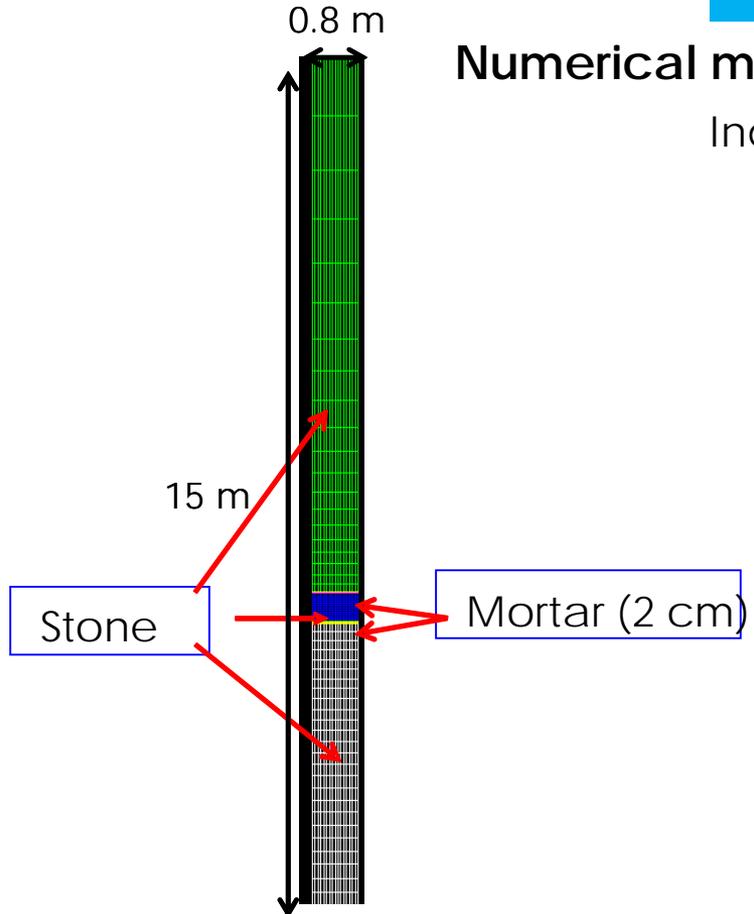


Coherent conclusions , but .... :

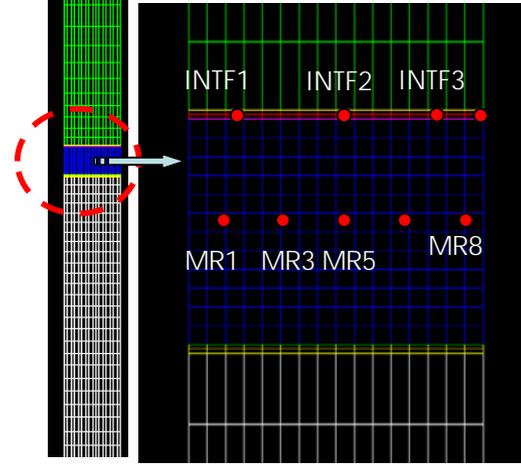
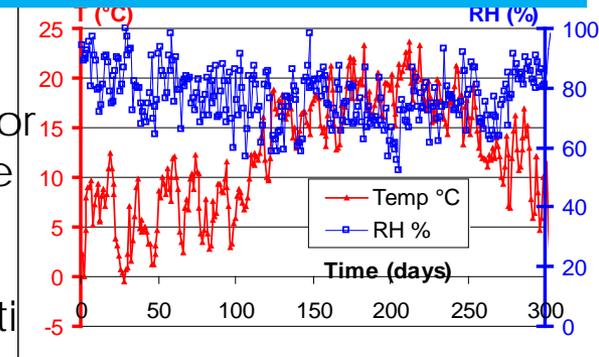
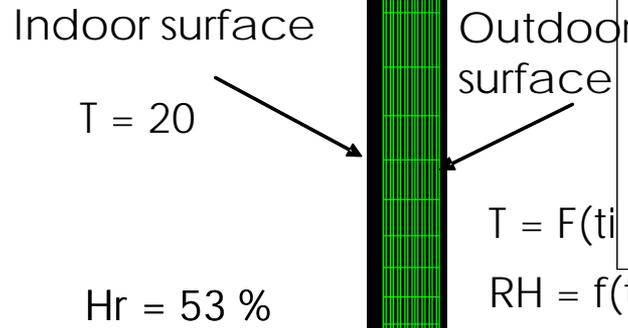
*“The moisture lag areas speed up the moisture movement in a localized zone and they facilitate the local degradation of the individual bricks”*

*The mechanically induced stresses are overall geometry dependent and they change with different brick size and mortar thickness. Hence, it is straightforward to find out the hot zones at the brick corners*

## 2-INVESTIGATION : Contrainte THM



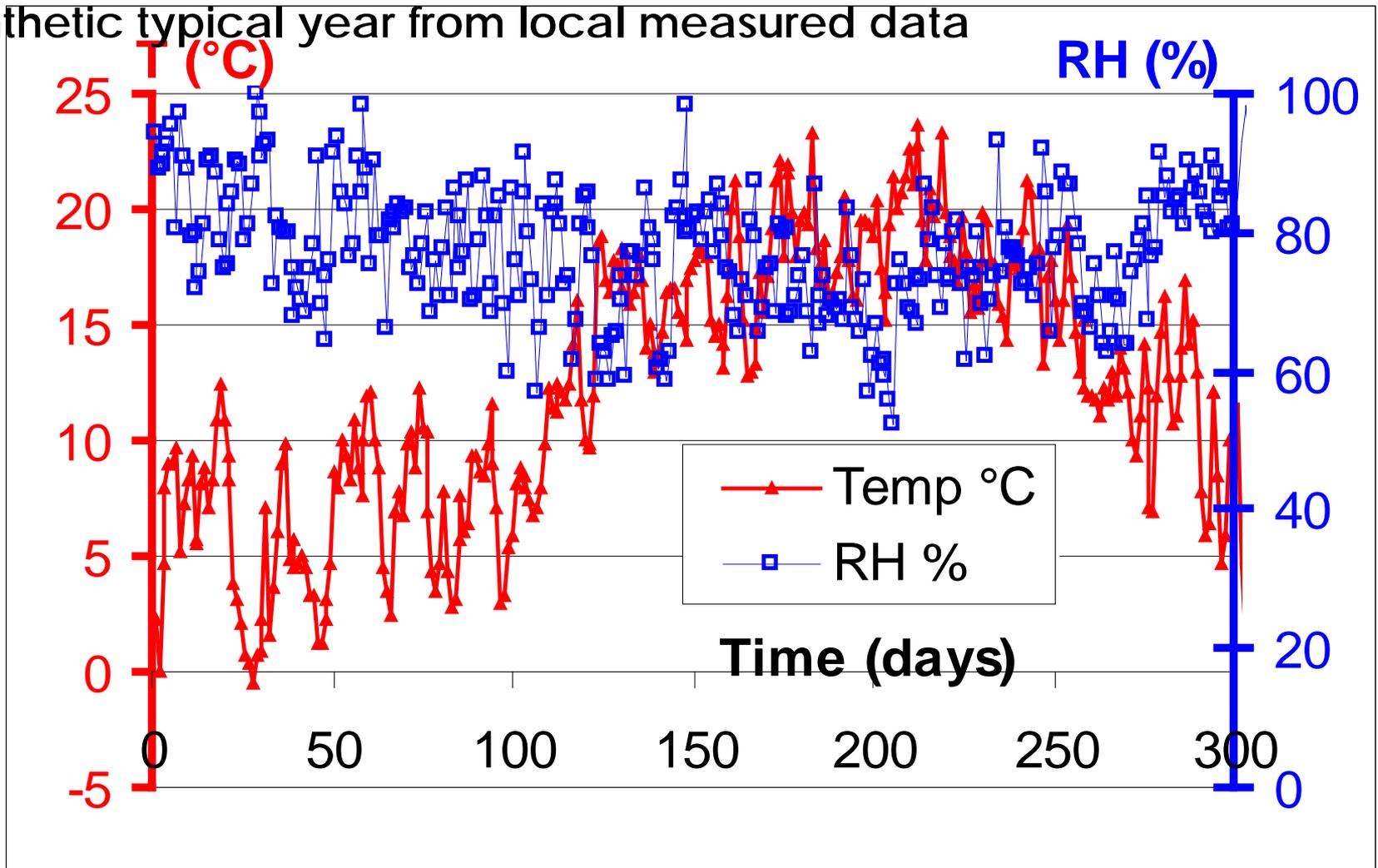
### Numerical model



$U_x = 0.0, U_y = 0.0$

## 2-INVESTIGATION : Contrainte THM

Synthetic typical year from local measured data



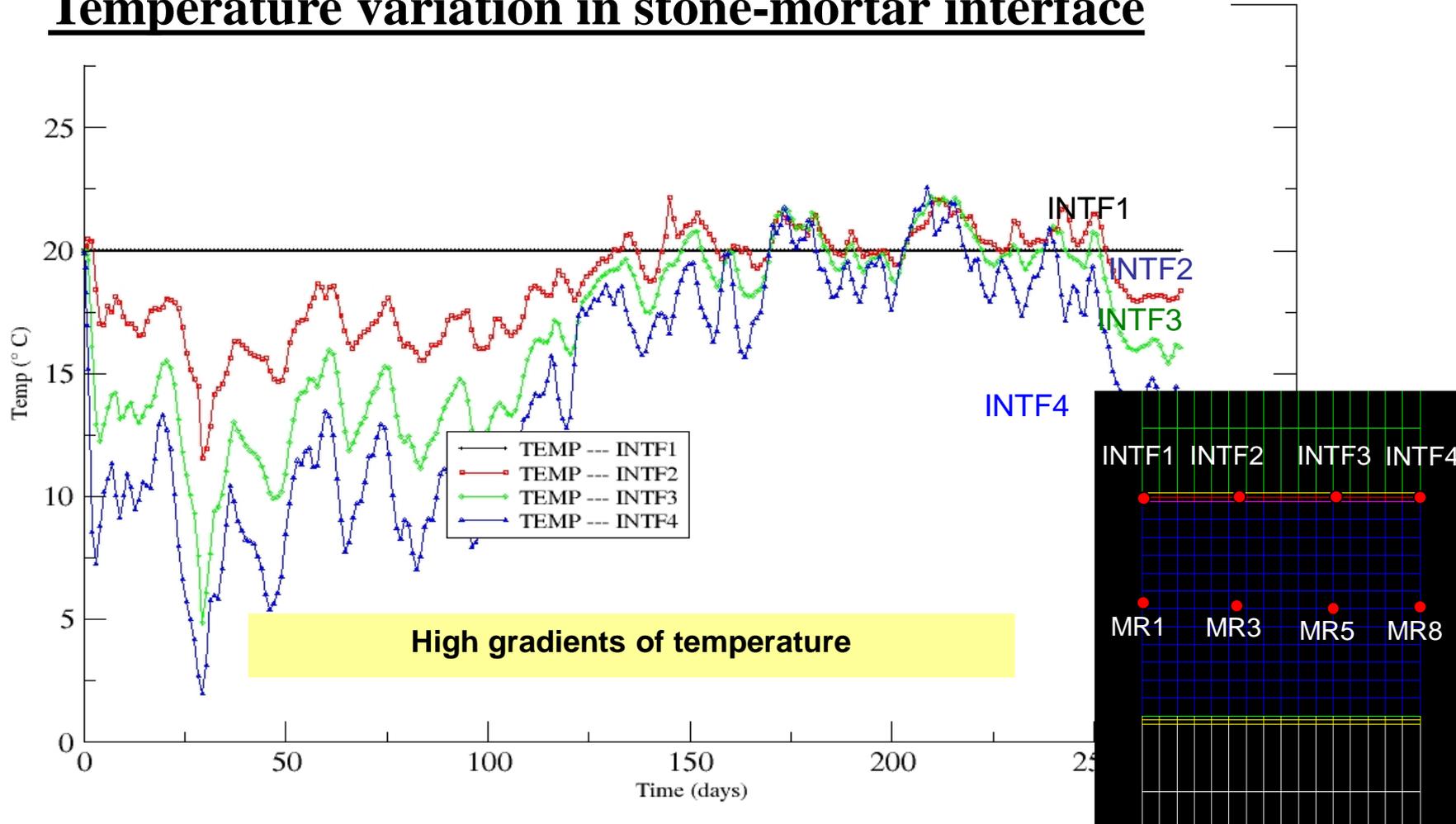
### Material parameters (stone and mortar)

- ✓ Most of parameters identified from laboratory tests.
- ✓ Some are calibrated from in situ measurement)

		Stone tuff	Mortar
Mechanics	Young's modulus Poisson coefficient	$E_0=1953 \text{ MPa}$ $\nu_0=0.19$	$E_m=1604 \text{ MPa}$ $\nu_m=0.205$
Hydraulics	Intrinsic permeability Porosity Fick's diffusion coefficient	$k_{\text{int}} = 10^{-13} \text{ m}^2$ $\Phi = 42\%$ $F=2.05 \times 10^{-6} \text{ m}^2/\text{s}$	$k_{\text{int}} = 0.2 \cdot 10^{-13} \text{ m}^2$ $\phi = 50\%$ $F=2.05 \times 10^{-6} \text{ m}^2/\text{s}$
Thermics	Thermal conductivity Specific heat	$\lambda=0.56 \text{ W.m}^{-1}.\text{K}^{-1}$ $C_p=800 \text{ J.kg}^{-1}.\text{K}^{-1}$	$\lambda=0.56 \text{ W.m}^{-1}.\text{K}^{-1}$ $C_p=800 \text{ J.kg}^{-1}.\text{K}^{-1}$
Coupling THM	Biot's coefficient	$b=0.5$	$b=0.5$
	Retention curve	<b><math>n=1.37</math></b> <b><math>Pr =0.013 \text{ MPa}</math></b>	<b><math>n=1.37</math></b> <b><math>Pr =0.013 \text{ MPa}</math></b>
	Relative permeability	<b><math>m=3</math></b> $k_l^{\text{rel}}(S_l) = S_l^m$ ; $k_g^{\text{rel}}(S_l) = (1 - S_l^m)$	<b><math>m=3</math></b>
	Thermal expansion coefficient	$\alpha=6 \times 10^{-6} \text{ K}^{-1}$	$\alpha=12 \times 10^{-6} \text{ K}^{-1}$

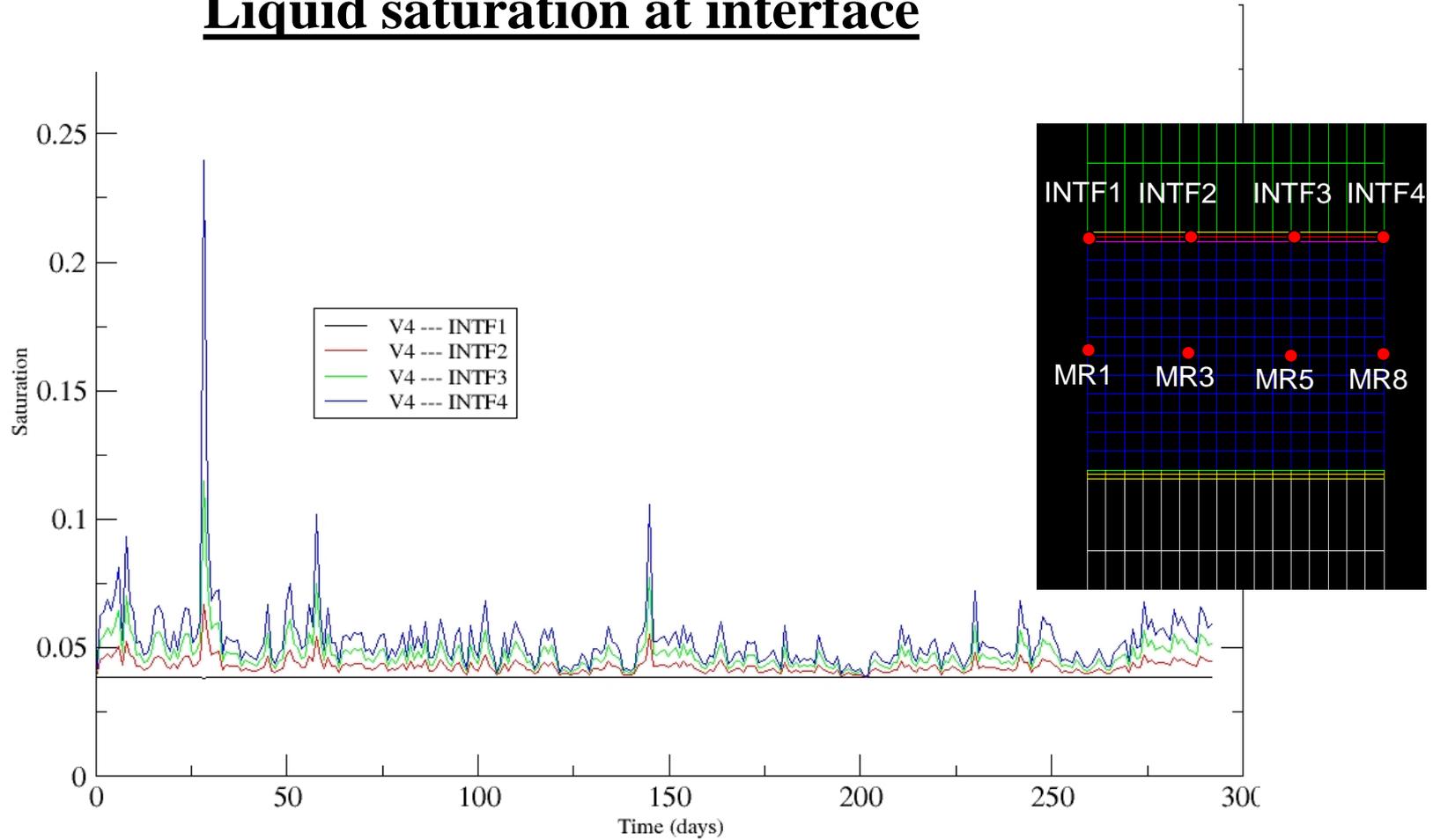
## 2-INVESTIGATION : Contrainte THM

### Temperature variation in stone-mortar interface



# 2-INVESTIGATION : Contrainte THM

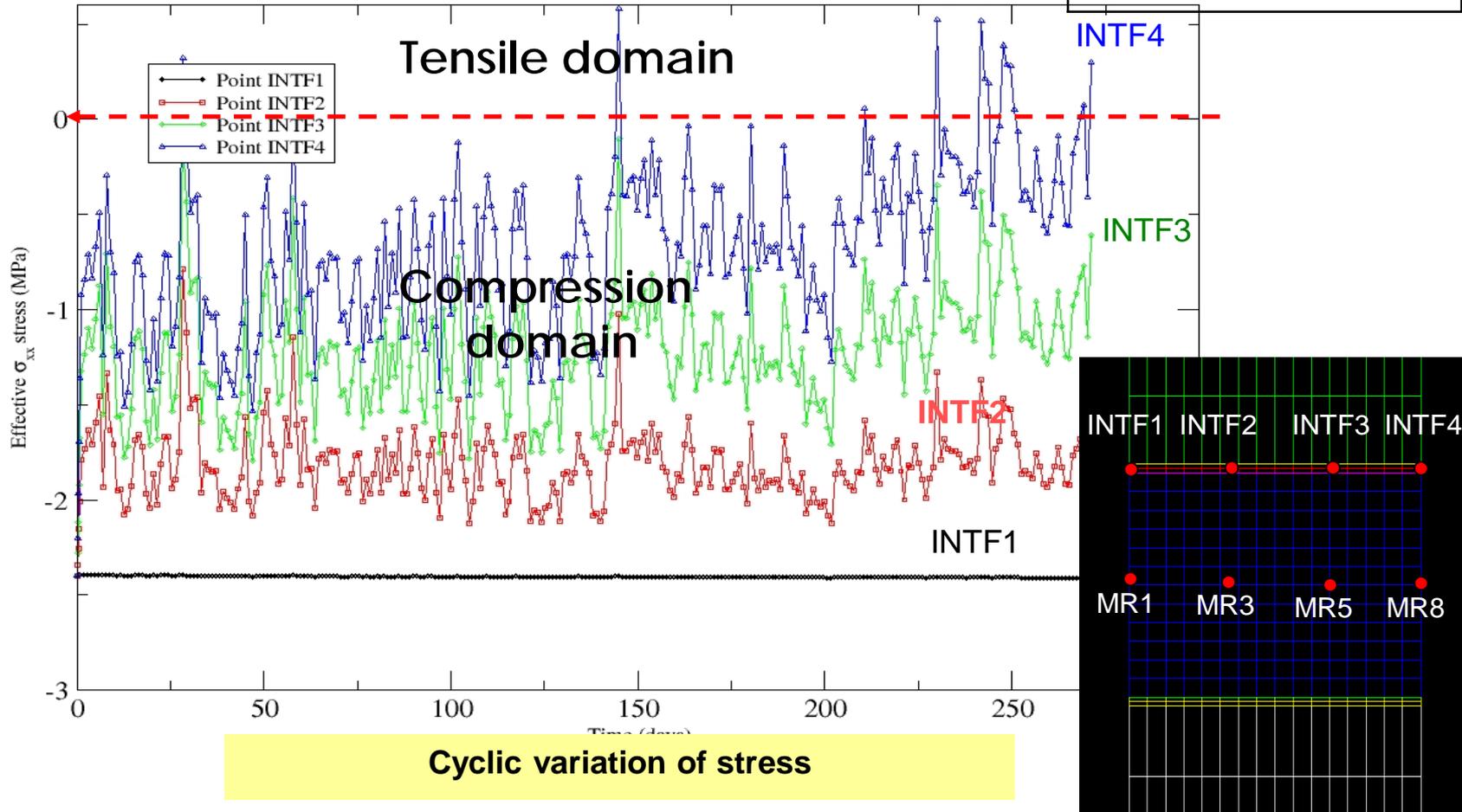
## Liquid saturation at interface



**2-INVESTIGATION : Contrainte THM**

**Effective stress variation in interface**

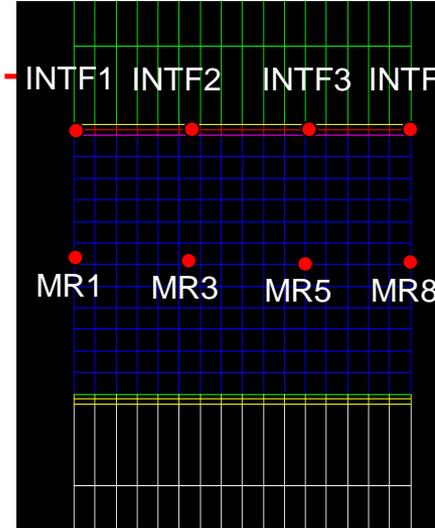
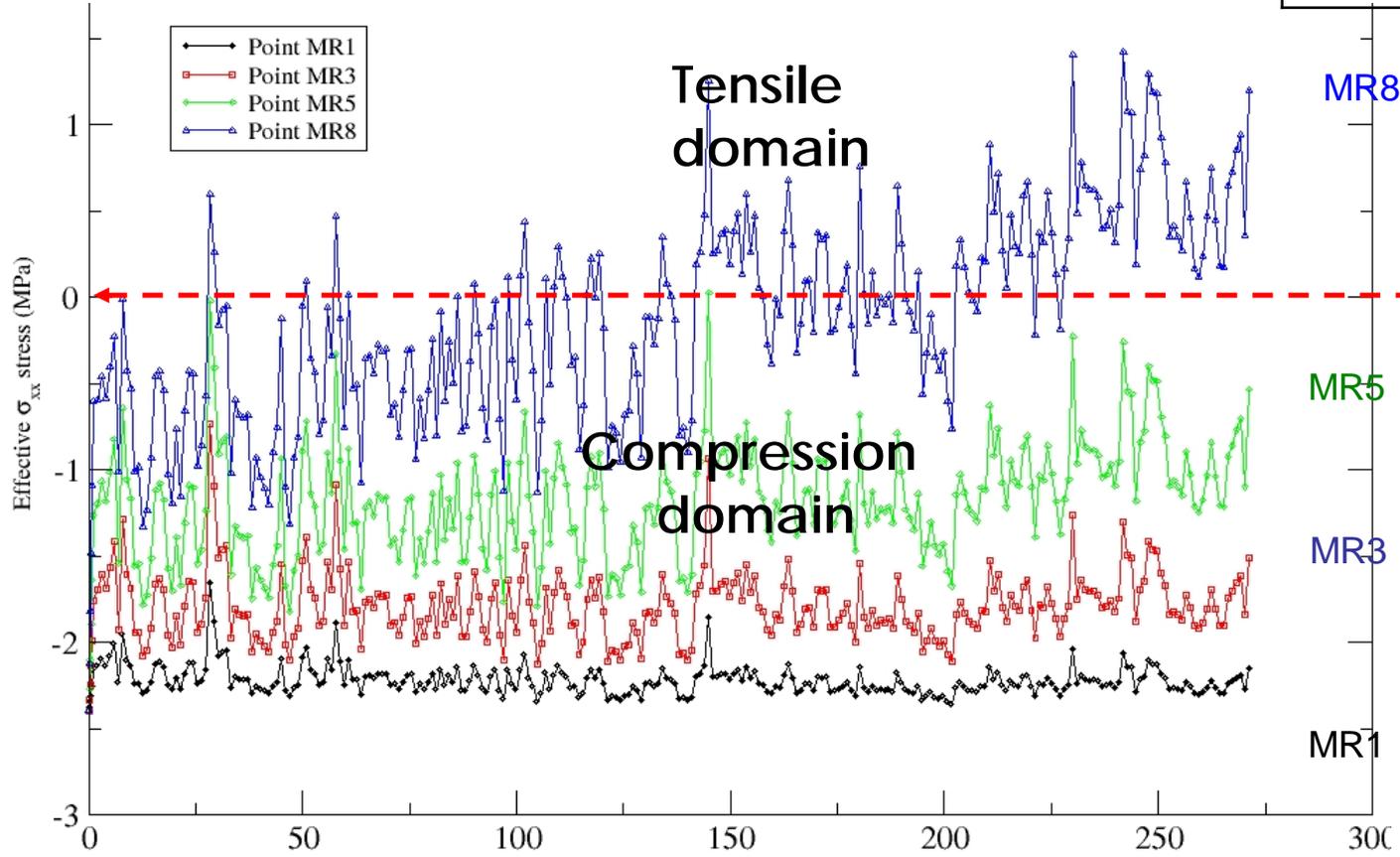
$\alpha = 12 \times 10^{-6} \text{ K}^{-1}$



## 2-INVESTIGATION : Contrainte THM

### Effective stress variation in stone

$$\alpha = 12 \times 10^{-6} \text{ K}^{-1}$$



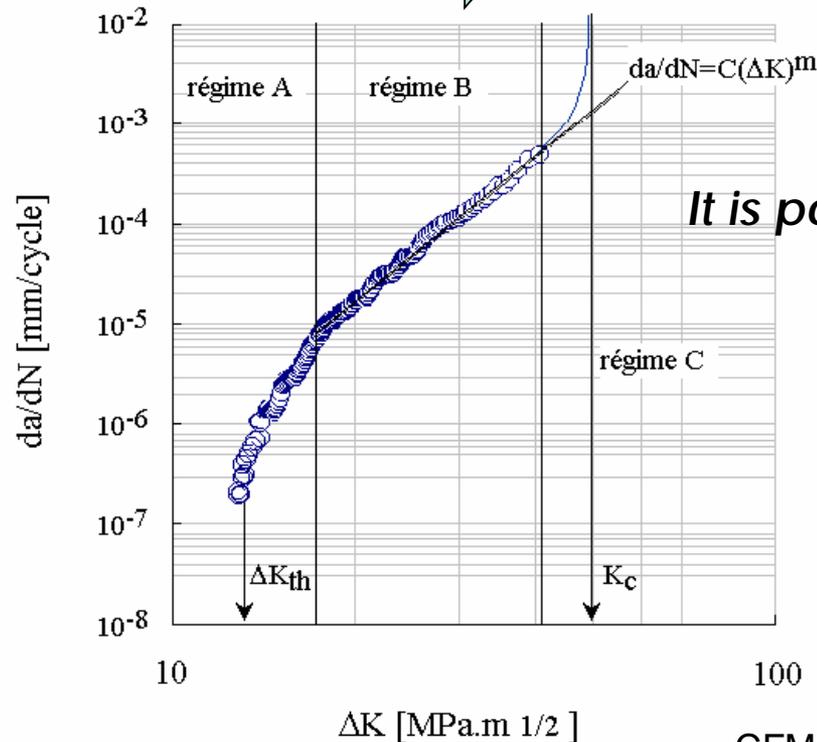
**High amplitude of stress variation in outdoor surface of the wall**

## 2-INVESTIGATION : Contrainte THM

- The stress values are inferior to the limits of strength materials
- However stress variation due to meteorological factors are to be studied carefully



Damage by fatigue ? Subcritical crack growth ?



Paris law of fatigue :

*It is possible to make prediction of time to failure*

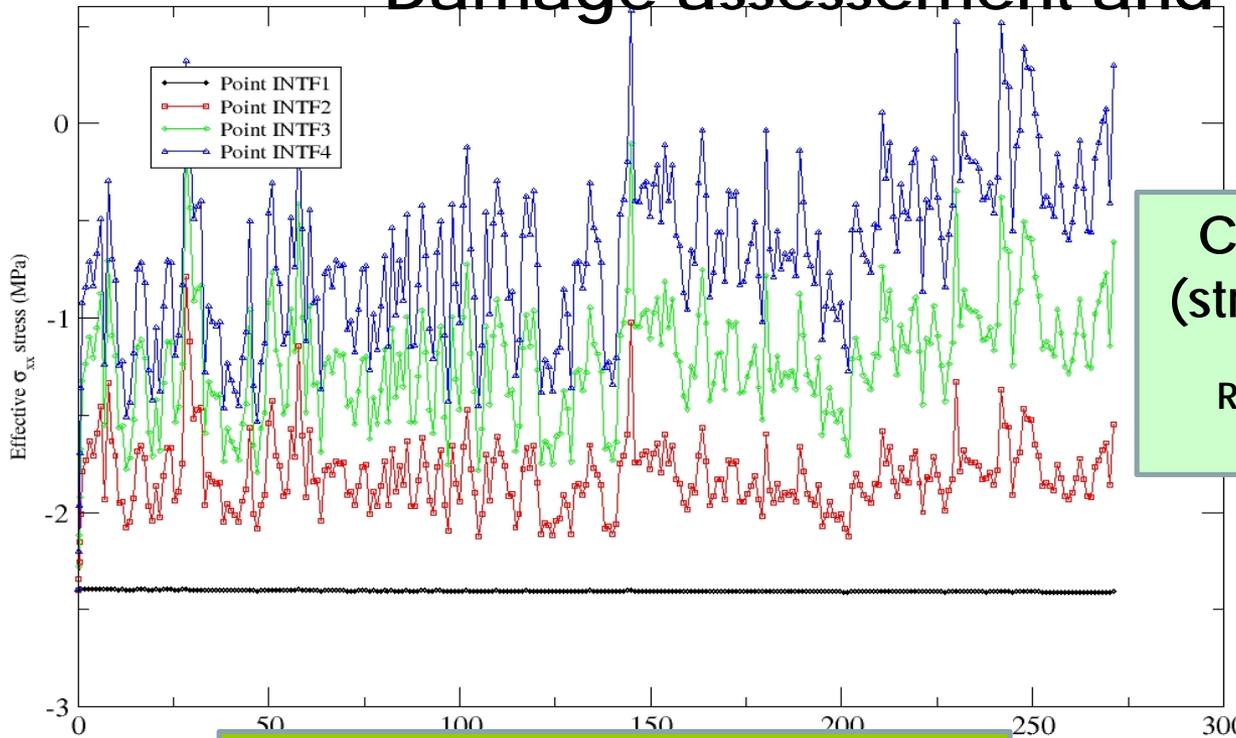
$$K = K_c \Rightarrow S_y \sqrt{\pi a_c} \qquad K_c \Rightarrow a_c = \frac{1}{\pi} \left( \frac{K_c}{S_y} \right)^2$$

$$\underbrace{\frac{da}{dN} = C \cdot \Delta K^m}_{\text{Loi de Paris}} \Rightarrow N = \int_{a=a_0}^{a=a_c} \frac{da}{C \cdot (\Delta S_y \sqrt{\pi a})^m}$$

Calcul de la durée de vie par intégration de la loi de Paris entre  $a_0$  et  $a_c$

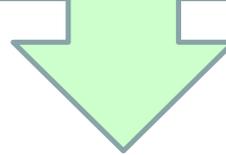
## 2-INVESTIGATION : Contrainte THM

### Damage assesement and modeling



**Cycles assesement  
(strains, stress, energy)**

Rainflow counting method,  
RCC\_M



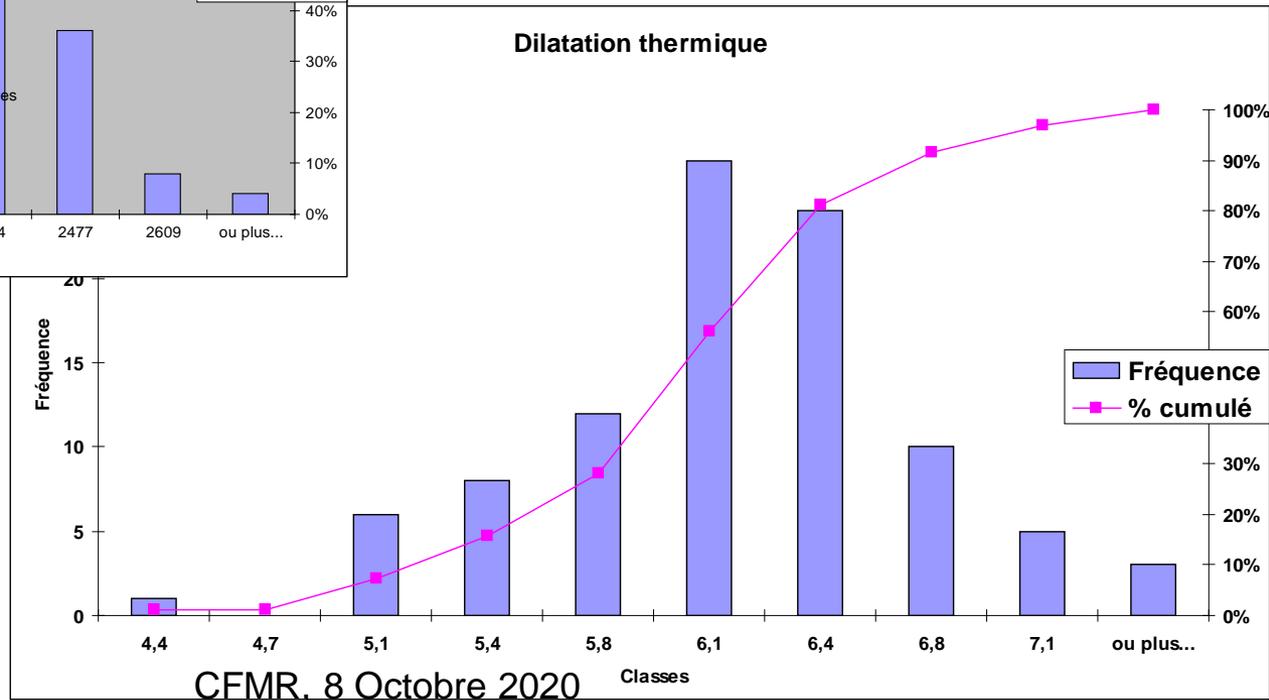
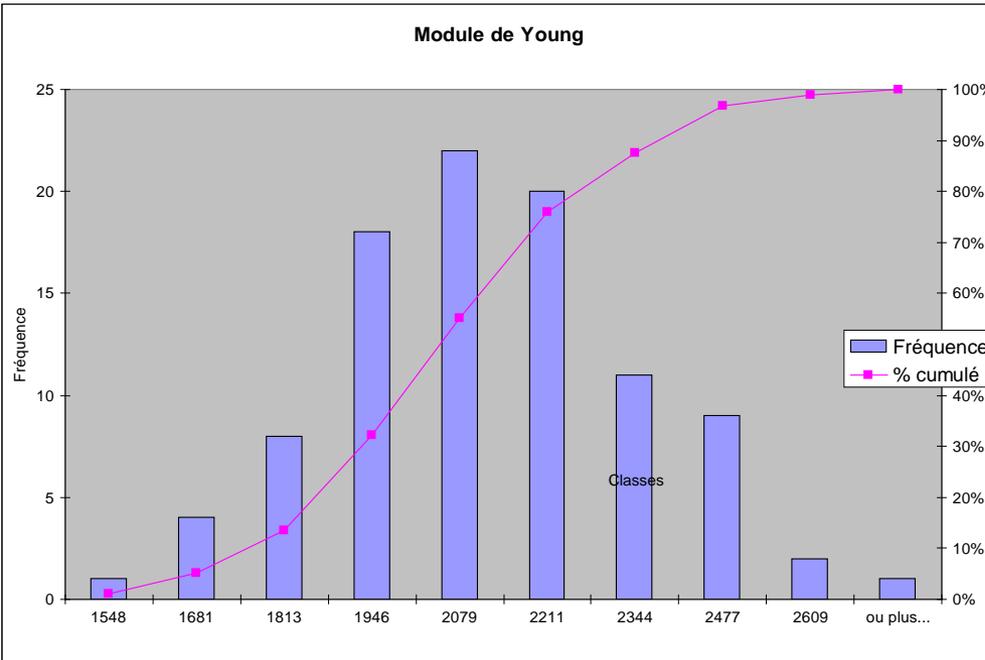
**Modeling**

Lemaitre model



**Restoration Works  
previsions**

■ **Taking account for the spatial variation of parameters on the wall**





LaMé

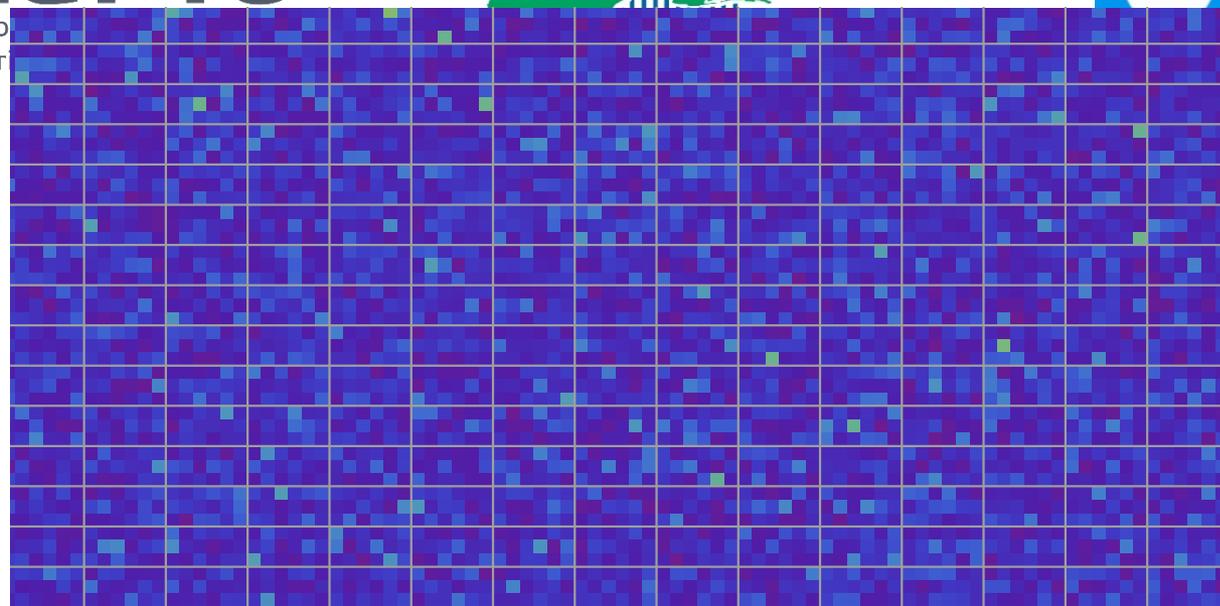
Lafont  
Gabriel



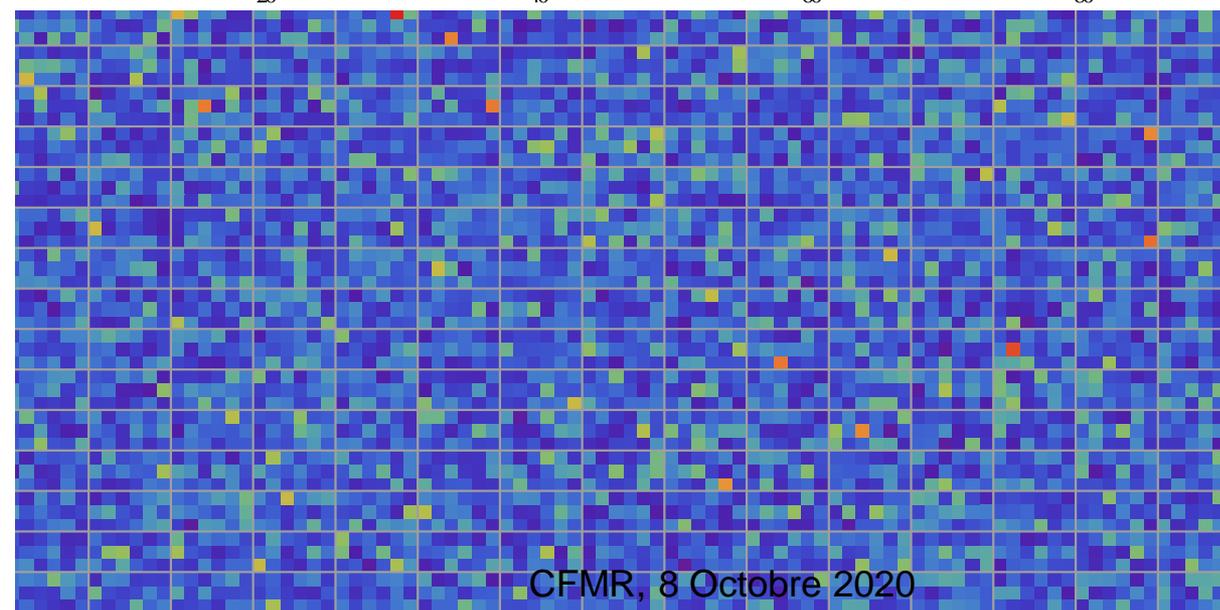
POLYTECH<sup>®</sup>  
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Damage distribution : North Face

15m



30 years



100 years

CFMR, 8 Octobre 2020

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- **Interaction hydro-mécano-chimique avec l'environnement**

## 3- Conclusions



1100 1200 1300 1400 1500 1600 1700 1800 1900 2000

Rôle des agents naturels

Depuis l'ère industrielle:

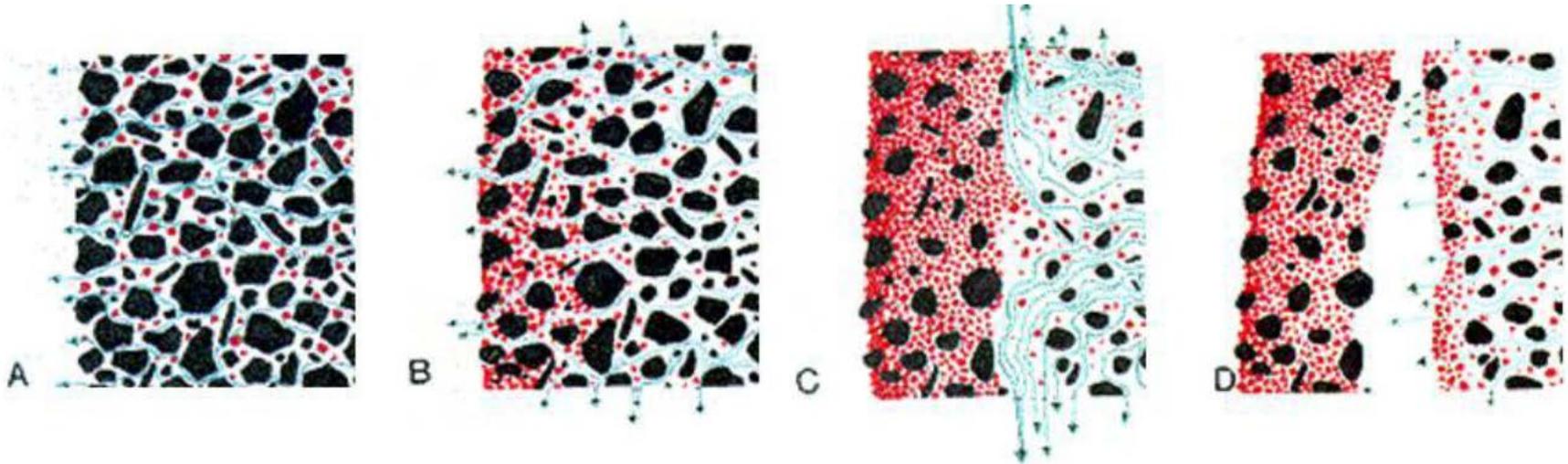
+ Rôle majeur des polluants



Crédits d'illustration K. Beck (2017)

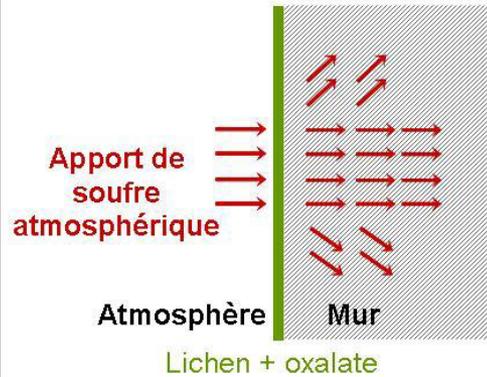
## 2-INVESTIGATION : Couplage THM-C

Mécanisme de formation d'une altération en plaque



(D'APRES BRUNET-IMBAULT, 1999 ET RAUTUREAU, 2001)

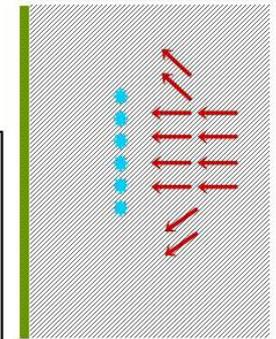
**1) Imbibition de la pierre**  
(Pluie, humidité relative élevée)  
Formation de gypse sous forme soluble



K. Beck (2018)

**2) Séchage de la pierre**  
(Vent)

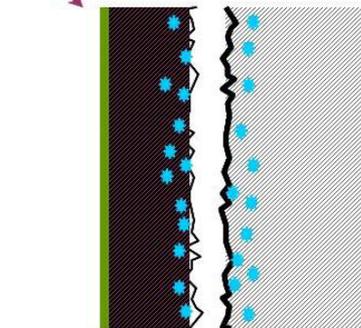
Cristallisation du gypse si séchage rapide



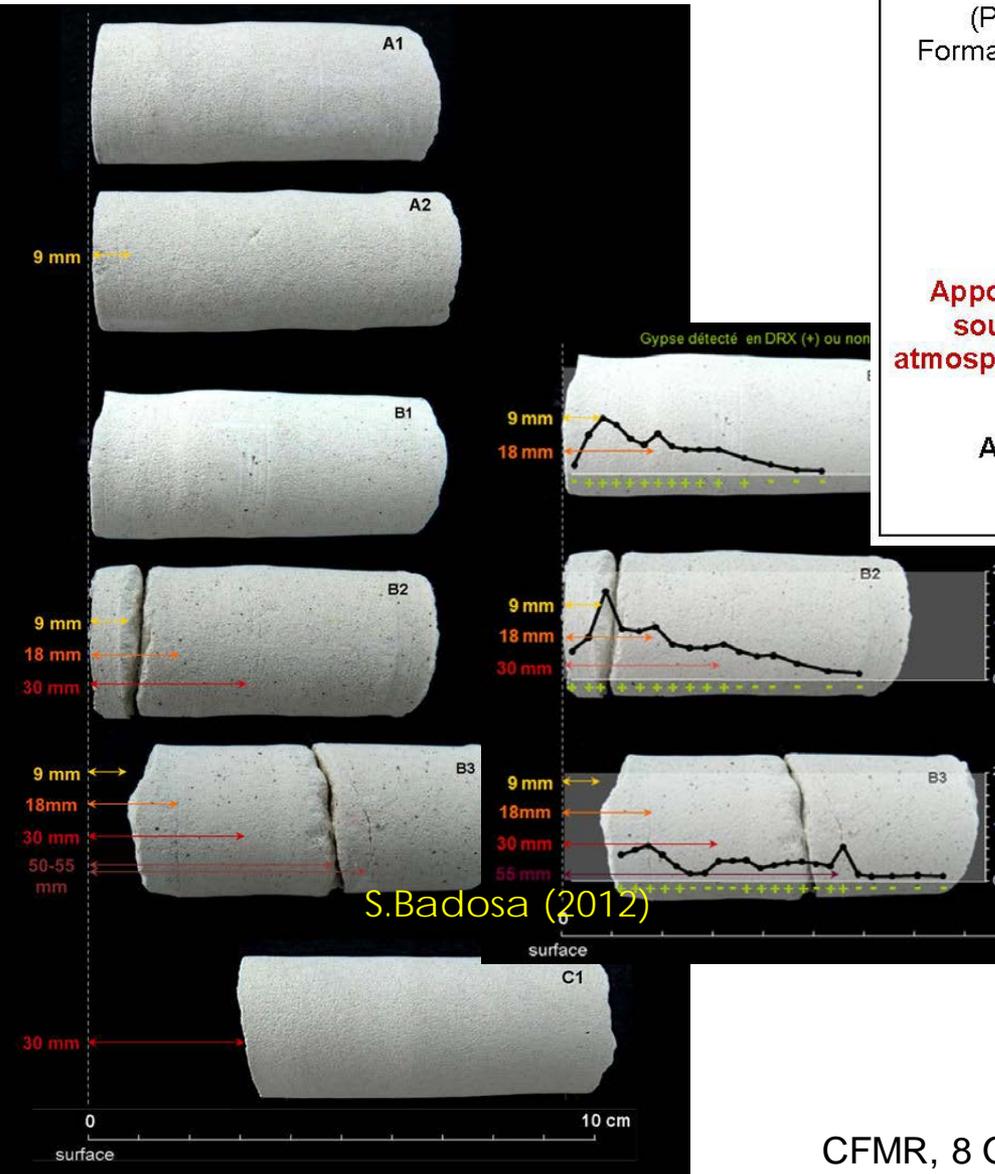
+ oxalate

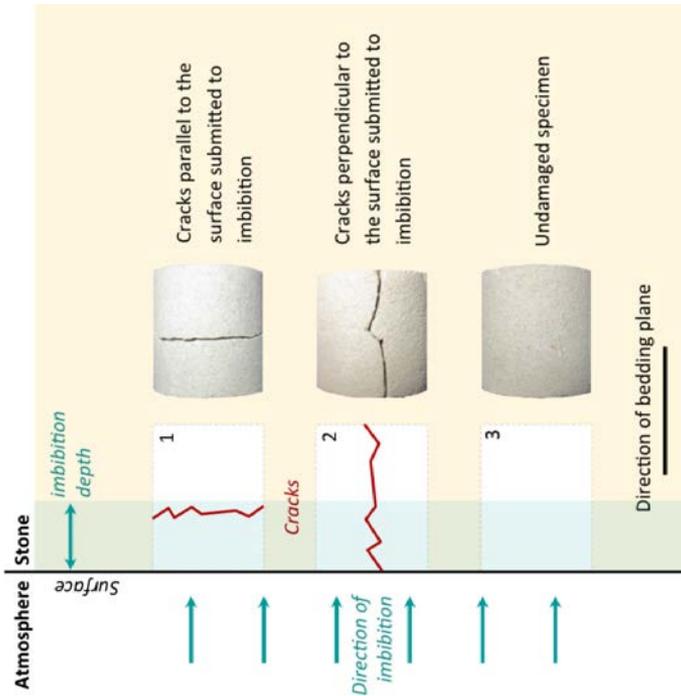
**3) Altération observée**

Formation de plaque  
Cristaux de gypse à l'interface

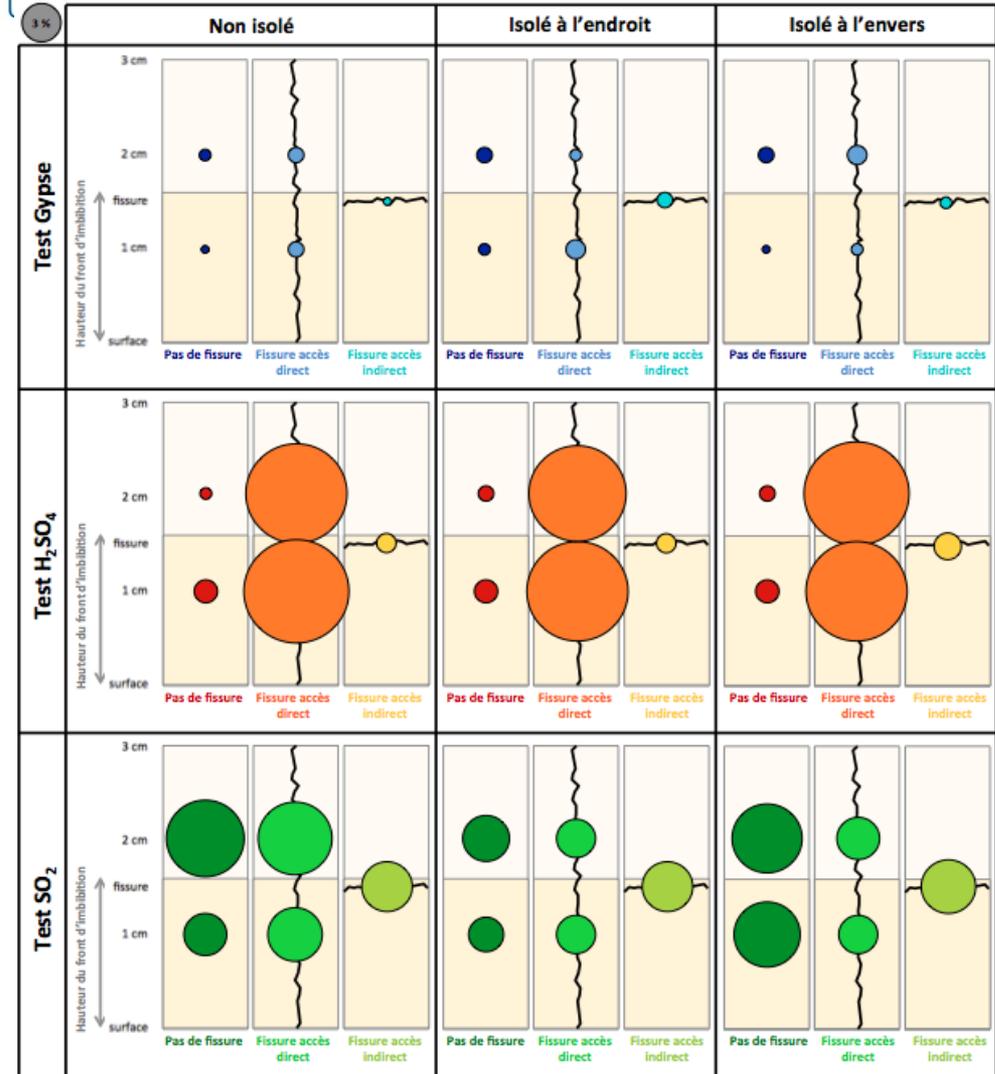


CFMR, 8 C





Simulation expérimental de formation de gypse (Badosa et al 2015)



## 2-INVESTIGATION : Contrainte THM-C

Est-ce que les concentrations dans la nature des polluants, la cinétique d'imbibition et de séchage permettent la précipitation du gypse?

## Modélisation THM-C

## 2-INVESTIGATION : Contrainte THM-C

Usually derived from a rigorous thermodynamic framework:

- state functions
- state variables
- thermodynamic principles

### Principal hypothese

*H-M-T-C additif potentials*

*H-M-T-C additif potentials*



## 2-INVESTIGATION : Contrainte THM-C

-Chemical potential and chemical activity

$$\mu_i = \mu_i^0 + RT \ln a_i$$

Phase gas

$$d \mu_i = RT d \ln f_i$$

Fugacity

Perfect gas  $\rightarrow$

$$\left\{ \begin{array}{l} p_i = x_i p_G \\ a_i = x_i = \frac{p_i}{p^0} \end{array} \right.$$

- Chemical reaction
- Cinétique of reaction .....
- Enthalpie variation .....



## 2-INVESTIGATION : Contrainte THM-C

Transport of a given solute variety

$$\underline{j}_e = \lambda_{lq}^H \left( - \underline{grad}(p_{lq} + p_s) + \rho_{lq} \underline{\mathbf{F}}^m \right) \quad \text{advection}$$

$$\underline{j}_\alpha = -D_\alpha \underline{grad}(\phi S_{lq} C_\alpha) \quad \text{diffusion}$$

$$\underline{j}_{d\alpha} = -\underline{\underline{\mathbf{D}}}. \underline{grad}(\phi S_{lq} C_\alpha) \quad \text{dispersion}$$

Mass conservation

$$\frac{\partial}{\partial t} (\phi S_{lq} C_\alpha) + \text{div}(\underline{j}_e + \underline{j}_\alpha + \underline{j}_{d\alpha}) = 0 \quad (\text{sum over all varieties})$$

## 2-INVESTIGATION : Contrainte THM-C

Proposal for a sequential solving schema

Hypothesis :

Weak M->C coupling (but strong C->M coupling)

$$\underline{\underline{d\varepsilon}} = \underline{\underline{d\varepsilon}}^m + \underline{\underline{d\varepsilon}}^h + \underline{\underline{d\varepsilon}}^{th} + \underline{\underline{d\varepsilon}}^{ch} = \underline{\underline{d\varepsilon}}^{THM} + \underline{\underline{d\varepsilon}}^{ch}$$

$$\underline{\underline{d\sigma}} = \underline{\underline{C}} : (\underline{\underline{d\varepsilon}} - \underline{\underline{d\varepsilon}}^p) - b \cdot \underline{\underline{\delta dp}} - 3\alpha_t dT \cdot K \underline{\underline{\delta}}$$



$$\underline{\underline{d\sigma}} = \underline{\underline{C}}(c_i) : (\underline{\underline{d\varepsilon}} - \underline{\underline{d\varepsilon}}^p - \underline{\underline{d\varepsilon}}^{ch}) - b(c_i) \cdot \underline{\underline{\delta dp}} - 3\alpha_t(c_i) dT \cdot K \underline{\underline{\delta}}$$

$c_i$  Effective concentration

## 2-INVESTIGATION : Contrainte THM-C

On the effective concentration definition

$$c^* = \frac{c^{\text{int}} - c^{\text{ext}}}{c^{\text{int}} - c_{ep}}$$

$$ESP = \frac{[Na^+]}{CEC}$$

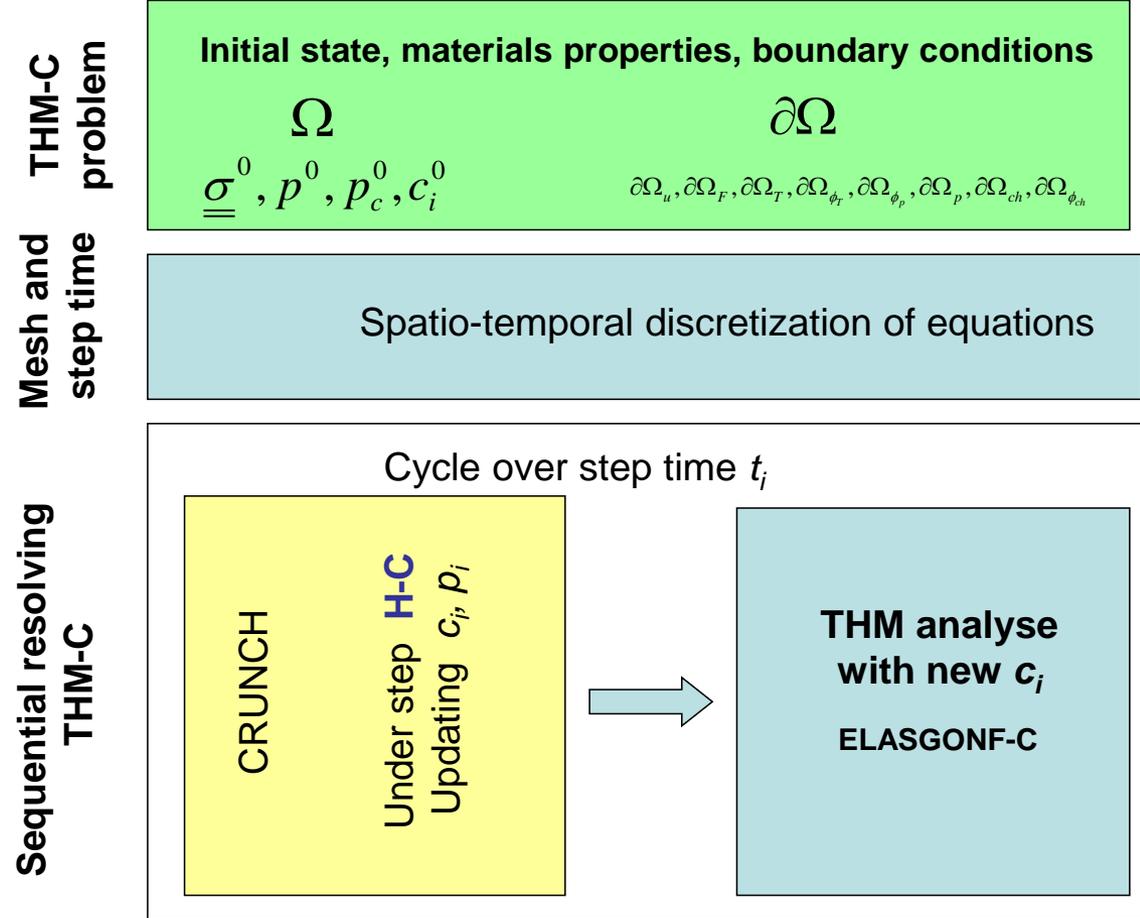
$$L_c = \frac{[Ca_L^{++}]}{[Ca_0^{++}]}$$

$$D = \left( 1 - \frac{V_{mgt}}{V_{i_s}} \right) + \frac{\sum V_{mgs}}{V_{i_s}}$$

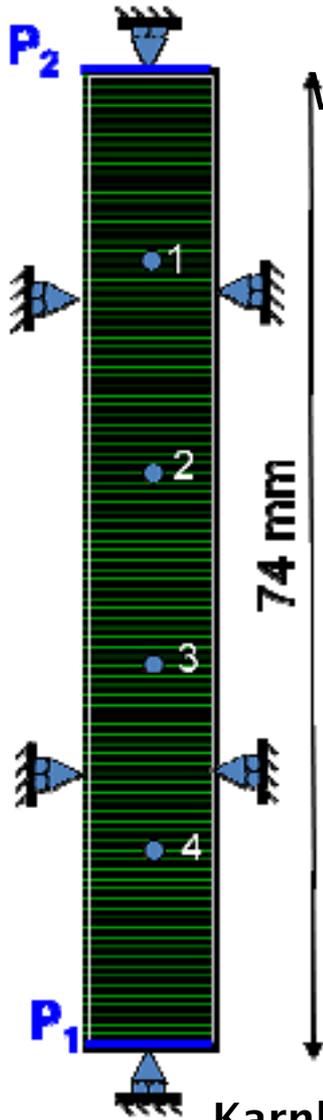
# 2-INVESTIGATION : Contrainte THM-C

## Numerical schema

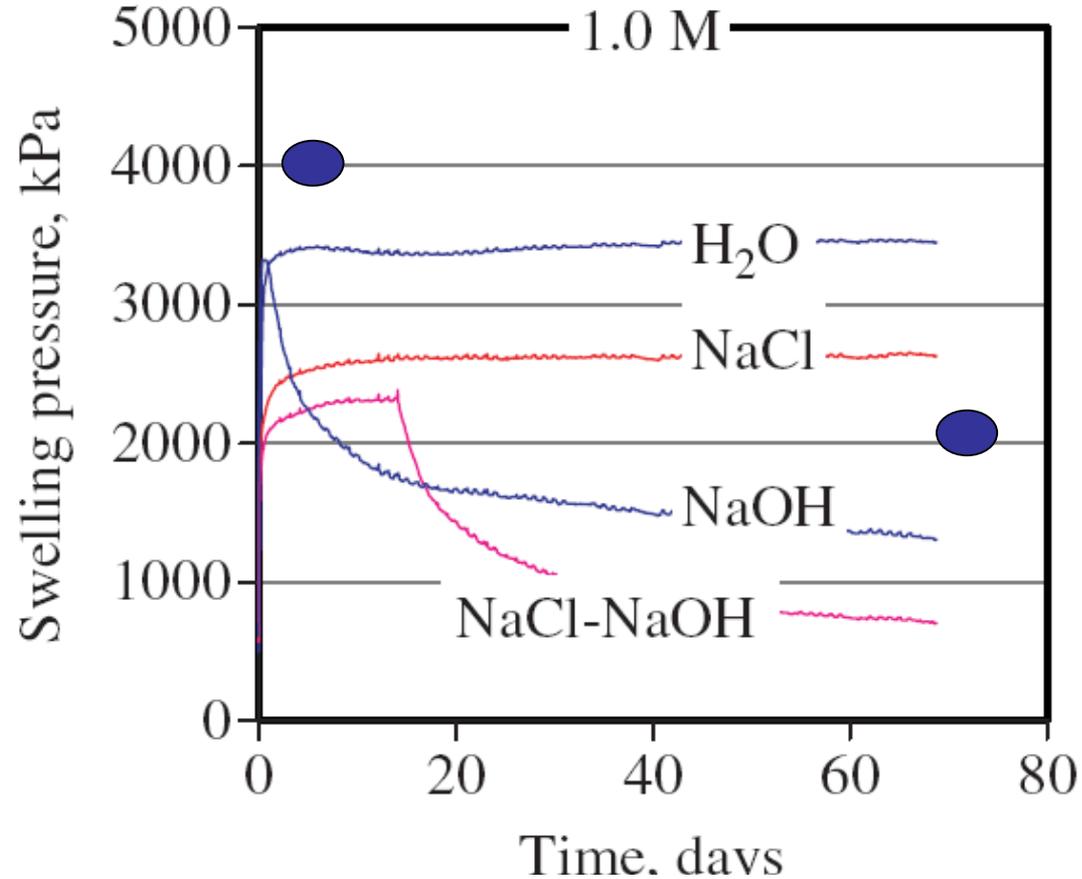
- **GIMRT**  
(General Implicit Multi Resolution Time)
- **OS3D**  
(Operator Splitting Diffusion Dispersion Dumping)  
*(weak Courant number)*



# Validation de l'approche : saturation de l'argile gonflante



What is the impact of chemical composition of water on swelling pressure ?



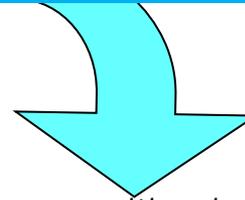
Karland O, et al. (2007) - Experimentally determined swelling pressures and geochemical interactions of compacted Wyoming bentonite with highly alkaline solutions, *Physics and Chemistry of the Earth* 32 275-286



Composition minéralogique d'un litre de bentonite MX-80 sec [GAU 04]

## Validation de l'approche : saturation de l'argile gonflante

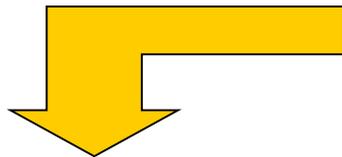
Minéral	MX-80	
	Masse (g)	mol/l
Cristobalite	157.1541	2.6192
Gypsum	9.4292	0.0548
Na-Montmorillonite	1178.6560	3.2151
Calcite	22.0016	0.2200
Pyrite	0.0025	2.095E-5
Autre	204.2979	-
Somme	1571.5414	0.0000
CEC cmol	81 meq/100g	1.27251



Water composition in equilibre with MX-80 [GAU 04]

Element	Eau de pores de bentonite	Unité
pH	7.39	
Eh	-192	mV
Na	3.21E-01	mol/kg eau
K	3.31E-03	mol/kg eau
Mg	5.35E-03	mol/kg eau
Ca	1.40E-02	mol/kg eau
Al	8.26E-10	mol/kg eau
Si	3.43E-04	mol/kg eau
S	1.48E-01	mol/kg eau
Cl	6.46E-02	mol/kg eau

n=43%  
k=2.4 10<sup>-9</sup> m/s

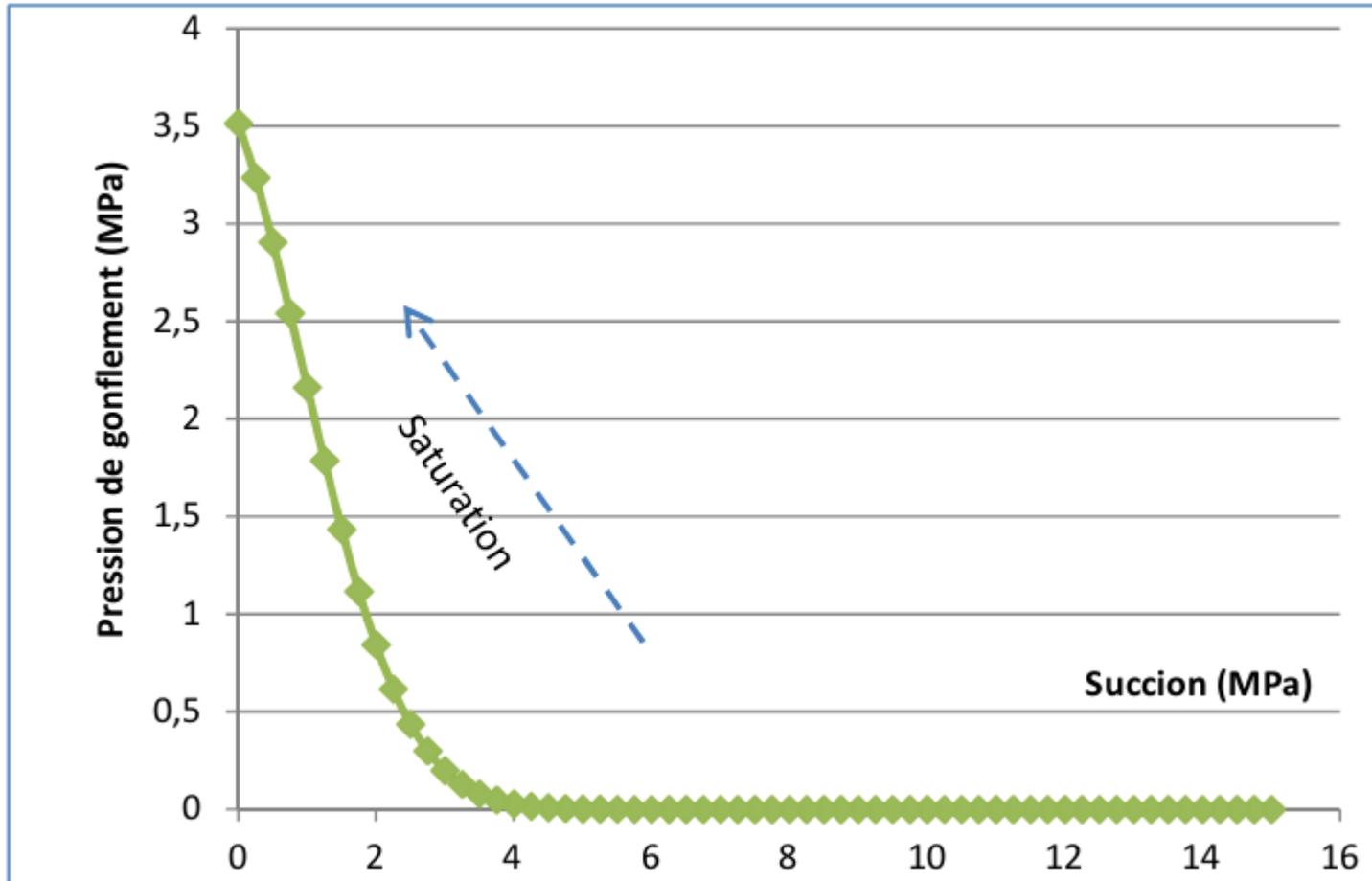


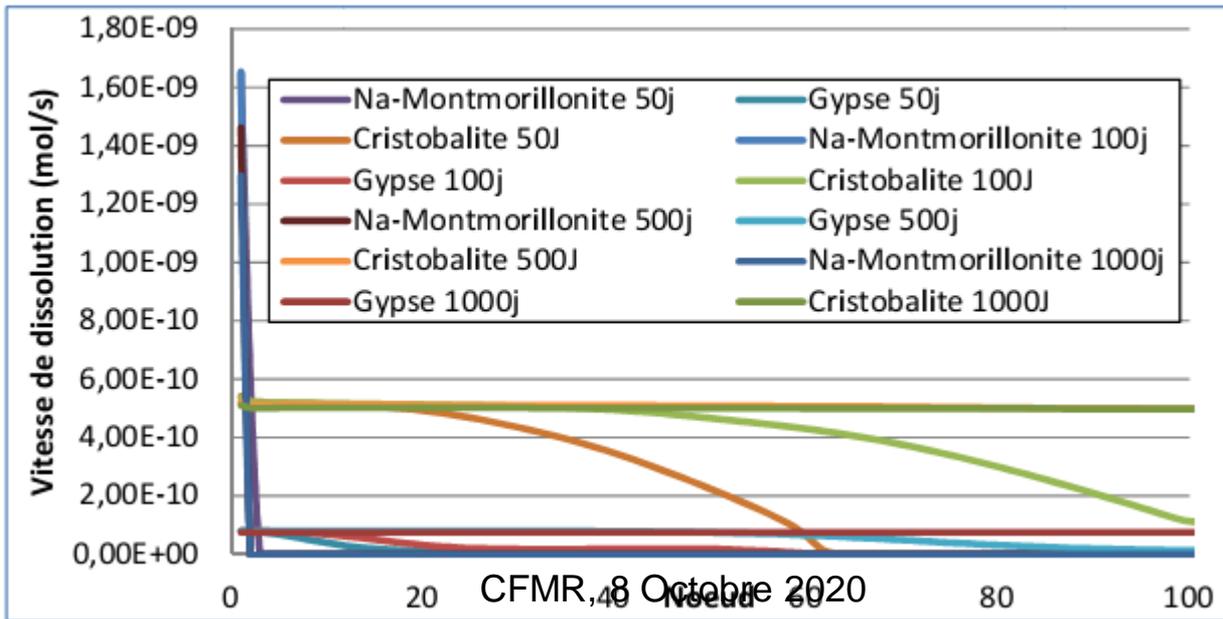
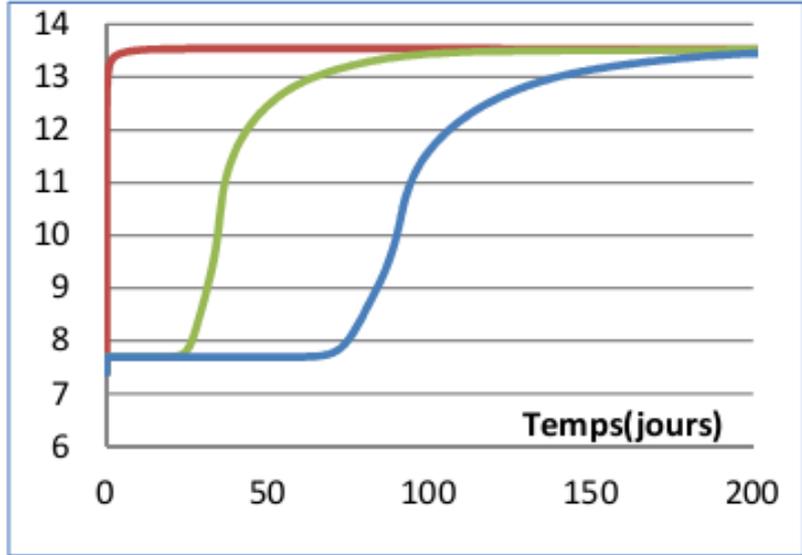
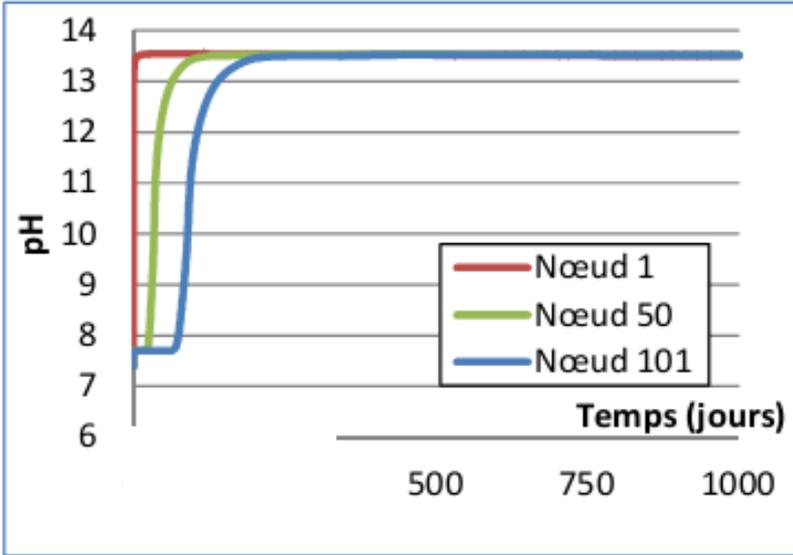
Infiltration by NaOH solution

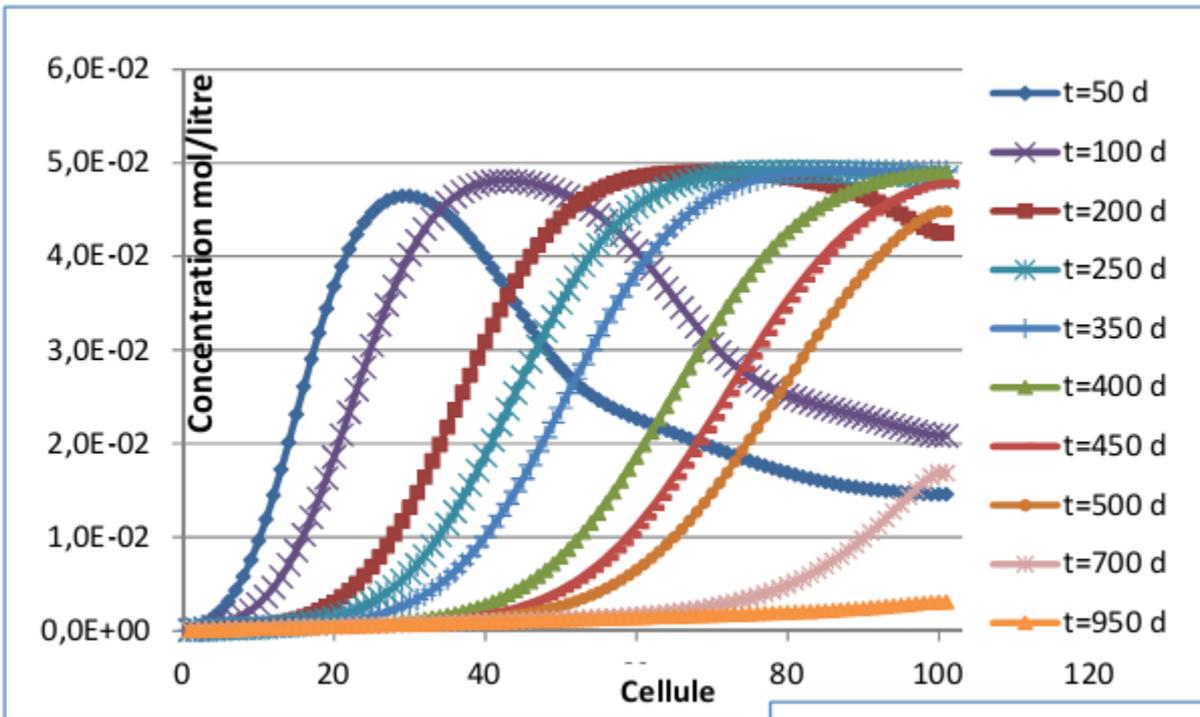


# Validation de l'approche : saturation de l'argile gonflante

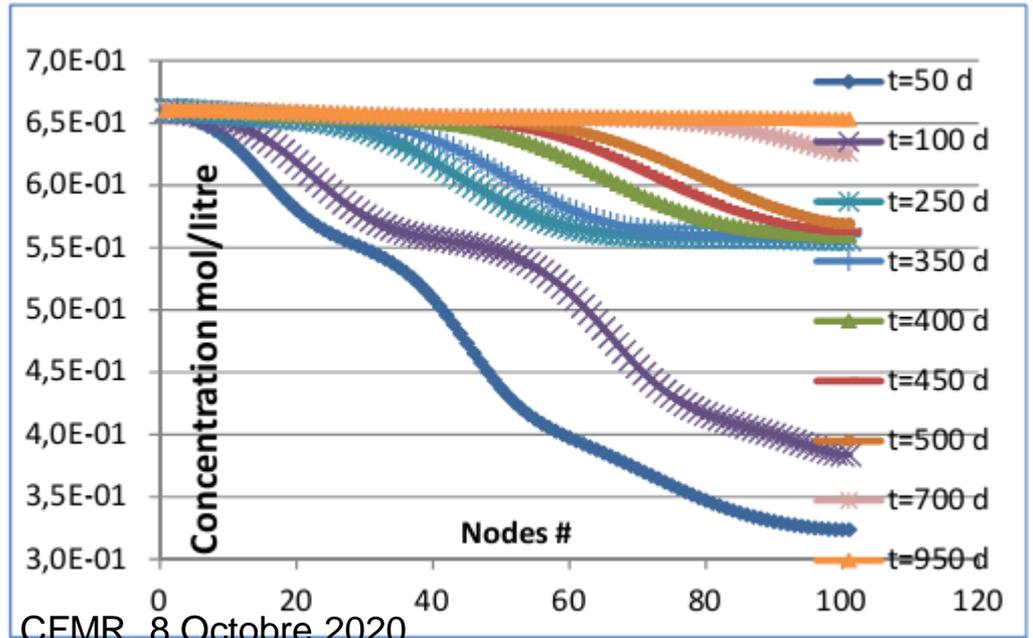
## Gonflement pendant la saturation à l'eau

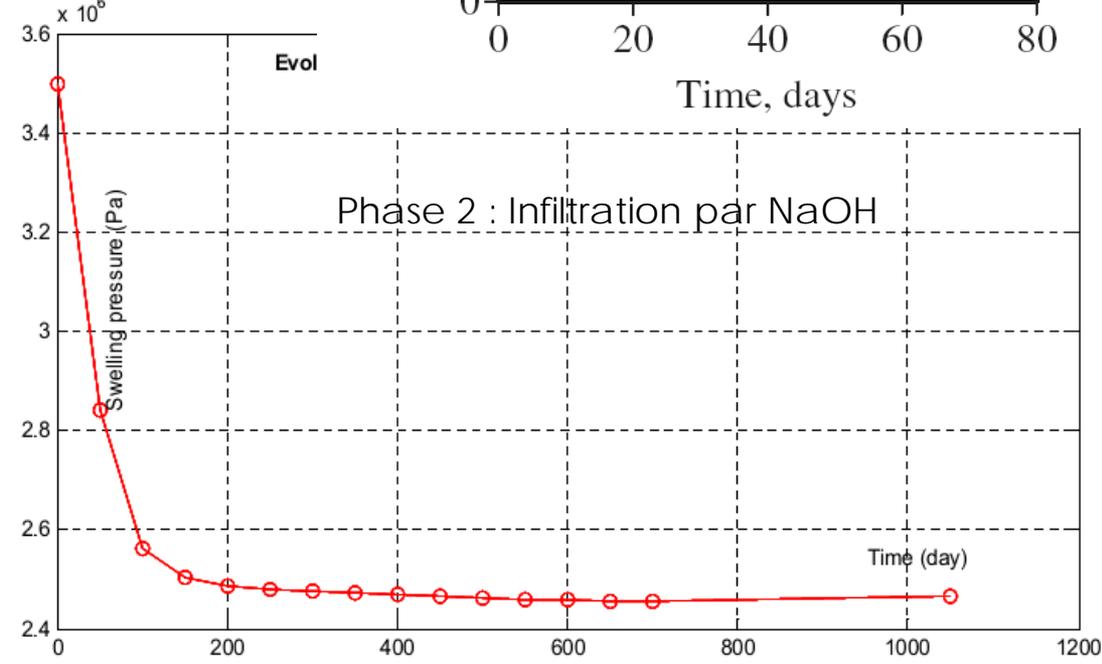
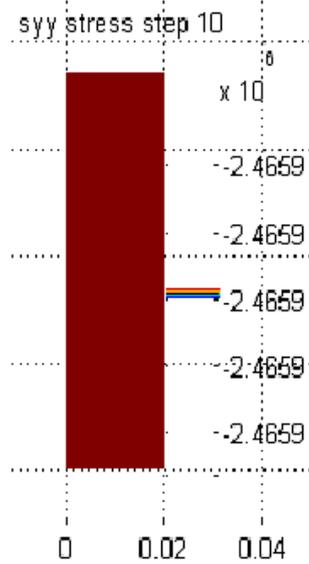
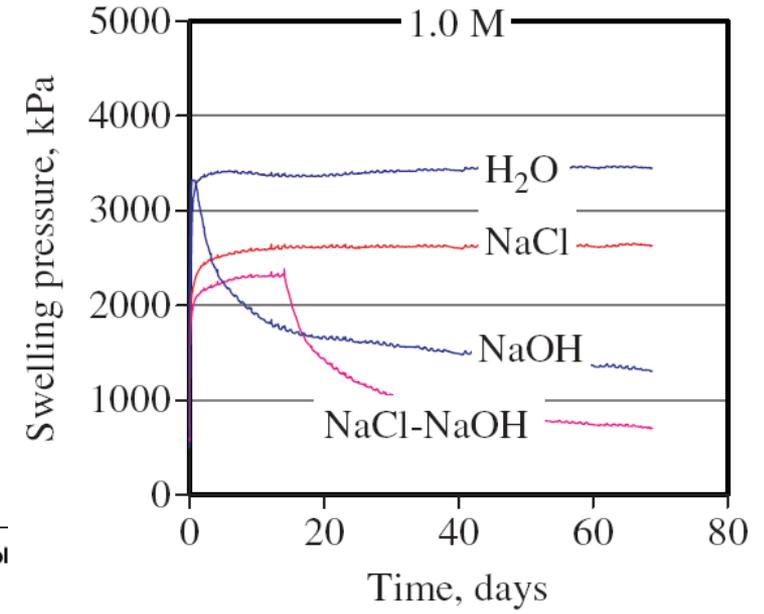
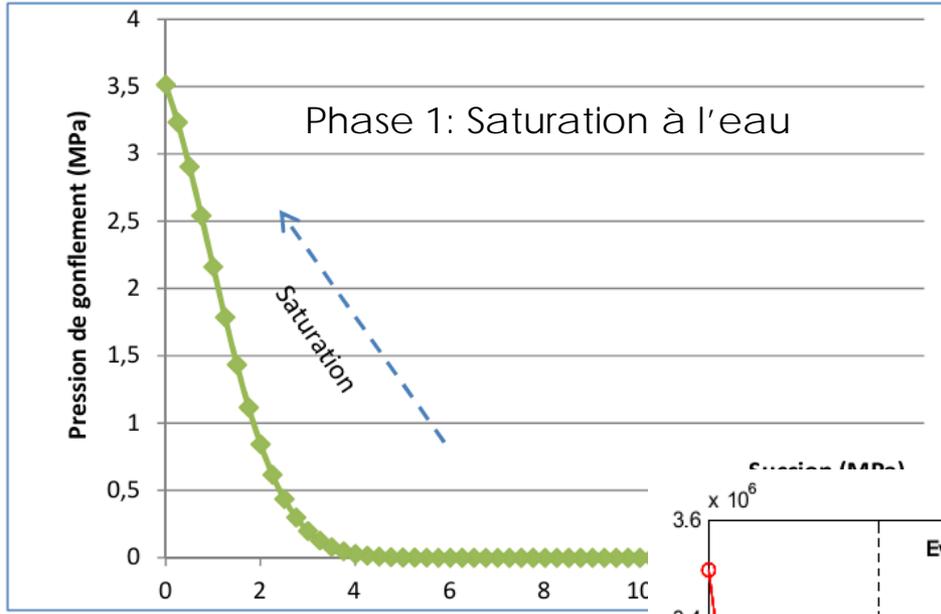






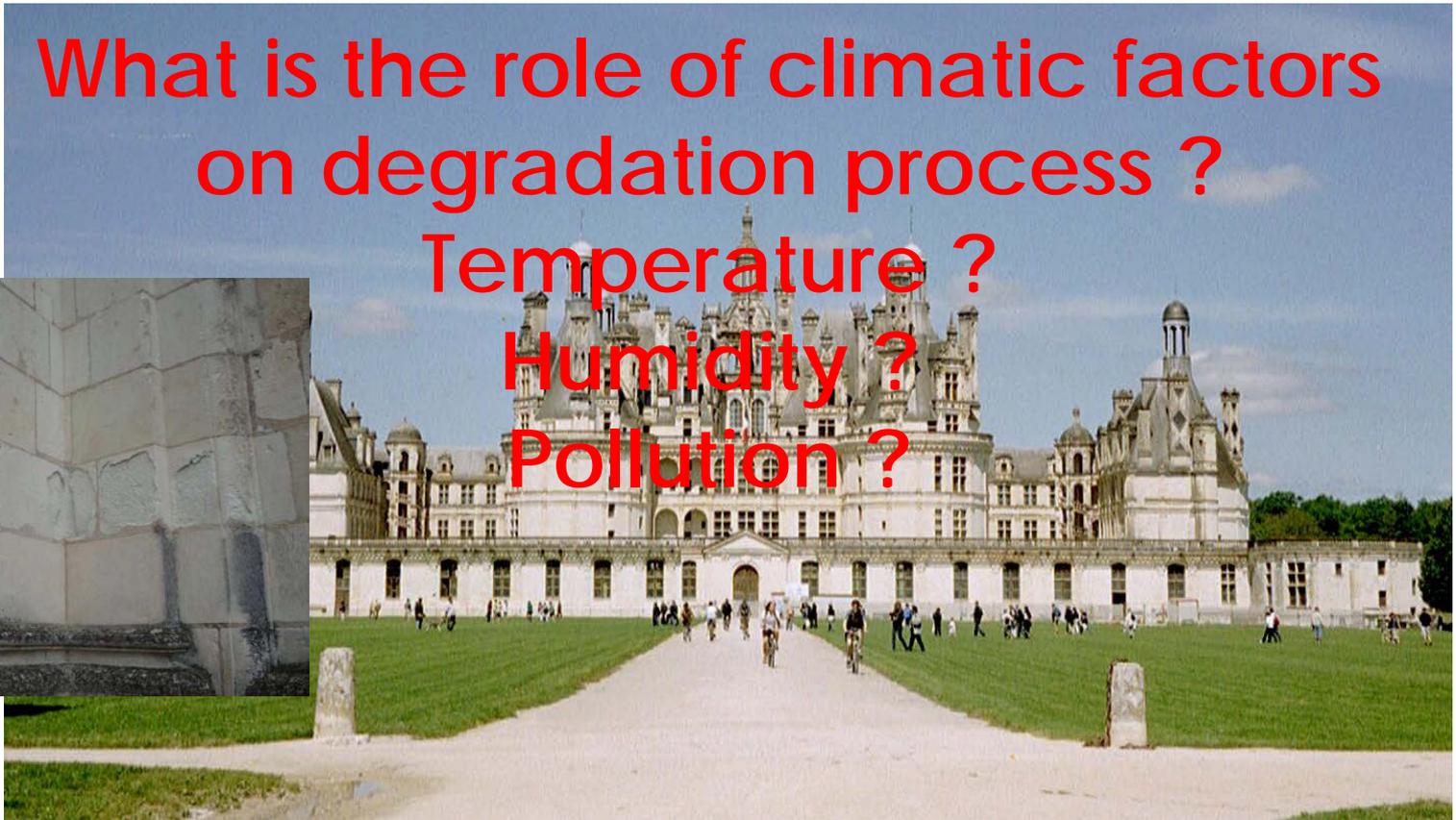
Na<sup>+</sup>





Peut il y avoir une précipitation de gypse dans les conditions naturelles et en présence des polluants ?

**What is the role of climatic factors  
on degradation process ?  
Temperature ?  
Humidity ?  
Pollution ?**

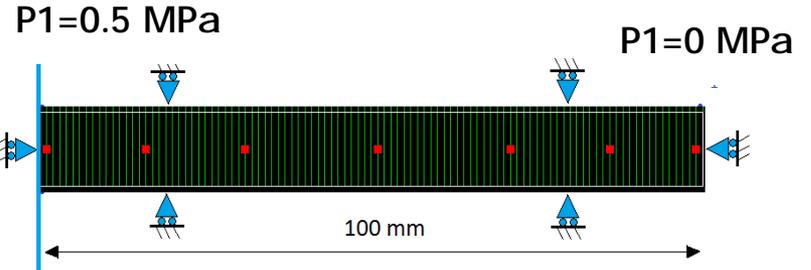




# 2-INVESTIGATION : Contrainte THM-C

## What about impact of pollution ?

First hypothesis : Air pollution

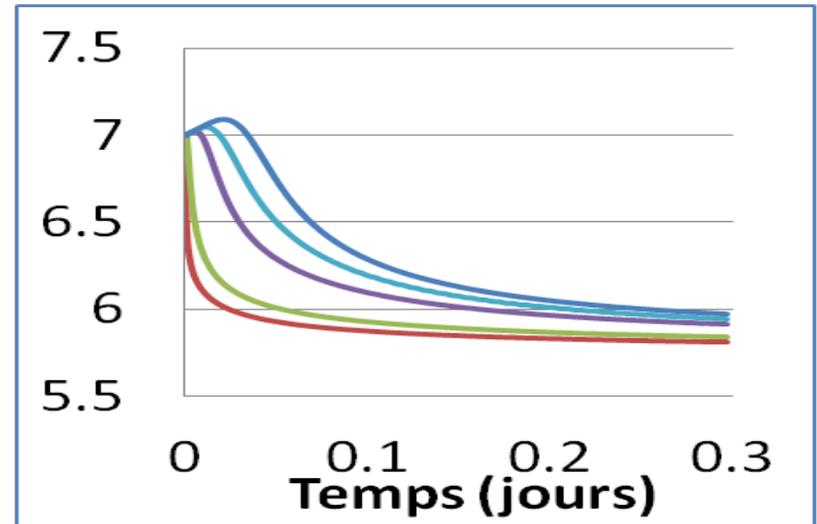
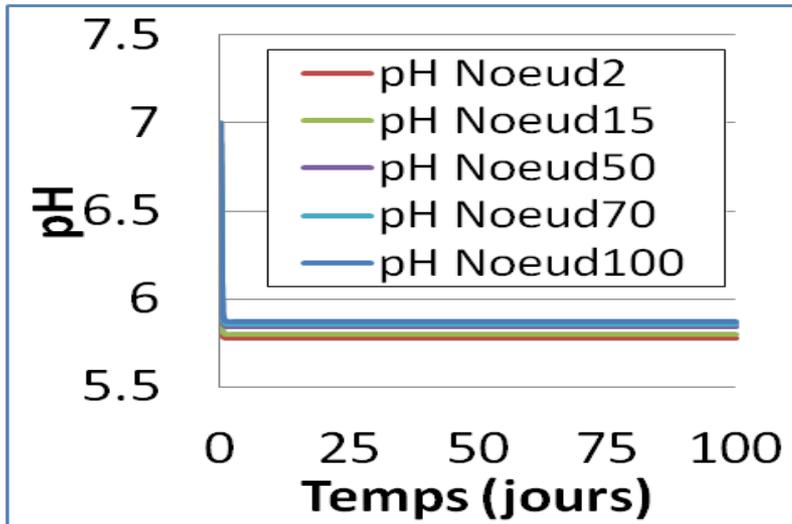


Partial gas pressures [SUR 00]

$\text{SO}_2$   $2.01\text{E-}7 \text{ atm}$

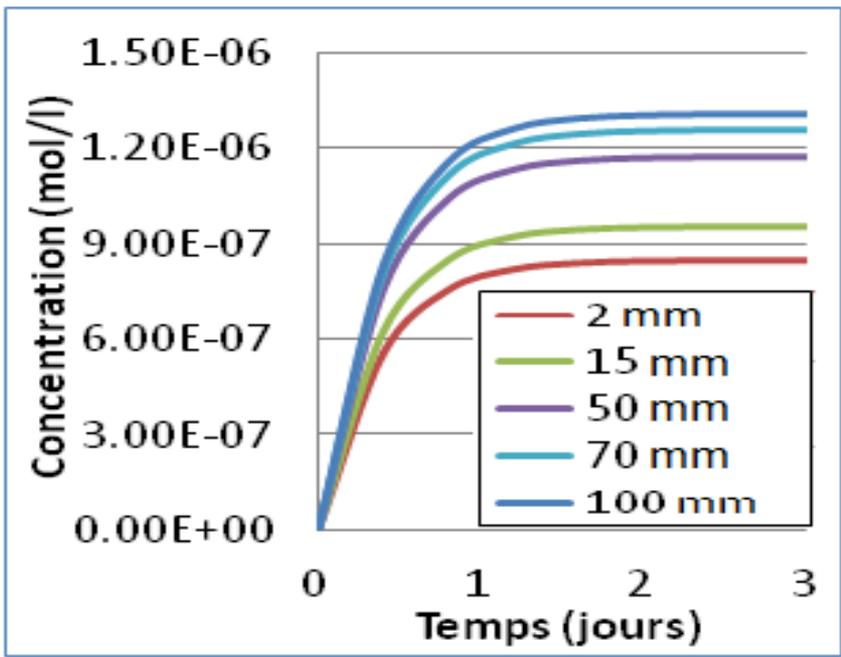
$\text{CO}_2$   $3.3\text{E-}4 \text{ atm}$

$\text{SO}_2$   
 $\text{CO}_2$

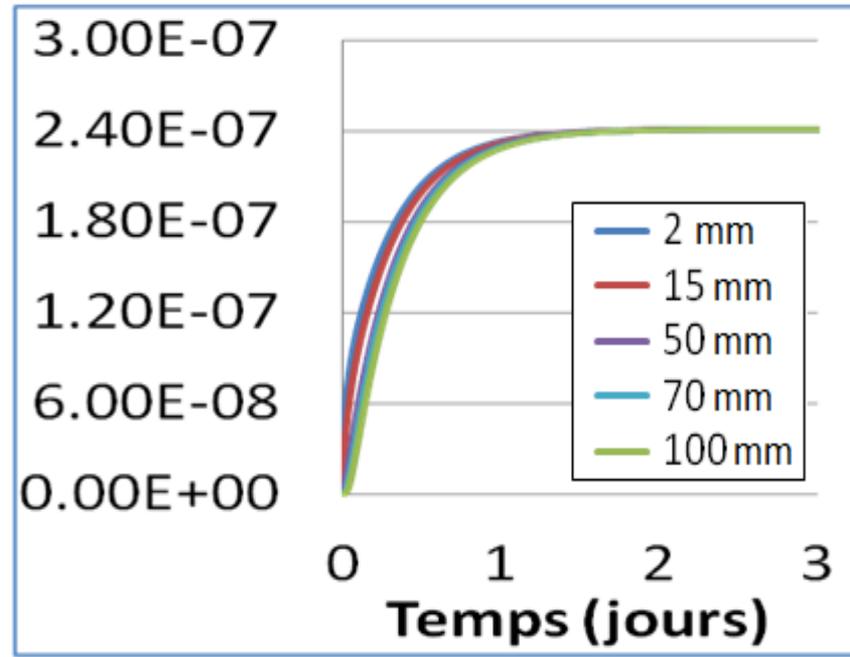


➤ pH decreases with the time

Ca<sup>2+</sup>



SO<sub>4</sub><sup>2-</sup>



➤ Increase of Ca<sup>2+</sup> and SO<sub>4</sub><sup>2-</sup> concentration

➤ **But not gypsum precipitation!!**

Second hypothese : Acid rain pollution AND air pollution

Partial gas pressure [SUR 00]

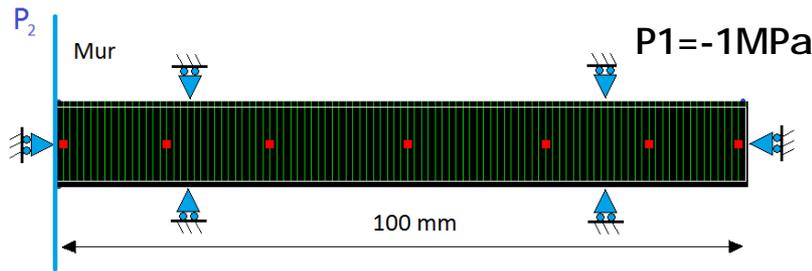
SO<sub>2</sub> 2.01E-7 atm CO<sub>2</sub> 3.3E-4 atm

Acid rain composition [PAR 99]

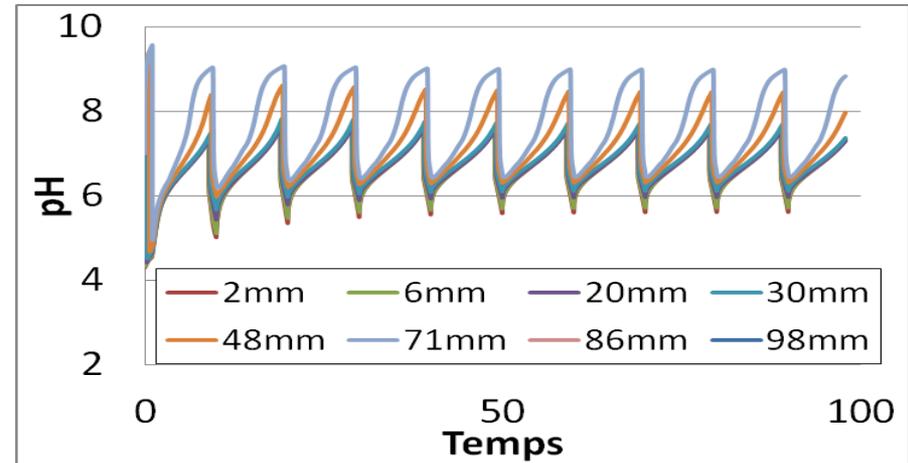
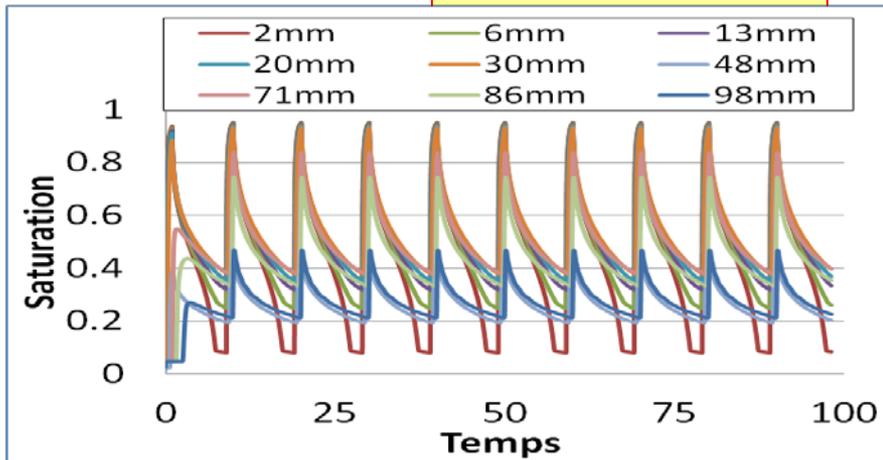
pH 4.23  
 Ca<sup>2+</sup> 9.6E-6 mol/l  
 Na<sup>+</sup> 6.1E-6mol/l  
 CO<sub>3</sub><sup>2-</sup> équilibre phase de CO<sub>2</sub>  
 SO<sub>4</sub><sup>2-</sup> 4.1E-5mol/l  
 NH<sub>4</sub><sup>+</sup> 1.5E-5 mol/l  
 NO<sub>3</sub><sup>-</sup> 1.7E-5mol/l

SO<sub>2</sub>  
CO<sub>2</sub>

Pluie

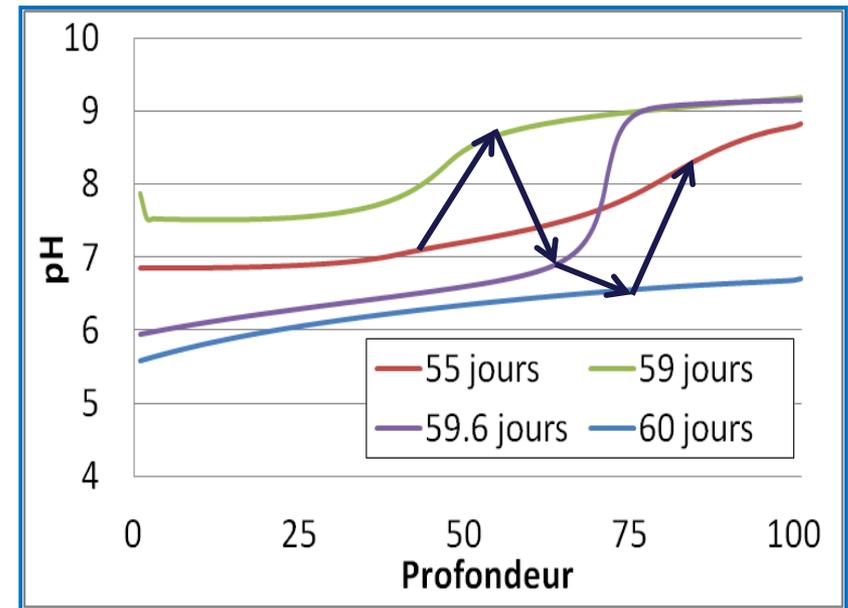
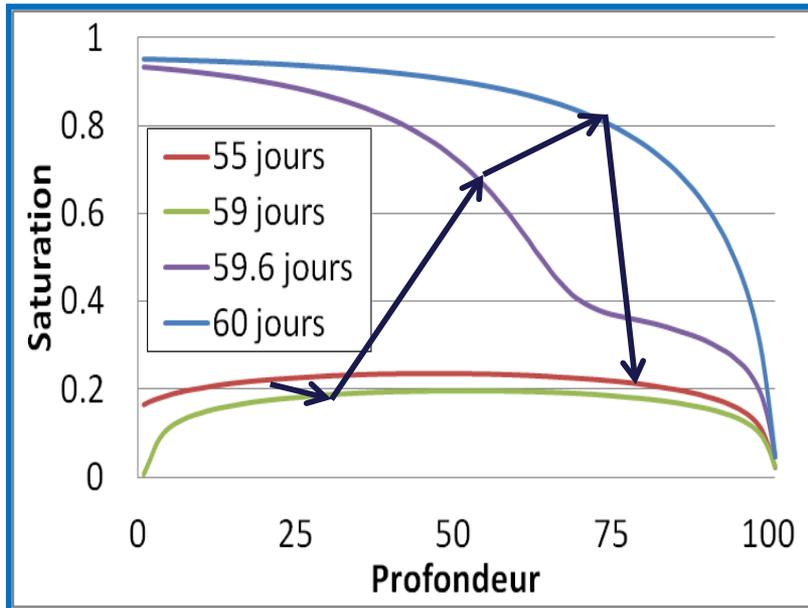


Partially saturated state



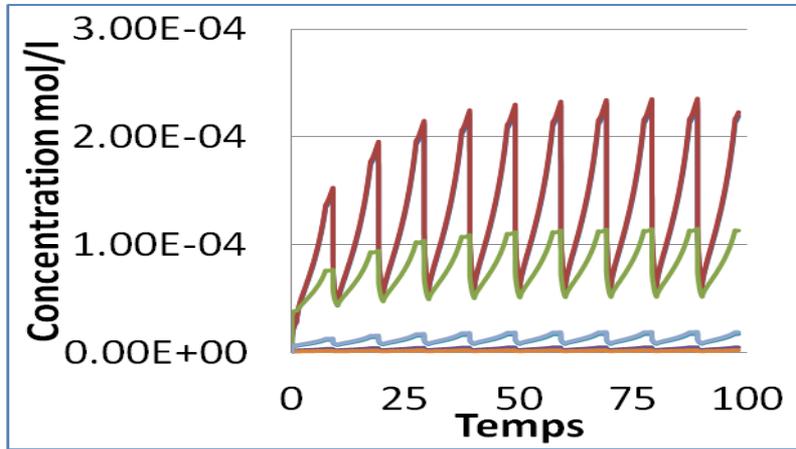
➤ Variation en cycle pluie-séchage  
 CFMR, 8 Octobre 2020

## Hydric state variation

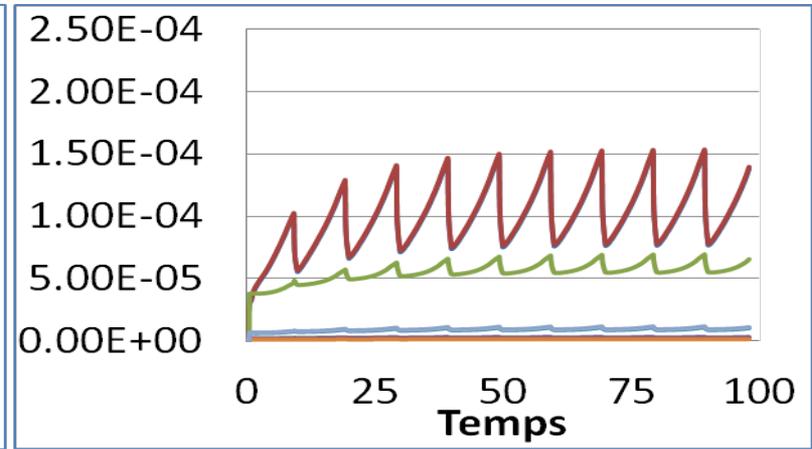


- ① Middle drying period
- ③ Middle raining period

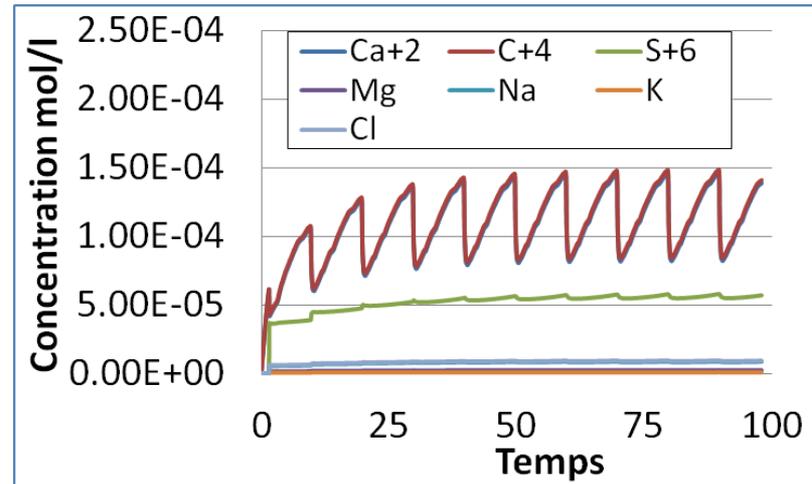
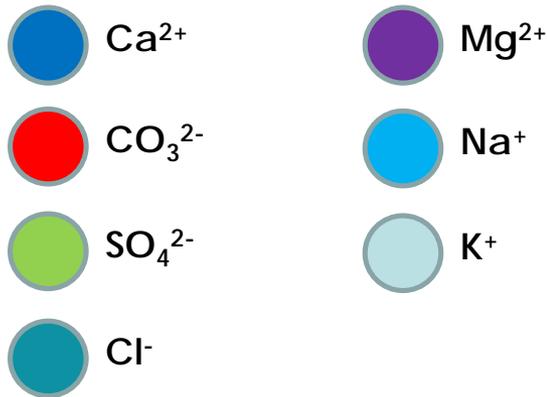
- ② Just before rain
- ④ Just after rain



At 2 mm from the surface

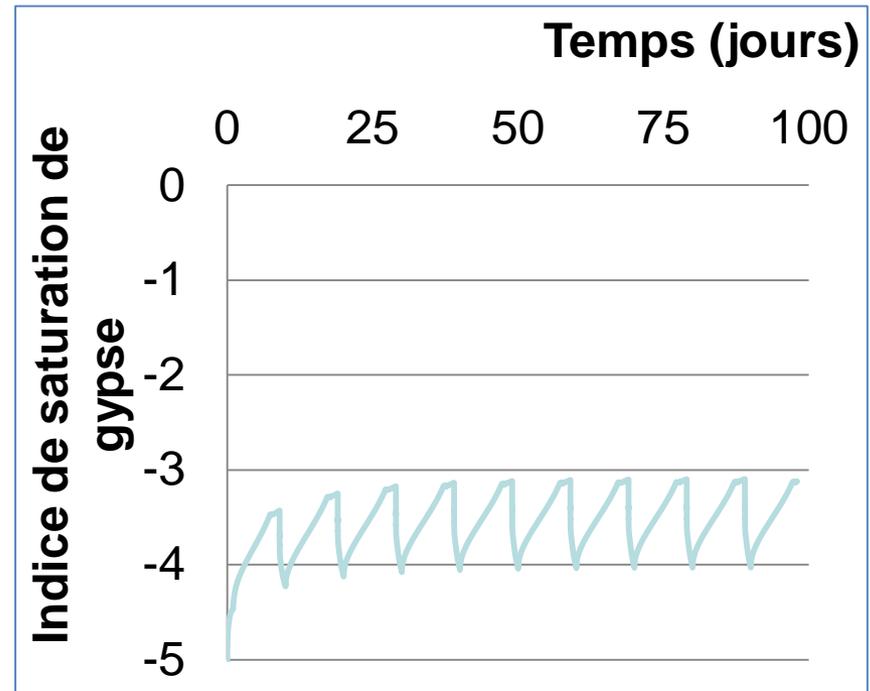
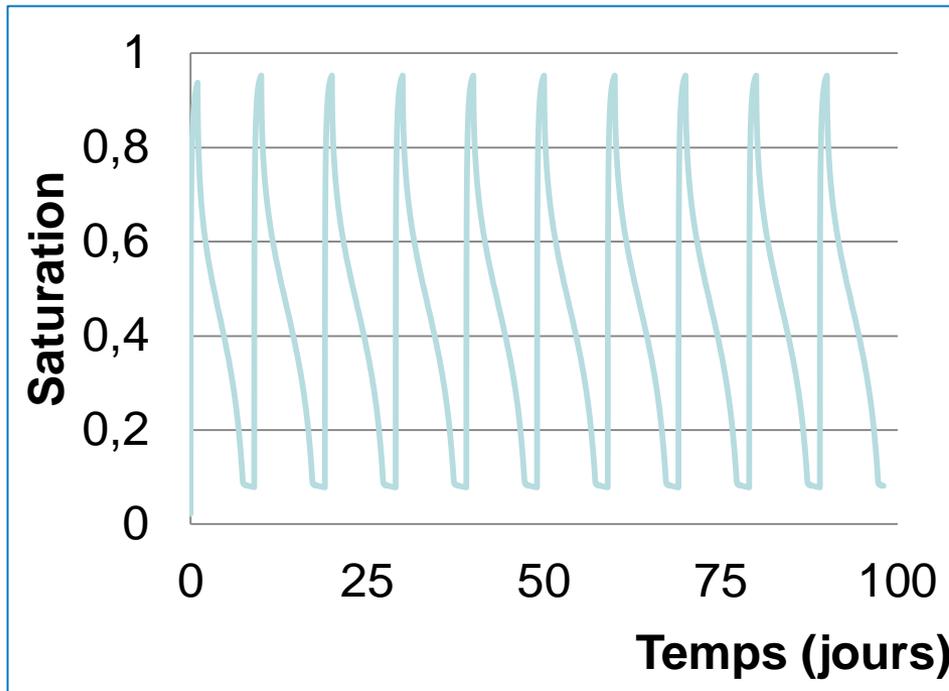


At 48 mm



At 86 mm

At 2 mm from the surface



- Water saturation varies between 0.008 and 0.94
- No gypse precipitations !!!

# Conclusions

1- Les mécanismes de dégradation des pierres de construction sont multiples. La fatigue THM semble un mécanismes plausible

2- Si la présence de gypse dans les fractures créées par la desquamation en plaque est avérée, son origine et son impact reste à être établi.  
L'origine aérienne du SO<sub>2</sub> semble peu probable