Numerical modeling of cracking with thermo-hydro-mechanical process considering rock heterogeneity

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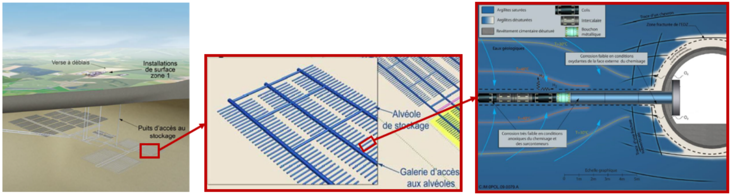
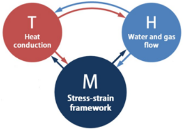
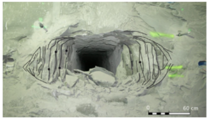
Study background

Study supported by ANDRA(French national radioactive waste management agency)





Numerical tools



THM coupling behaviors

Damage/cracking behaviors

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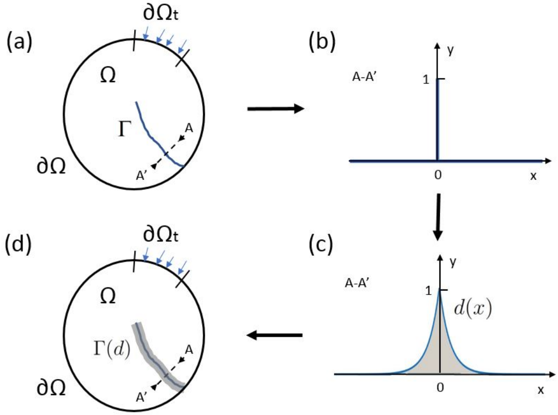


FIGURE – *(a)The real sharp crack Γ in the solid Ω ; (b)The real sharp crack in the 1-D coup A-A'; (c) The diffused crack by Phase-field in the 1-D coup A-A'; (d)The diffused crack with its equivalent surface $\Gamma(d)$.*

Diffusive crack function :

$$d(x) = e^{-\frac{|x|}{l_d}} \tag{1}$$

Equivalent crack surface :

$$\Gamma(d) = \int_{-\infty}^{+\infty} \frac{1}{2}\left(\frac{1}{l_d}d^2 + l_d d'^2\right)dx = \int_{-\infty}^{+\infty} \gamma(d, \nabla d)dx \tag{2}$$

The minimisation of the energy functional :

$$E(u,d) = \int_{\Omega} g(d)\Psi_0(\varepsilon(u))dV + g_c \int_{\Omega} \gamma(d, \nabla d)dV \tag{3}$$

Phase field method based on tensile and shear crack

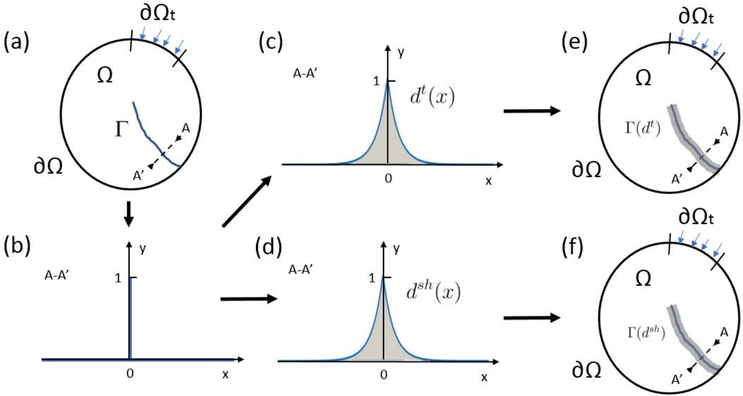


FIGURE – *(a)The real sharp crack Γ in the solid Ω ; (b)The real sharp crack in the 1-D coup A-A' ; (c)and(d) The diffused tensile&shear crack by phase field method in the 1-D coup A-A' ; (e)and(f)The diffused tensile&shear crack with its equivalent surface $\Gamma(d^t)$&$\Gamma(d^{sh})$.*

The new modified phase-field model is defined by two types of damage d^t and d^{sh}.
The minimisation of the energy functional is rewritten as :

$$E(u,d) = \underbrace{\int_\Omega \Psi(\varepsilon(u), d^t, d^{sh}) dV}_{\text{stored energy}} + \underbrace{g_c^t \int_\Omega \gamma_t(d^t, \nabla d^t) dV}_{\text{tensile fracture energy}} + \underbrace{g_c^{sh} \int_\Omega \gamma_{sh}(d^{sh}, \nabla d^{sh}) dV}_{\text{shear fracture energy}} \tag{4}$$

Following the thermodynamic theory, the damage criterion can be written as :

$$\begin{cases} f^t = -\frac{\partial W}{\partial d^t} = -\frac{\partial \Psi(\varepsilon, d^t, d^s)}{\partial d^t} - g_c^t(\frac{d^t}{l_d} - l_d \Delta d^t) \leq 0 \\ f^s = -\frac{\partial W}{\partial d^s} = -\frac{\partial \Psi(\varepsilon, d^t, d^s)}{\partial d^s} - g_c^s(\frac{d^s}{l_d} - l_d \Delta d^s) \leq 0 \end{cases} \tag{5}$$

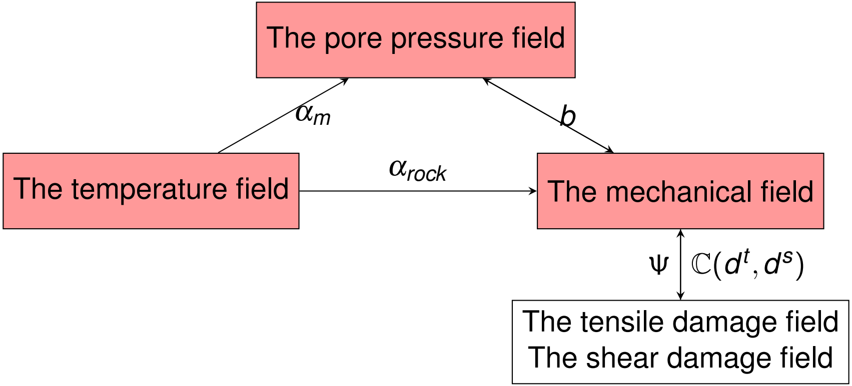
The pore pressure field

The temperature field

The mechanical field

The tensile damage field
The shear damage field

- The pore pressure field : $[R_h](P) = (f_h)$
- The temperature field : $[R_T](T) = (f_T)$
- The mechanical field : $[R_m](u) = (F_m)$
- The tensile damage field : $[R_{d^t}](d^t) = (f_{d^t})$
- The shear damage field : $[R_{d^s}](d^s) = (f_{d^s})$



- α_m : Differential expansion between rock and water
- b : Biot's coefficient
- α_{rock} : Thermal expansion coefficient of rock

Some parameters influenced by damage field d (here we only consider d^t) :

- Permeability : $k = k_0 \exp(\beta d^t)$
- Biot coefficient : $b(d^t) = b_{initial} + (1 - b_{initial})d^t$
- Porosity : $\Phi(d^t) = \Phi_{initial} + (1 - \Phi_{initial})d^t$
- Biot module : $\frac{1}{M(d^t)} = \frac{(1-b(d^t))(b(d^t)-\Phi(d^t))}{K_s} + \frac{\Phi(d^t)}{K_f}$
- Differential expansion : $\alpha_m(d^t) = (b(d^t) - \Phi(d^t))\alpha_s + \Phi_{ini}\alpha_f$

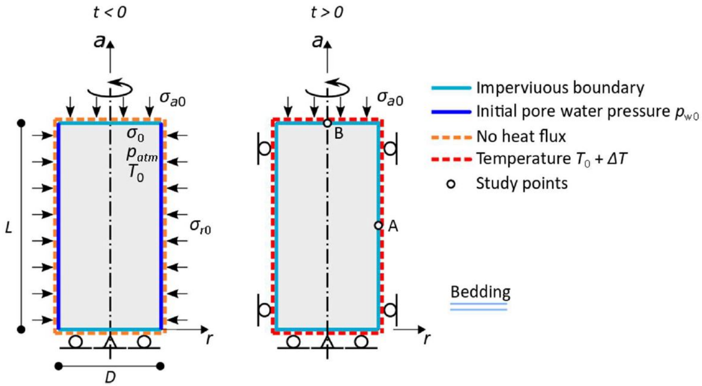
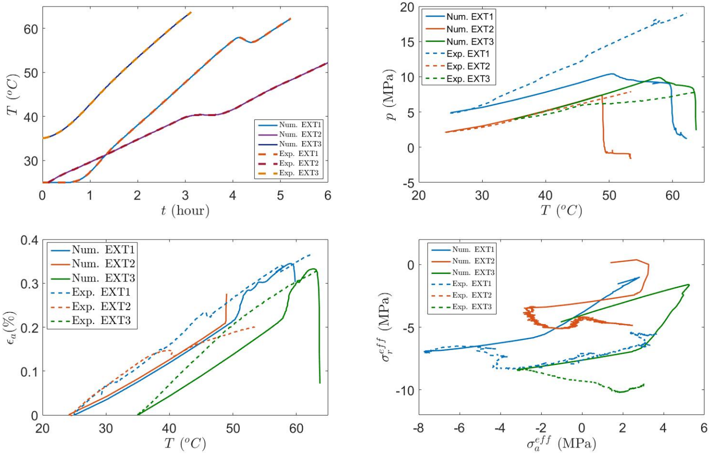


FIGURE – *Modelling sequence of the thermal extension test : initial, and boundary conditions.(from Deco2023 specifications and [Braun, 2019])*

Section 3 : Thermal extension tests



Weibull probability distribution(WPD) for porosity f_p and inclusion fraction f_{in} :

$$f_i(x) = \frac{m}{\beta_i}(\frac{x}{\beta_i})^{m-1} e^{-(x/\beta_i)^m}; \quad i = p, in$$

with average fraction $\beta_p = 0.18$; $\beta_{in} = 0.4$

Mori-Tanaka homogenization scheme :
Microscopic scale :

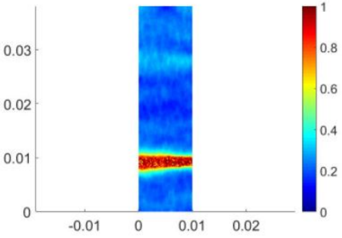
$$\mathbb{C}^I_{hom} = (1 - f_p)\mathbb{C}_0 : [(1 - f_p)\mathbb{I} + f_p(\mathbb{I} - \mathbb{P}^I_{hom} : \mathbb{C}_0)^{-1}]^{-1}$$

Mesoscopic scale :

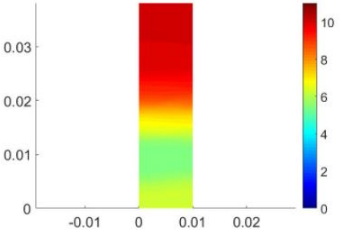
$$\mathbb{C}^{II}_{hom} = \mathbb{C}^I_{hom} + [f_{in}(\mathbb{C}_{in} - \mathbb{C}^I_{hom}) : \mathbb{D}_{in}] : [\mathbb{I} + f_{in}(\mathbb{C}_{in} - \mathbb{I})]^{-1}$$

Section 3 : Thermal extension tests

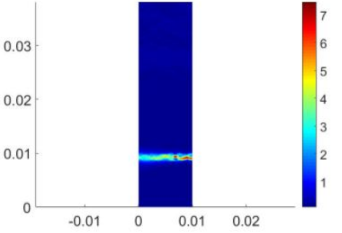
Photo from [Braun, 2019]



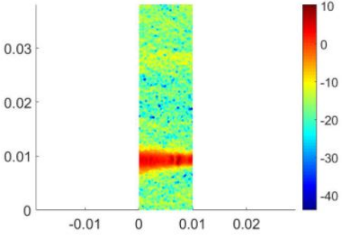
Damage (-)



Pore pressure (MPa)



Axial strain (%)



Axial stress (Mpa)

Application of GCS test :

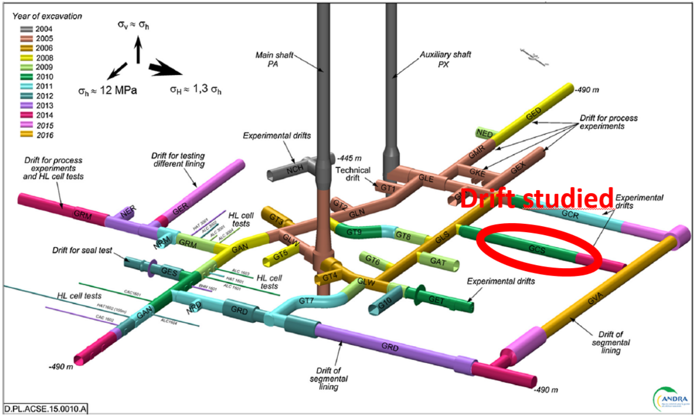


FIGURE – *General view of the GCS experiment*

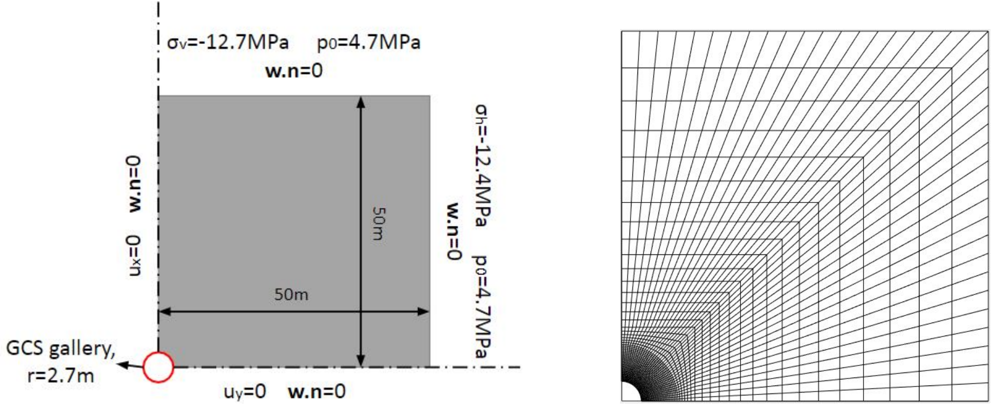
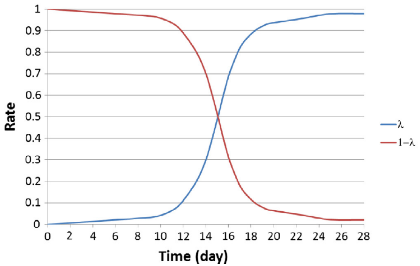


FIGURE – *Boundary conditions (left) and finite element mesh (right)*

Excavations take place during the 28 days :



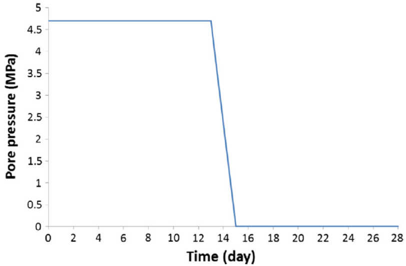
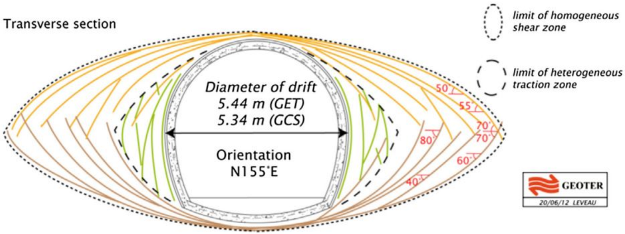
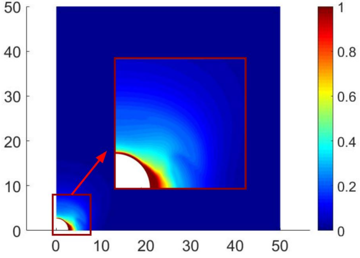


FIGURE – *Mechanical (left) and hydraulic (right) deconfinement curves.*

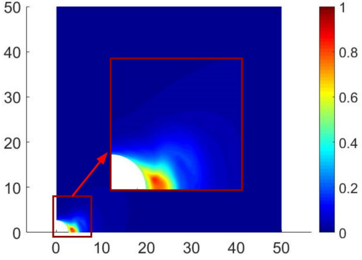
Elastic parameters	Young's modulus	$E_{\parallel}$=6GPa
		$E_{\perp}$=3.5GPa
	Poisson's ratio	$\nu_{\parallel}$=0.24
		$\nu_{\perp}$=0.35
Hydraulic parameters	Permeability	$k_{0\parallel}=6\times10^{-20}m^2$
		$k_{0\perp}=3\times10^{-20}m^2$
	Biot coefficient	b=0.6
	Porosity	Φ=0.16
Crack fields parameters	Toughness	g_c^t=1800N/m
		g_{c0}^s=4500N/m
	Crack length	l_d=0.1m
	Permeability rate	β=12
	Viscoplastic effect	χ=0

Section 3 : Excavation induced crack zone around GCS gallery



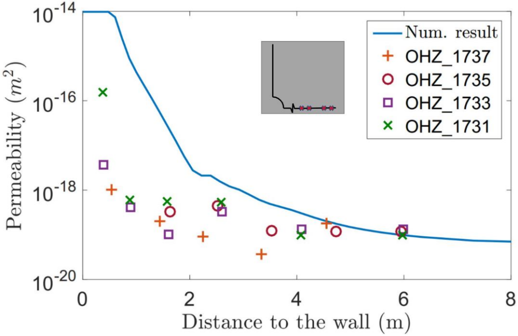


(Tensile damage)

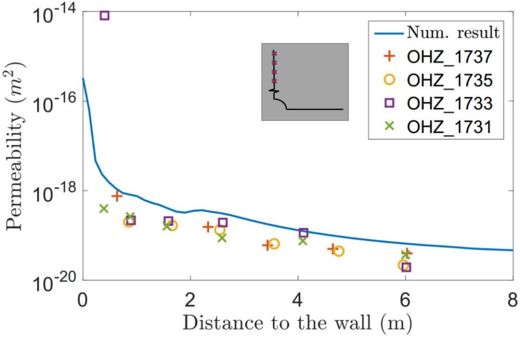


(Shear damage)

Permeability : $k = k_0 \exp(\beta d^t)$



(Horizontal direction)



(Vertical direction)

Pore pressure :

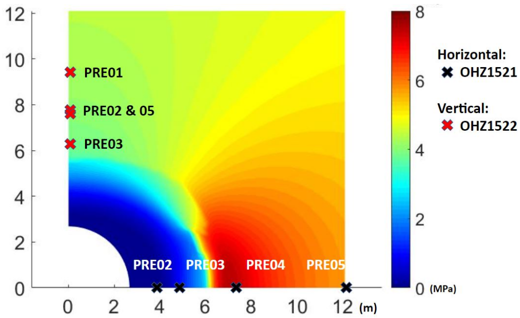
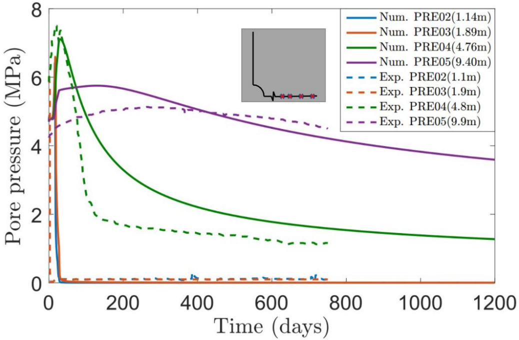
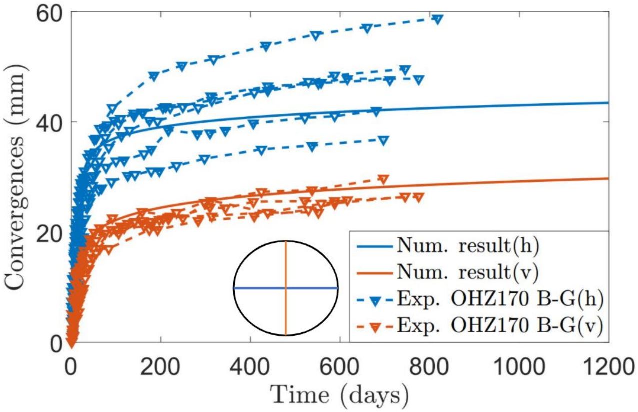


FIGURE – *Distribution of pore pressure at end of excavation (t=28 days)*





Convergences (mm)
0
20
40
60
Time (days)
0
200
400
600
800
1000
1200
Num. result(h)
Num. result(v)
Exp. OHZ170 B-G(h)
Exp. OHZ170 B-G(v)

Section 3 : ALC heating test, heating induced cracking

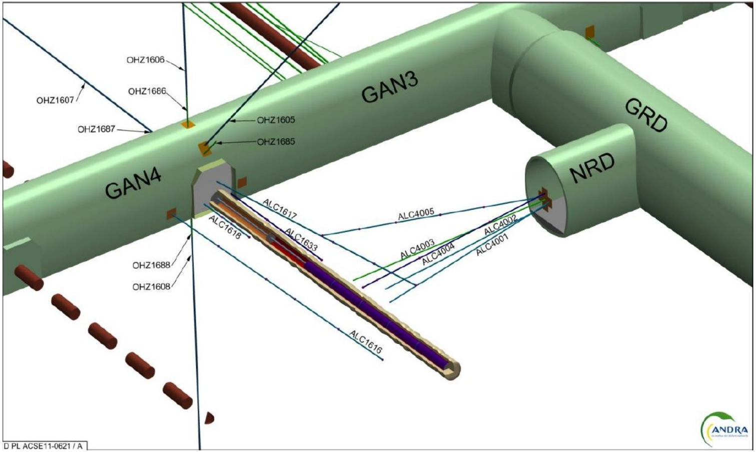


FIGURE – *General view of the ALC heating experiment*

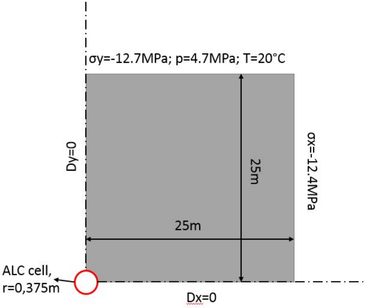


FIGURE – *Modeling domain of the alveolus in 2D plane strain*

Elastic parameters :

- $E_{\parallel} = 6GPa$; $E_{\perp} = 3GPa$; $\nu_{\parallel} = 0.2$; $\nu_{\perp} = 0.35$.

Hydraulic parameters :

- Permeability : $k_{initial\parallel} = 6 \times 10^{-20} m^2$; $k_{initial\perp} = 3 \times 10^{-20} m^2$.

Thermal parameters :

- Thermal conductivity : $\lambda_{\parallel} = 2 W.m^{-1}.K^{-1}$; $\lambda_{\perp} = 1.33 W.m^{-1}.K^{-1}$.

The time step size used in this example :

- 0-1 day (excavation) : 1 hour
- 1-176 days : 1 day
- 176-186 days (heating starting at 176 day) : 1 hour
- 186-2500 days : 1 day

Temperature results :

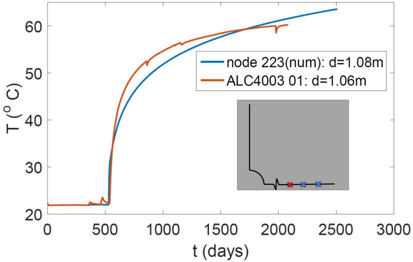


FIGURE – *Temperature evolution in ALC4003, sensor 01, d=1.06m*

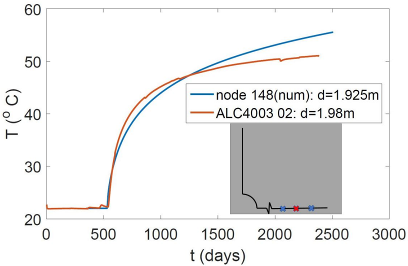


FIGURE – *Temperature evolution in ALC4003, sensor 02, d=1.98m*

Section 3 : ALC heating test, heating induced cracking

Pore pressure in horizontal direction :

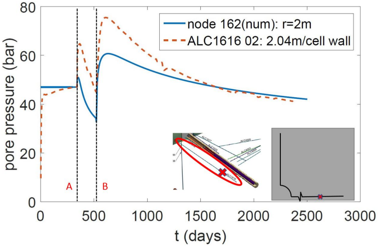


FIGURE – *Pressure evolution in ALC1616 (horizontal)*

Time A : Excavation ; Time B : Heating.

- Excavation induced over-pressure not correctly reproduced
  - Reasons : 3D geometrical effect, etc...
- Over-pressure due to heating almost well reproduced

Pore pressure in vertical direction :

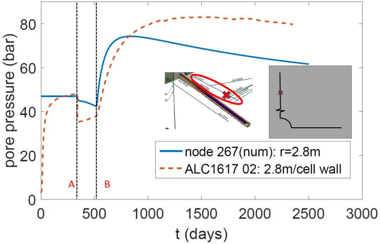


FIGURE – *Pressure evolution in ALC1617 (vertical)*

Time A : Excavation ; Time B : Heating.

- Excavation induced pressure decrease not correctly reproduced
  - Reasons : 3D geometrical effect, etc...
- Pressure increase due to heating quite well reproduced, but too early cooling process started

Excavation induced damage :

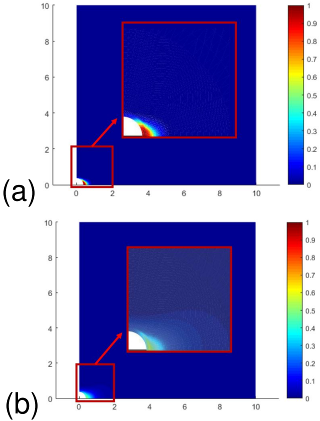
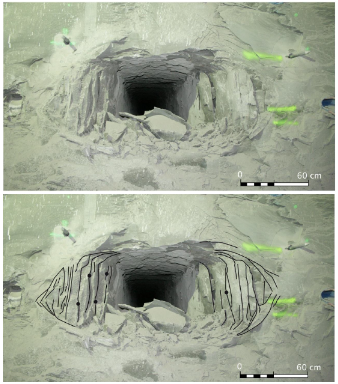


FIGURE – *Distribution of (a) tensile and (b) shear cracks at t=1 day*

Photos of cracks around the ALC :



Excavation induced damage :

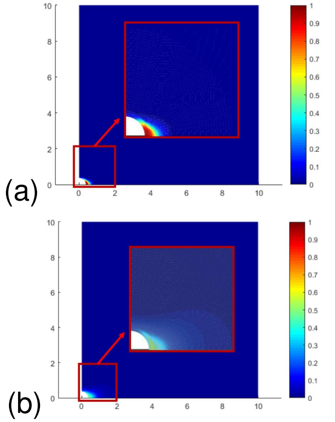


FIGURE – *Distribution of (a) tensile and (b) shear cracks at t=1 day*

Heating induced damage :

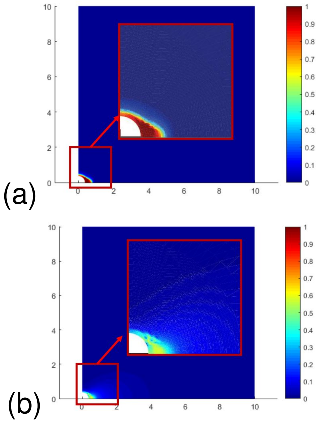


FIGURE – *Distribution of (a) tensile crack and (b) shear crack at t=1176 days*

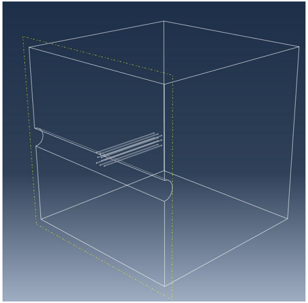
Concluding remarks

Conclusion :

- A new modified phase field method ;
  - It is possible to consider tensile and shear damage.
- Thermal extension tests
  - The tendencies of pore pressure, strain and stress are well reproduced ;
  - The crack path is well reproduced.
- Application of GCS test
  - The pore pressure variation is well reproduced ;
  - The convergences of diameter are well reproduced ;
  - The distributions of tensile and shear damage are reproduced.
- Application of ALC test
  - The temperature variation is well reproduced ;
  - The pore pressure's changing tendency is well reproduced ;
  - The distributions of tensile and shear damage are reproduced.

Future work :

- Consider heterogeneity of materials in strcture simulation
- 3D extension



Thank you for your attention !