Modeling of leaching-mechanical coupling in concrete

Dawei Hu, Fan Zhang, Hui Zhou, Jianfu SHAO

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ANDRA

LABORATOIRE de MECANIQUE de LILLE
UMR CNRS 8107
E.C. LILLE
E.N.S.A.M.

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Excerpt from the Proceedings of the 2011 COMSOL Conference in Stuttgart

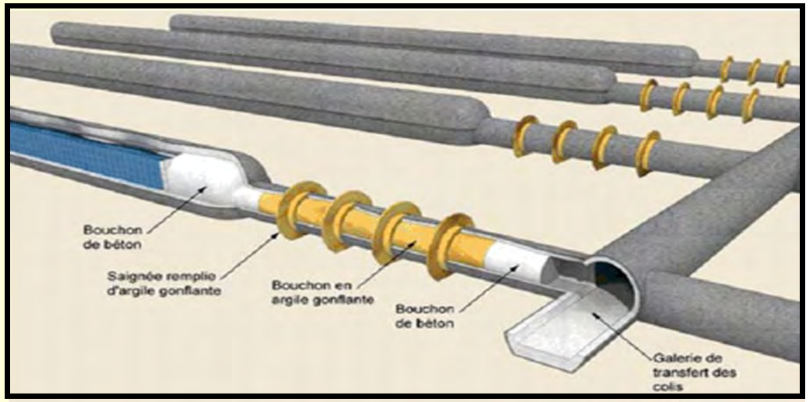
Plan

- Background and problem
- Mchanical model
- Leaching
- Coupling model
- Conclusions and perspectives

Background

Where is the studied concrete?

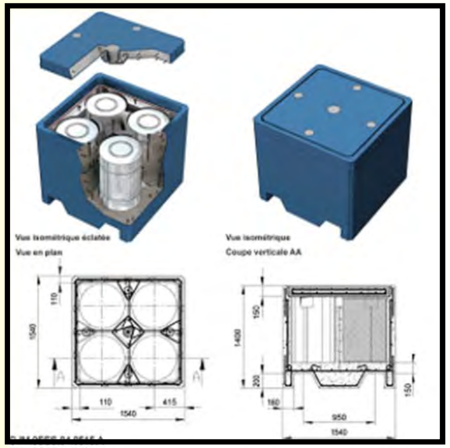
- Structures;
- Seal material;
- Stock cell of nulear waste B.



Representation of closed tunnel [ANDRA]

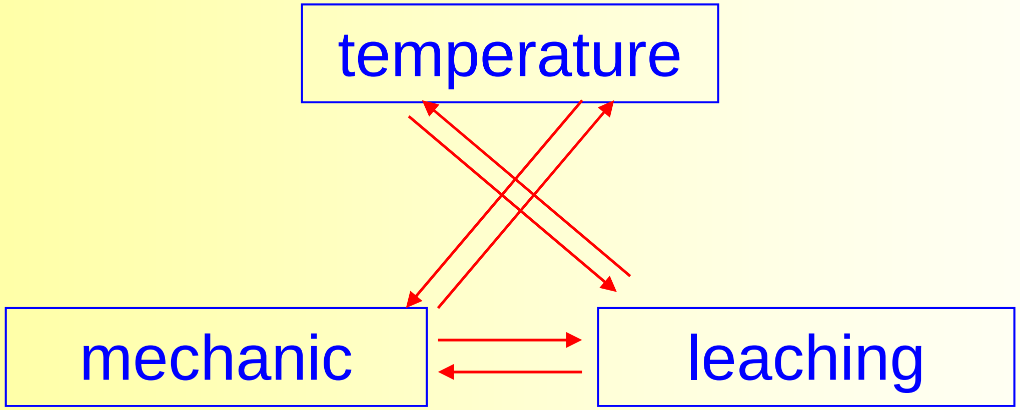
Which is the concrete subjected?

- Thermal load;
- Mechanical evolution;
- Chimical degradation.



Representation of stock cell of nuclear waste B [ANDRA]

Problem



Implemented models in COMSOL for concrete

- ✓ Mechanical
- ✓ Leaching
- ✓ Leaching-mechanical coupling

Mechanical model

1) Plastic damage modeling

- Plastic characterization

Criteron of Drucker-Prager

$$f_p(\sigma_{ij},\gamma^p,d_m) = q + \eta p - \alpha\left(\gamma^p,d_m\right)K = 0$$

$$\alpha(\gamma^p,d_m)=\left(1-d_m\right)\left[\alpha_0 + \left(\alpha_m - \alpha_0\right)\frac{\gamma^p}{b_1+\gamma^p}\right]$$

$$\eta = \frac{1}{\sqrt{3}}\left(\frac{2Rc}{Rt+Rc} - 1\right)$$

$$K = \frac{2}{\sqrt{3}}\left(\frac{Rt\cdot Rc}{Rt+Rc}\right)$$

Rc : Uniaxial compression strength

Rt : Tension strength

Mechanical model

1) Plastic damage modeling

- Associated plasticity

$$d\varepsilon_{ij}^{p} = d\lambda \frac{\partial f_p}{\partial \sigma_{ij}}$$

- Damage characterization

$$d_m = \bar{d}_{mc}\left[1 - \exp\left(-b_2 \gamma^{p}\right)\right]$$

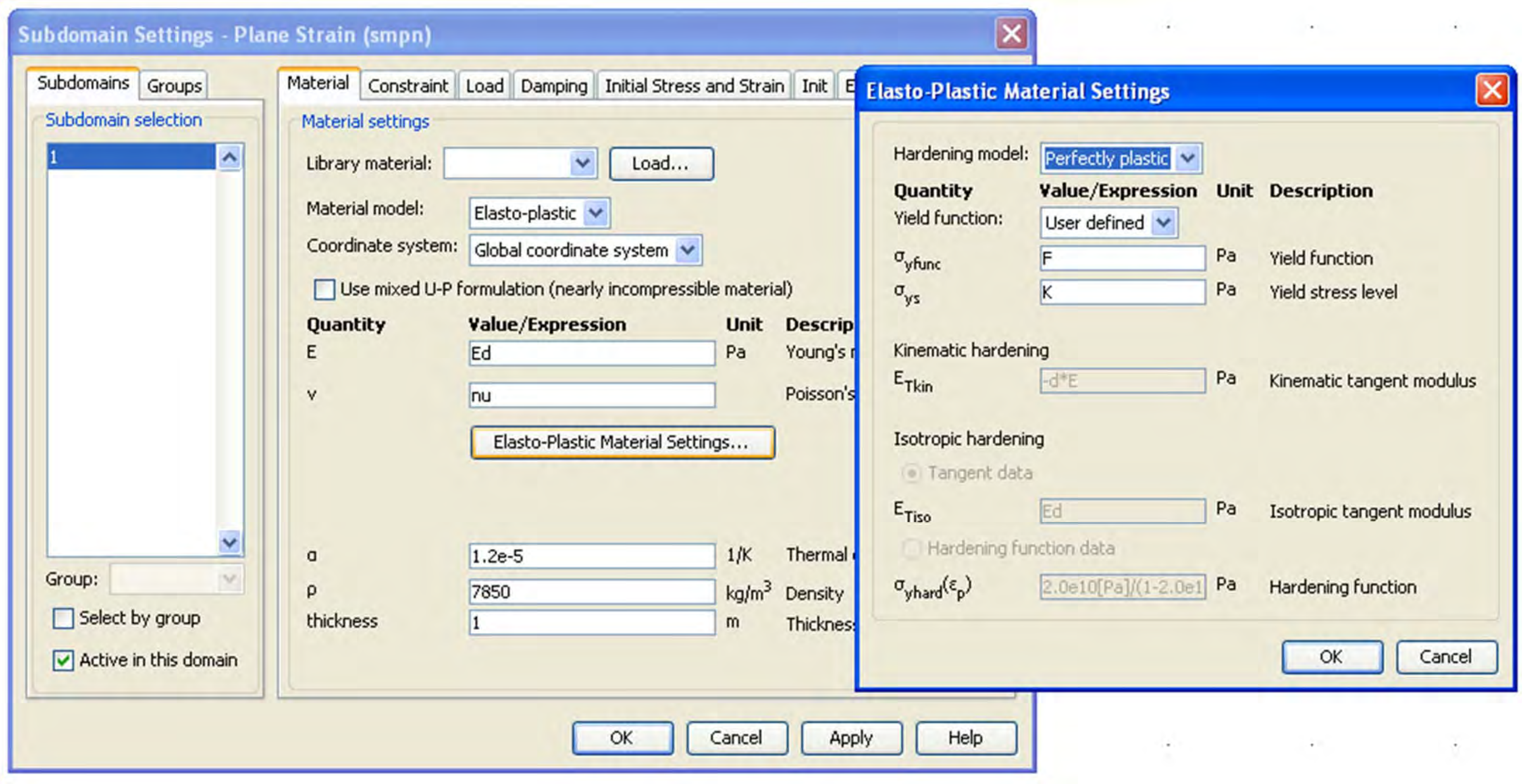
- Effective modulus

$$\sigma_{ij} = \left[\left(1 - d_m\right) C_{ijkl}^{0}\right] : \varepsilon_{kl}^{e}$$

Mechanical model

1) Plastic damage modeling

- **Plane stress module for plastic damage modeling**
  subdomain settings



Mechanical model

1) Plastic damage modeling

- **Plane stress module for plastic damage damage** scalar expressions

Scalar Expressions

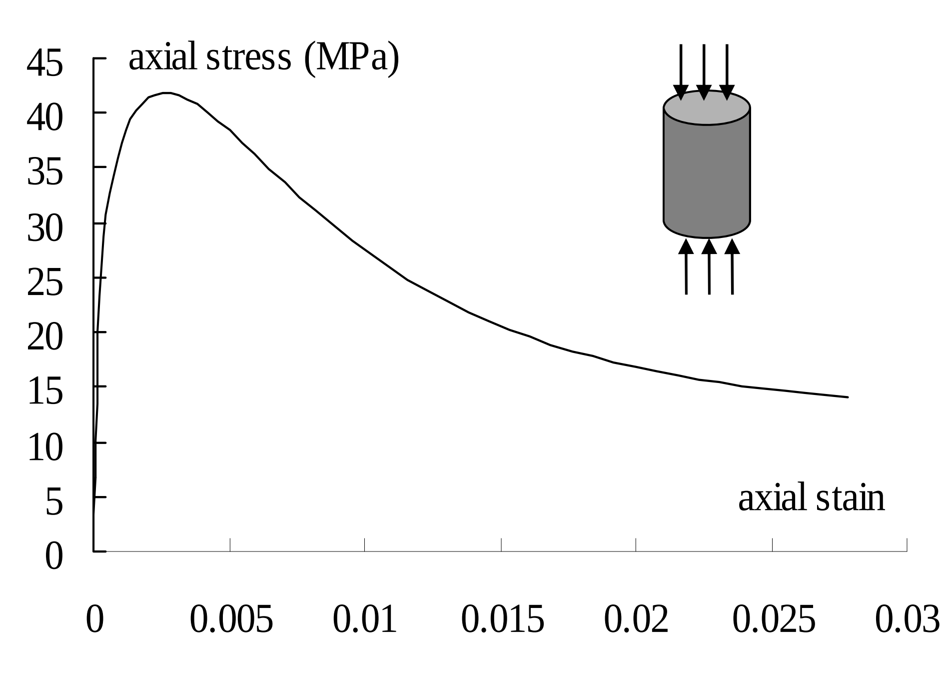
Name	Expression	Unit	Description
ALPHA	(1/sqrt(3))*(2*Rc/(Rc+Rt)-1)	1	
K	(2/sqrt(3))*(Rt*Rc/(Rt+Rc))*eta	Pa	
I1	(sx_smpn+sy_smpn+sz_smpn)/3	Pa	first stress invariant
dsx	sx_smpn-I1	Pa	
dsy	sy_smpn-I1	Pa	
dsz	sz_smpn-I1	Pa	
TOEQ	sqrt(0.5*(dsx^2+dsy^2+dsz^2)+sxy_smpn^2)	Pa	equivalent deviatoric stress
F	1.45*ALPHA*I1+TOEQ	Pa	plastic yield function
eta	(1-d)*(0.5+(1-0.5)*epe_smpn/(b1+epe_smpn))	1	
d	wc*(1-exp(-b*epe_smpn))		damage evolution law
Ed	(1-d)*E	Pa	effective modulus

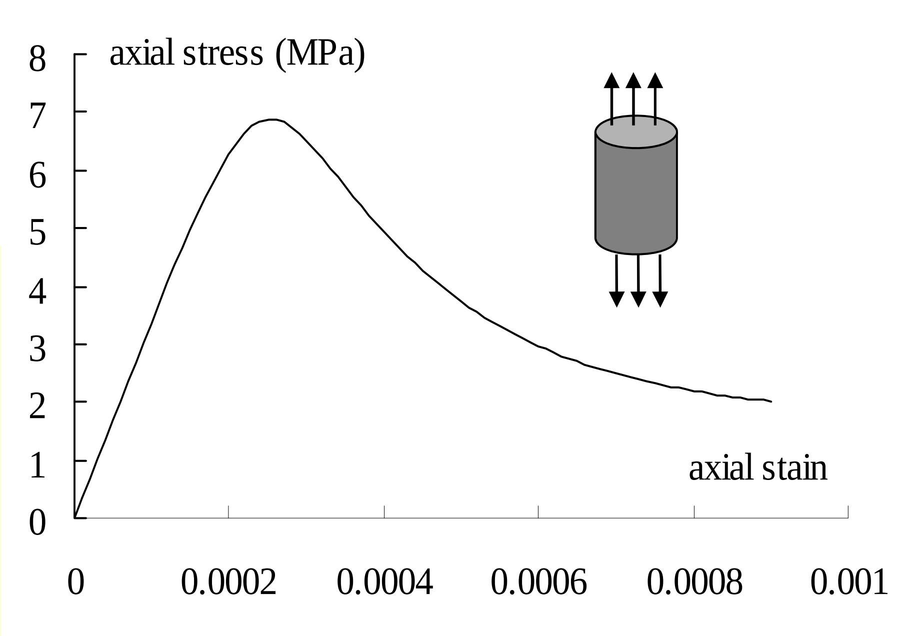
OK Cancel Apply Help

Mechanical model

1) Plastic damage simulation

Simulation of uniaxial compression and tension

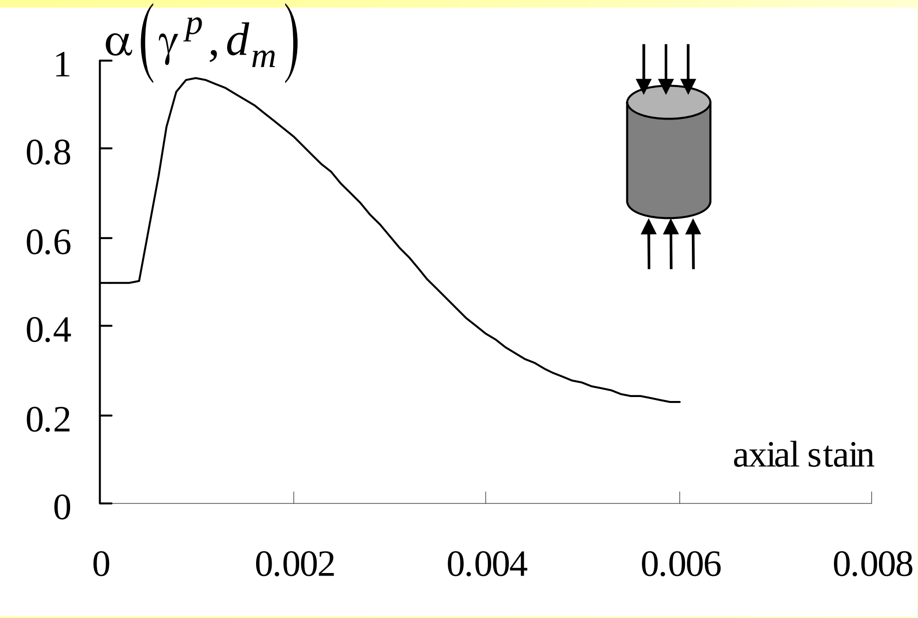


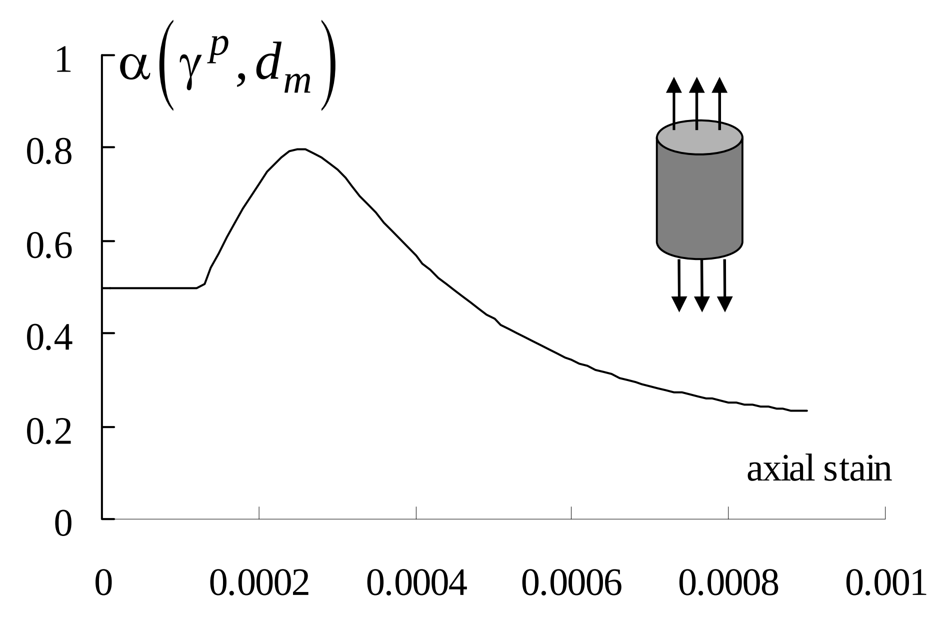


Mechanical model

1) Plastic damage simulation

Evolution of plastic hardening and softening function





Mechanical model

2) Creep characterization

- Creep strain

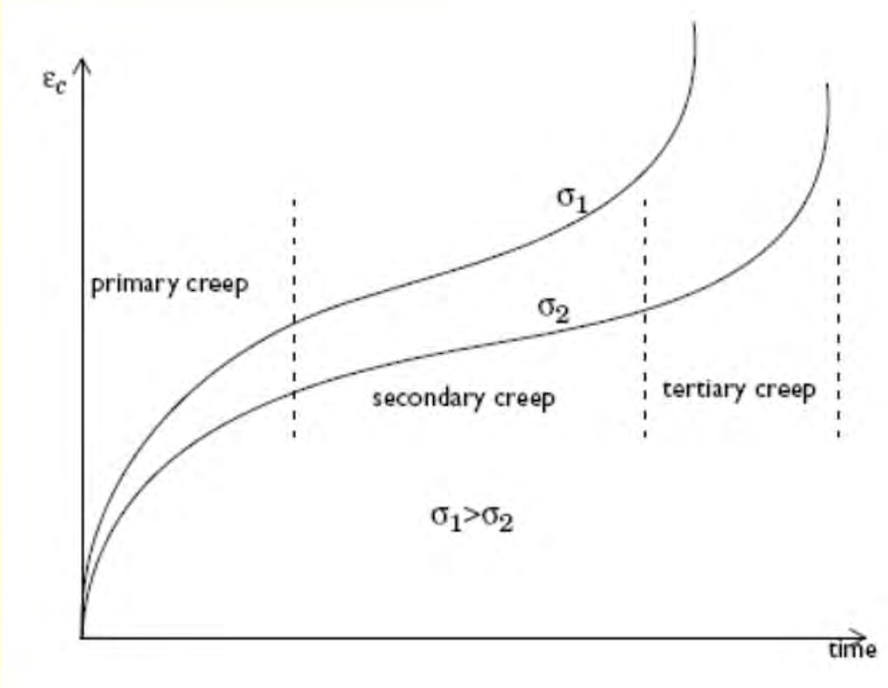
  in compression

$$\dot{\varepsilon}^{cpc} = A_c\left(\underline{A_1 m t^{m-1}} + \underline{A_2}\right)\boldsymbol{\sigma}, 0 < m < 1$$

First creep   Second creep

In tension

$$\dot{\varepsilon}^{cpt} = A_t\left(A_1 m t^{m-1} + A_2\right)\boldsymbol{\sigma}, 0 < m < 1$$



- Total strain

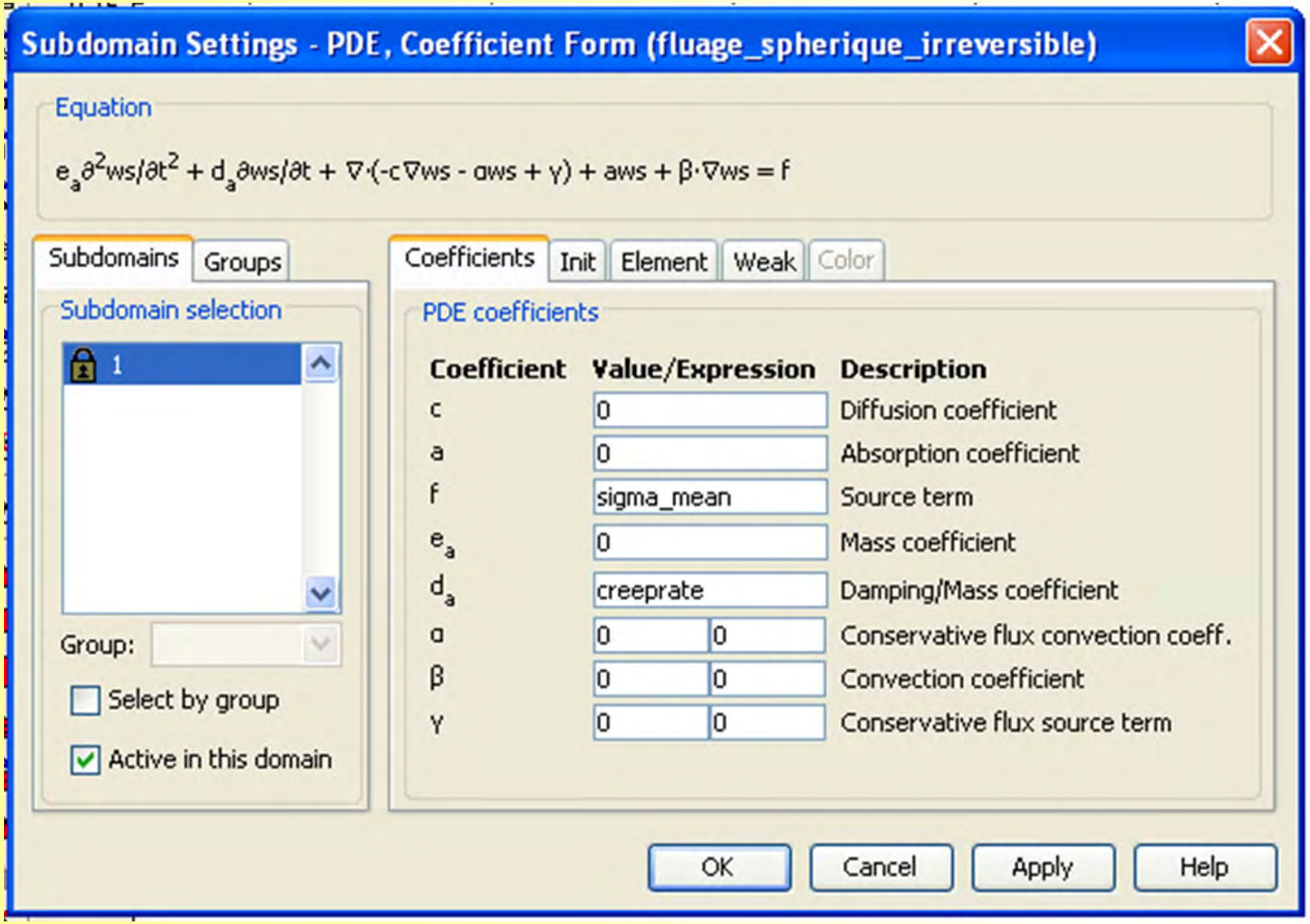
  Elastic + Plastic + Creep

$$\varepsilon_{ij} = \varepsilon_{ij}^{e} + \varepsilon_{ij}^{p} + \varepsilon_{ij}^{cp}$$

Mechanical model

2) Creep characterization

- **PDE module for creep**



Leaching model

1) Leaching characterization

- Mass balance equation

$$\frac{\partial Ca^{solid}}{\partial Ca^{2+}} \frac{\partial Ca^{2+}}{\partial t} = \nabla \cdot \left[D\left(Ca^{2+}\right) \nabla Ca^{2+} \right]$$

Hydric source of calcium ion

Diffusion coefficient of calcium ion

- Diffusion coefficient with ammonium nitrate

$$D\left(Ca\left(NO_3\right)_2\right) = \lambda D_e\left(Ca^{2+}\right) \nabla^2 Ca^{2+}$$

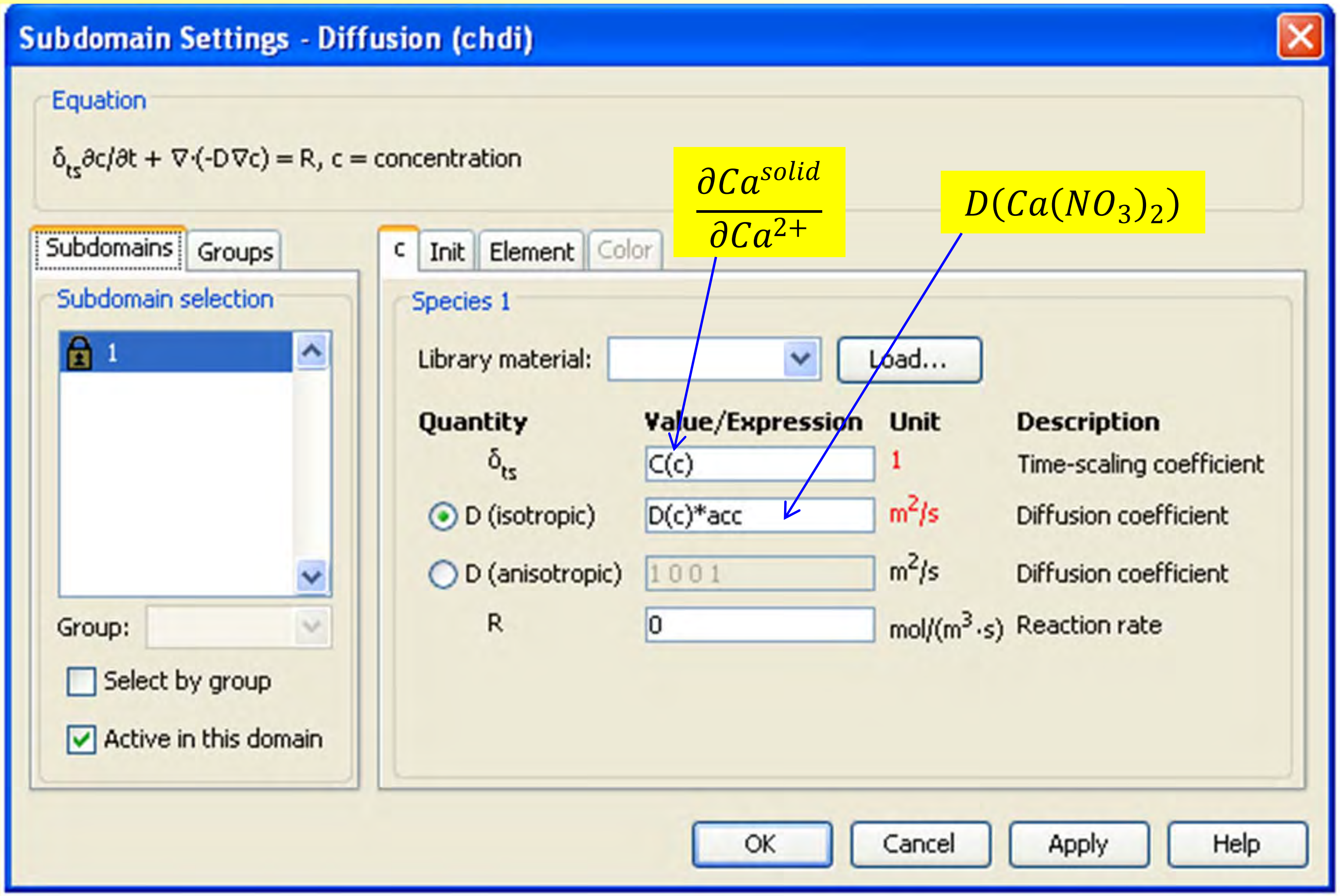
Acceleration parameter

Diffusion coefficient of calcium ion

Leaching model

1) Leaching characterization

➢ **Diffusion module for leaching**



Leaching model

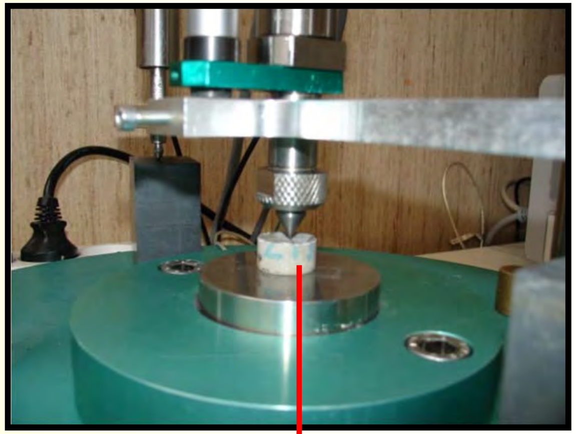
2) Leaching-plastic damage coupling

- Chemical damage

$$d_c = d_{c\max}\left[1-\exp\left(Ca^{2+}-Ca^{2+}\Big|_0\right)\right]$$

- Chemical damage-mechanical parameters

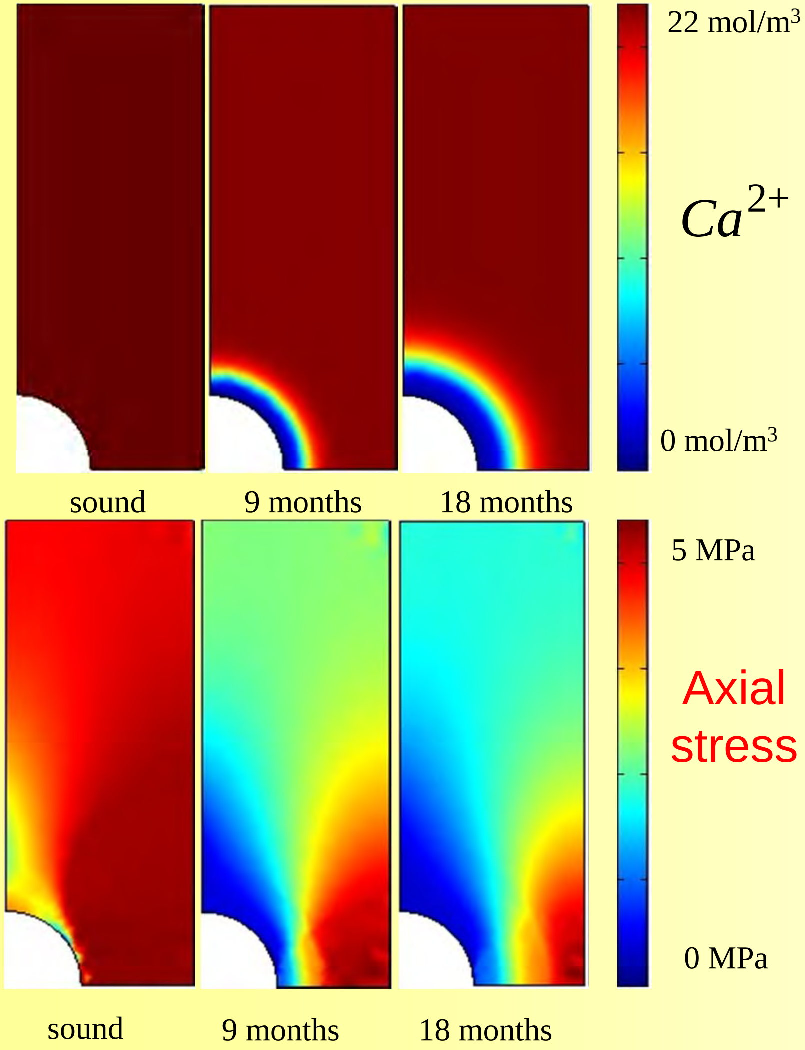
$$\begin{cases} E = E_0\left(1-d_c\right) \\ R_c = R_{c0}\left(1-d_c\right) \\ R_t = R_{t0}\left(1-d_c\right) \end{cases}$$

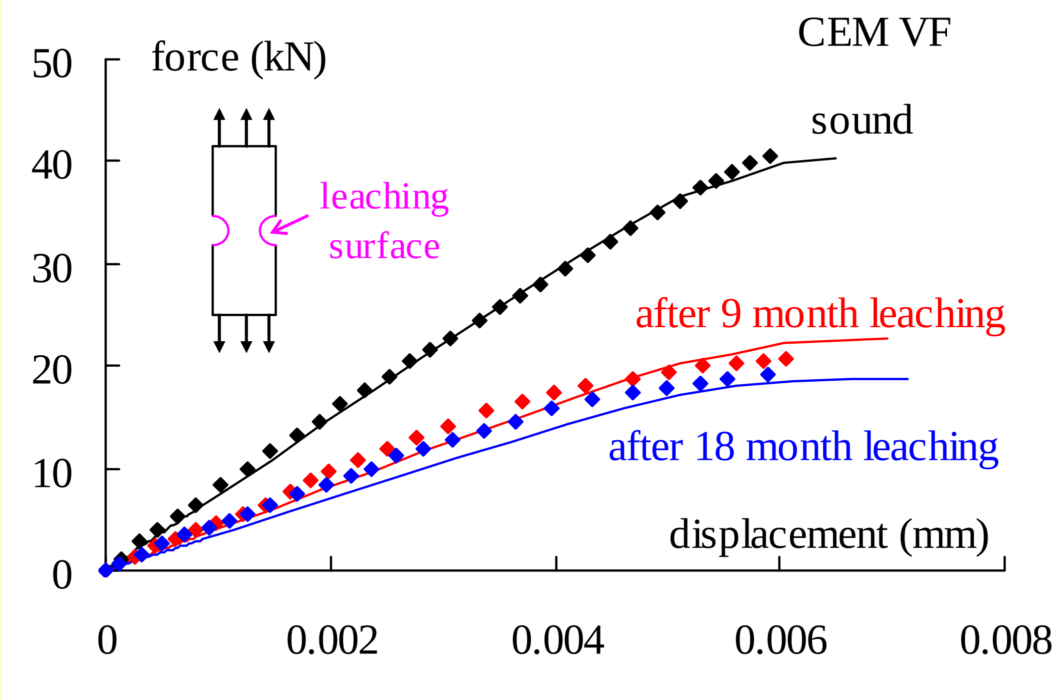


Test of micro indentation

Leaching model

2) Leaching-plastic damage simulation

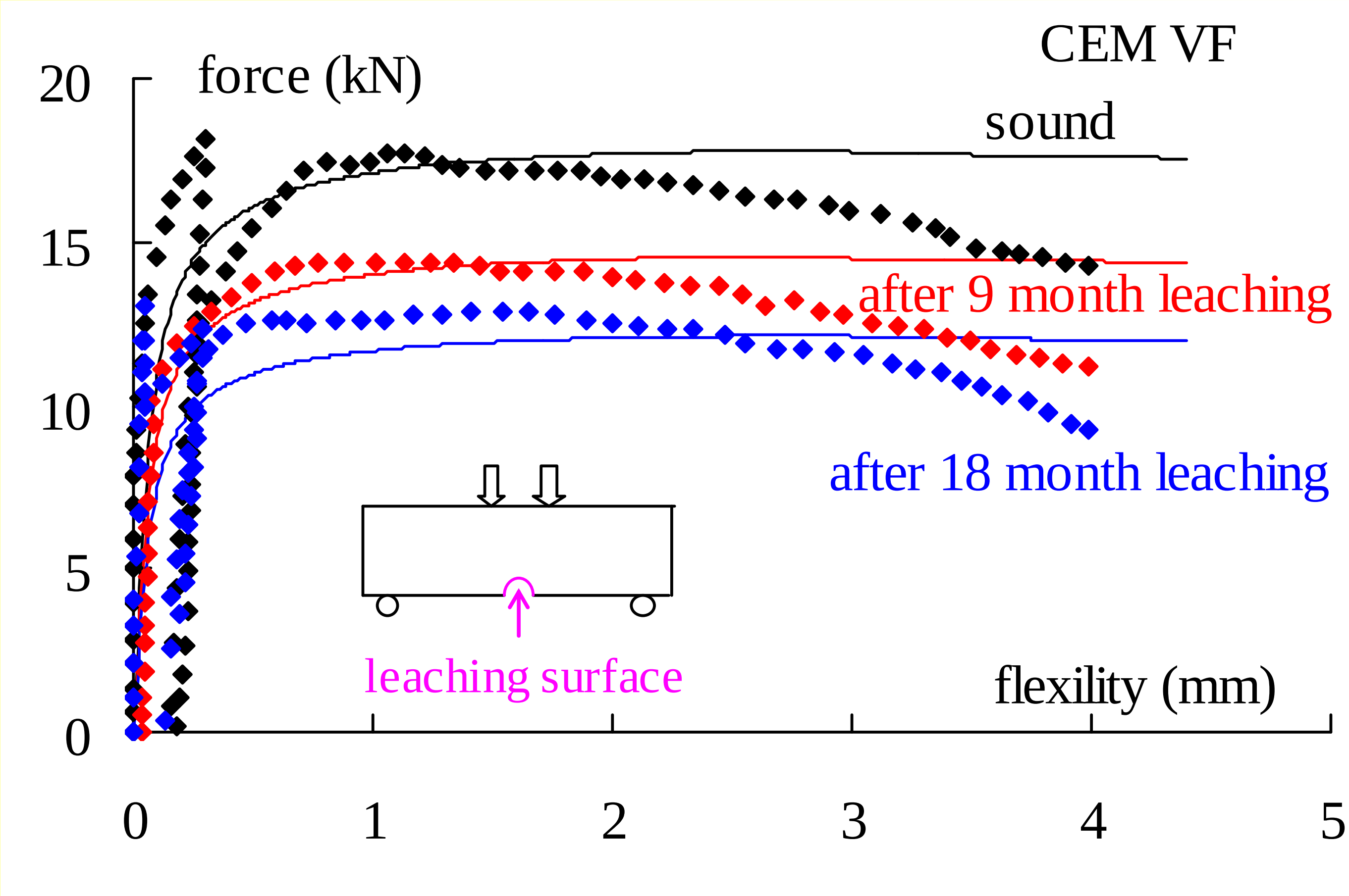




Directe tension test after different degradation times (data after Camps 2008)

Leaching model

2) Leaching-plastic damage simulation



Flextion test after different degradation times
(data after Camps 2008)

Coupling Model

1) Leaching-creep coupling characterization

- Variation of diffusion coefficient with plastic damage

$$D(d_m) = \lambda D_e (1 + \alpha_D d_m)$$

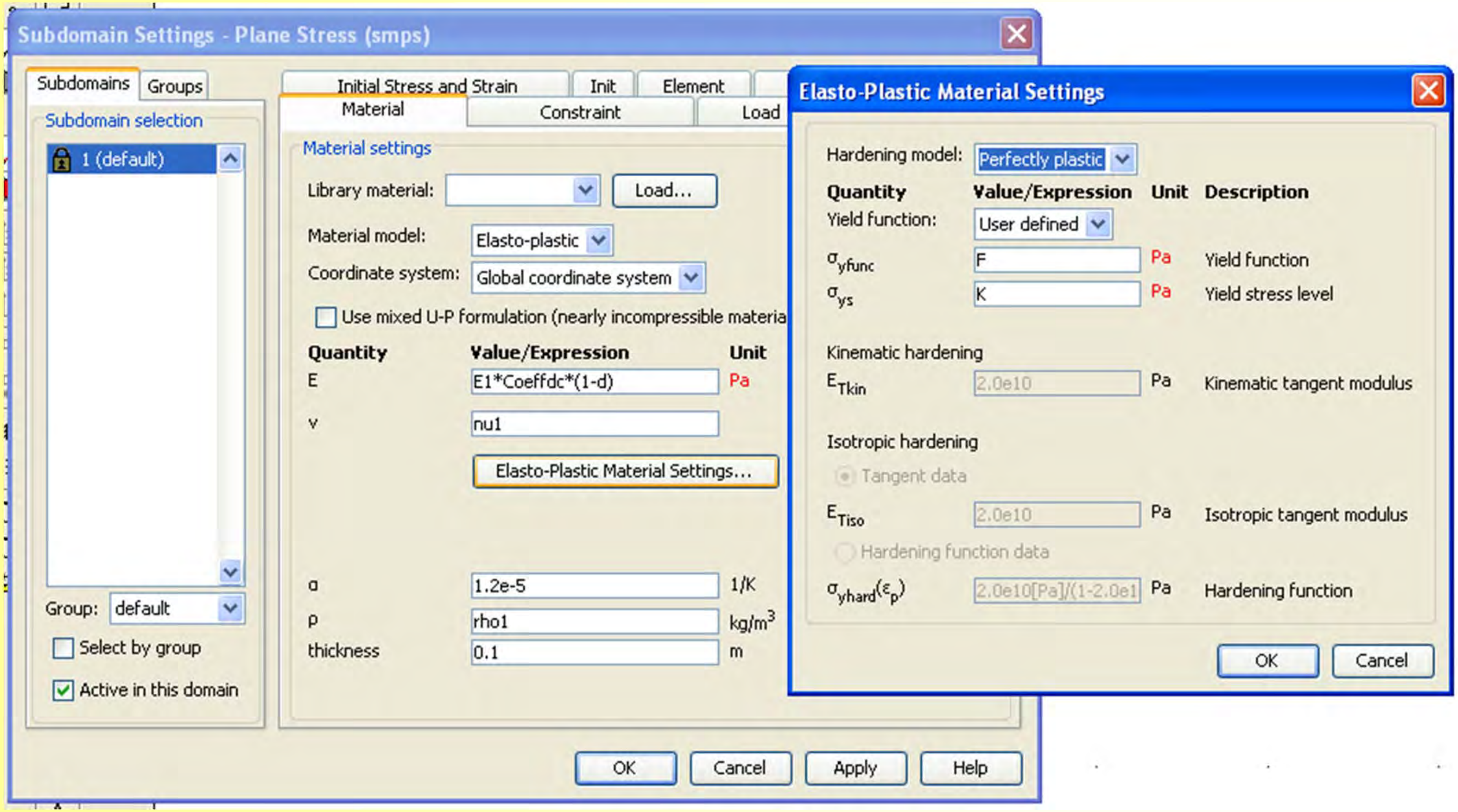
- Variation of creep strain rate with chemical damage

$$\begin{cases} \dot{\varepsilon}^{cpc} = A_c \left(A_1 m t^{m-1} + A_2 \right) \left(1 + \alpha_{dc} d_c \right) \boldsymbol{\sigma}, & \text{compressive stress} \\ \dot{\varepsilon}^{cpt} = A_t \left(A_1 m t^{m-1} + A_2 \right) \left(1 + \alpha_{dc} d_c \right) \boldsymbol{\sigma}, & \text{tensive stress} \end{cases}$$

Coupling Model

1) Leaching-creep coupling characterization

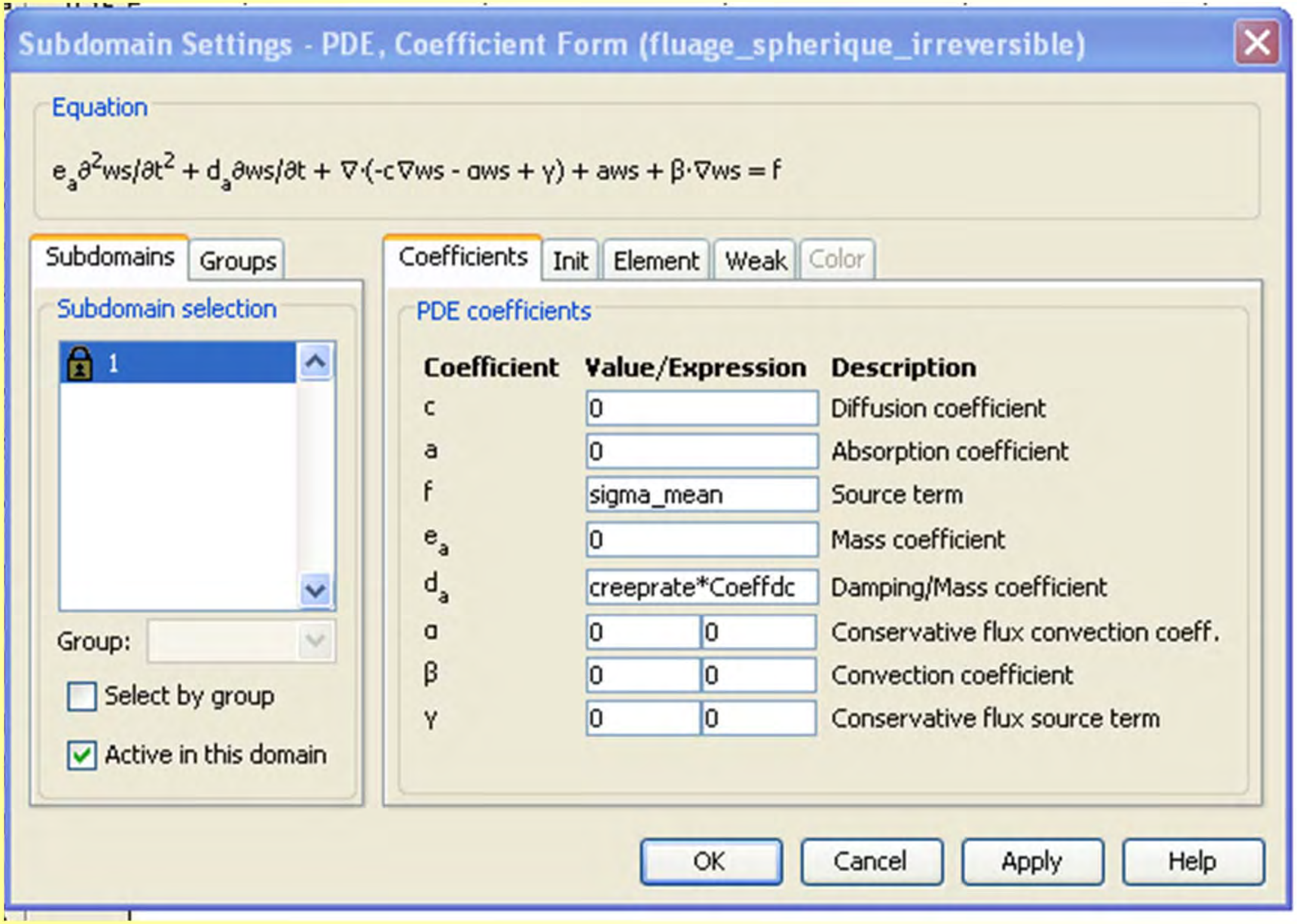
- **Plane stress module**



Coupling Model

1) Leaching-creep coupling characterization

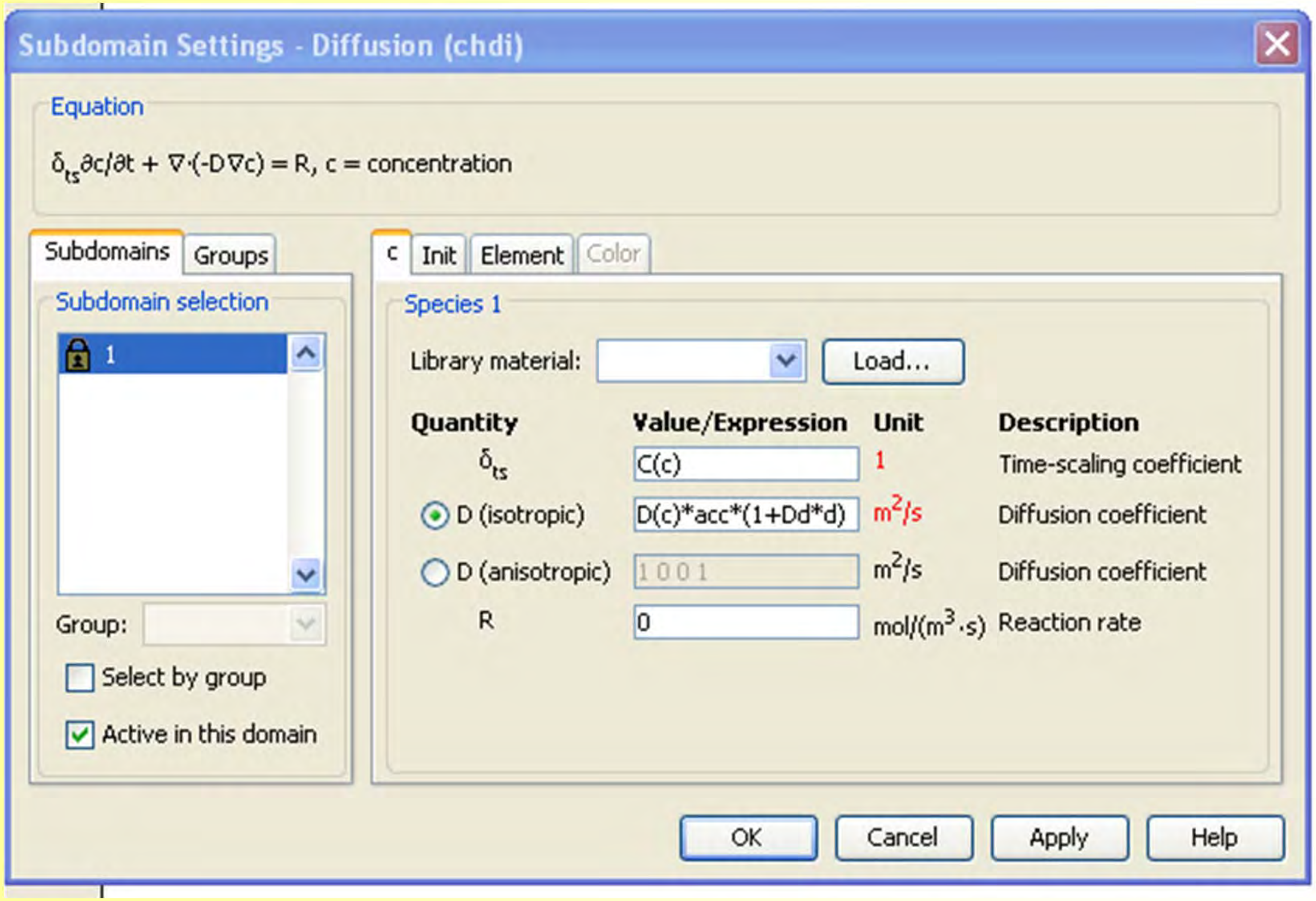
- **PDE module for creep**



Coupling Model

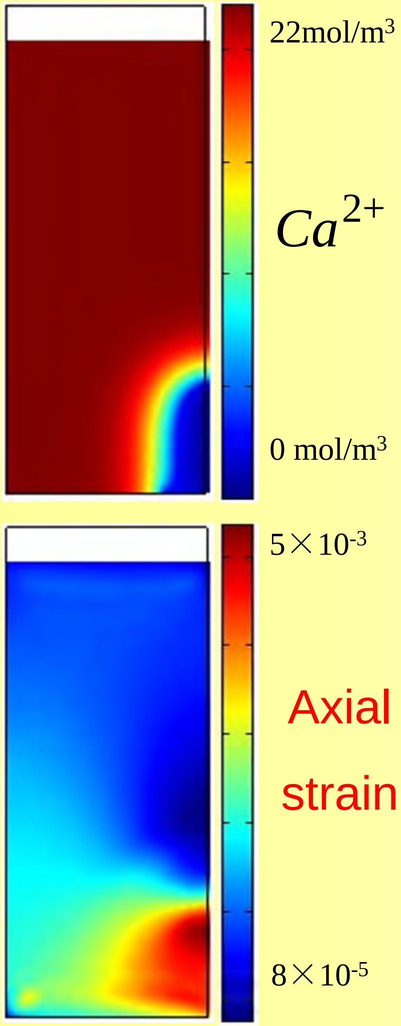
1) Leaching-creep coupling characterization

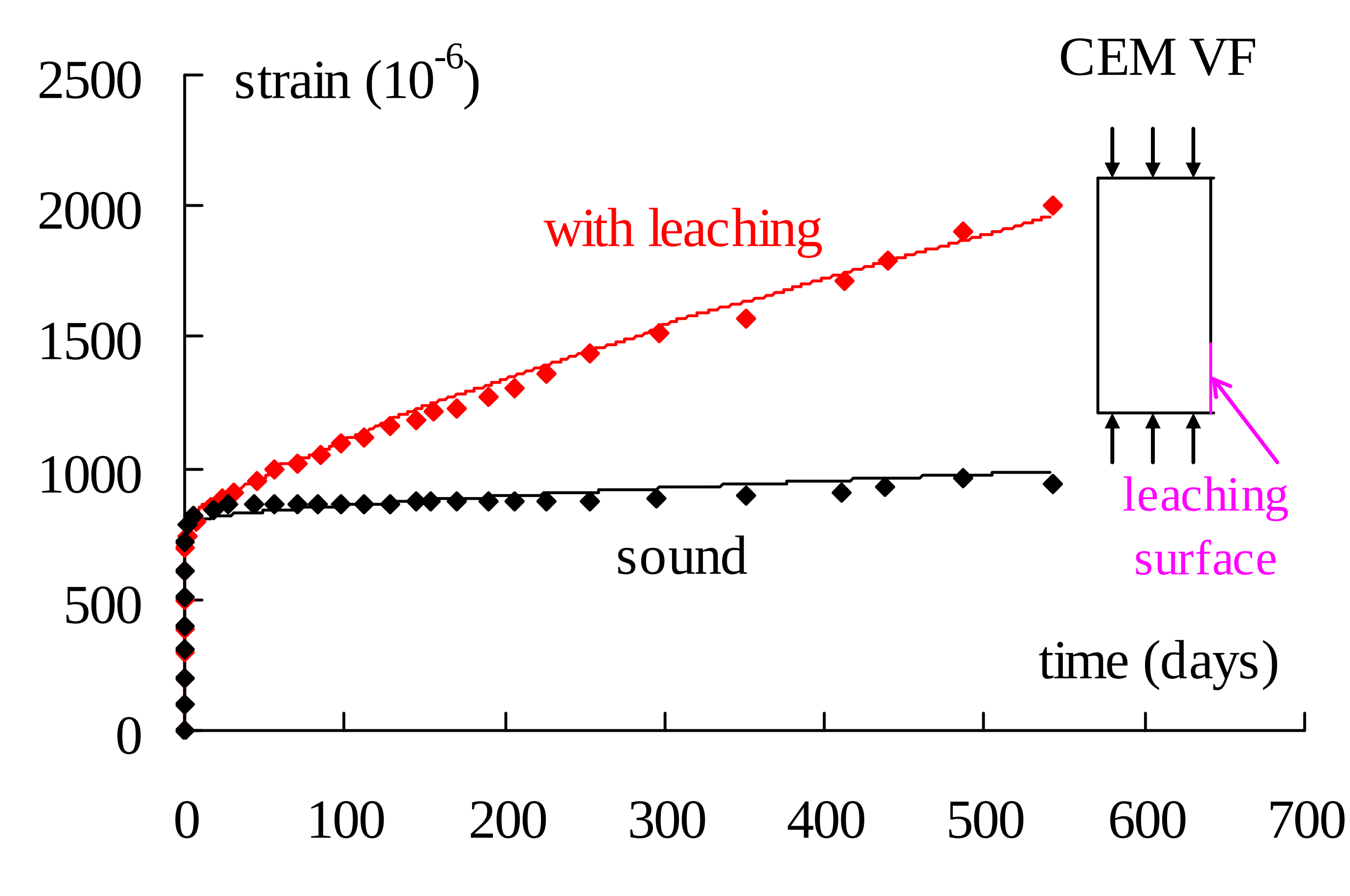
- **Diffusion module for leaching**



Coupling Model

2) Leaching-creep simulation

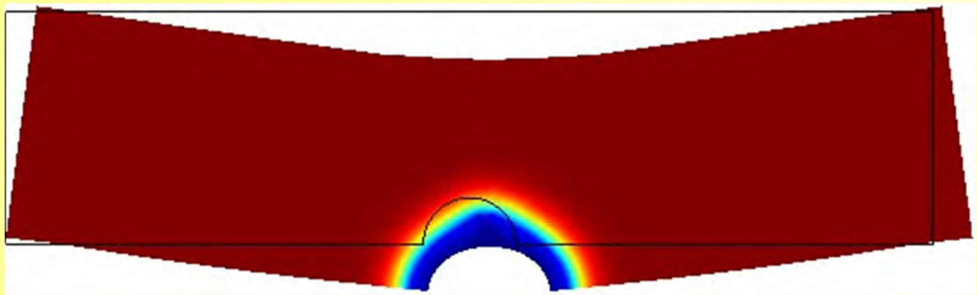




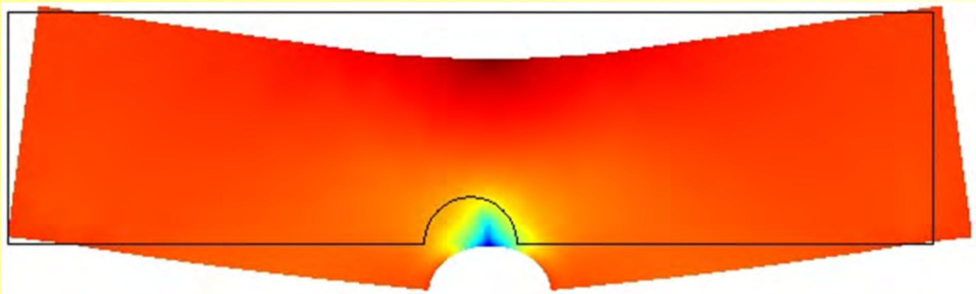
Creep compression test with degradation
(data after Camps 2008)

Coupling Model

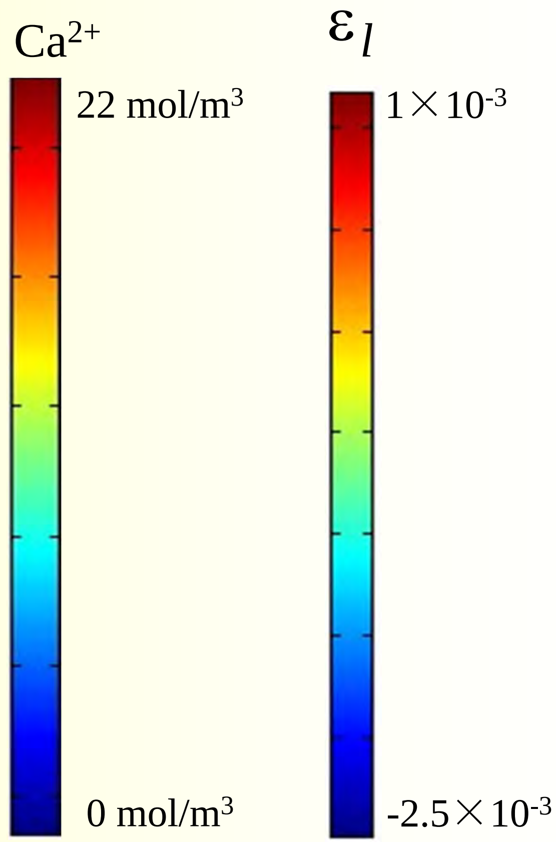
2) Leaching-creep simulation



Concentration of calcium ion



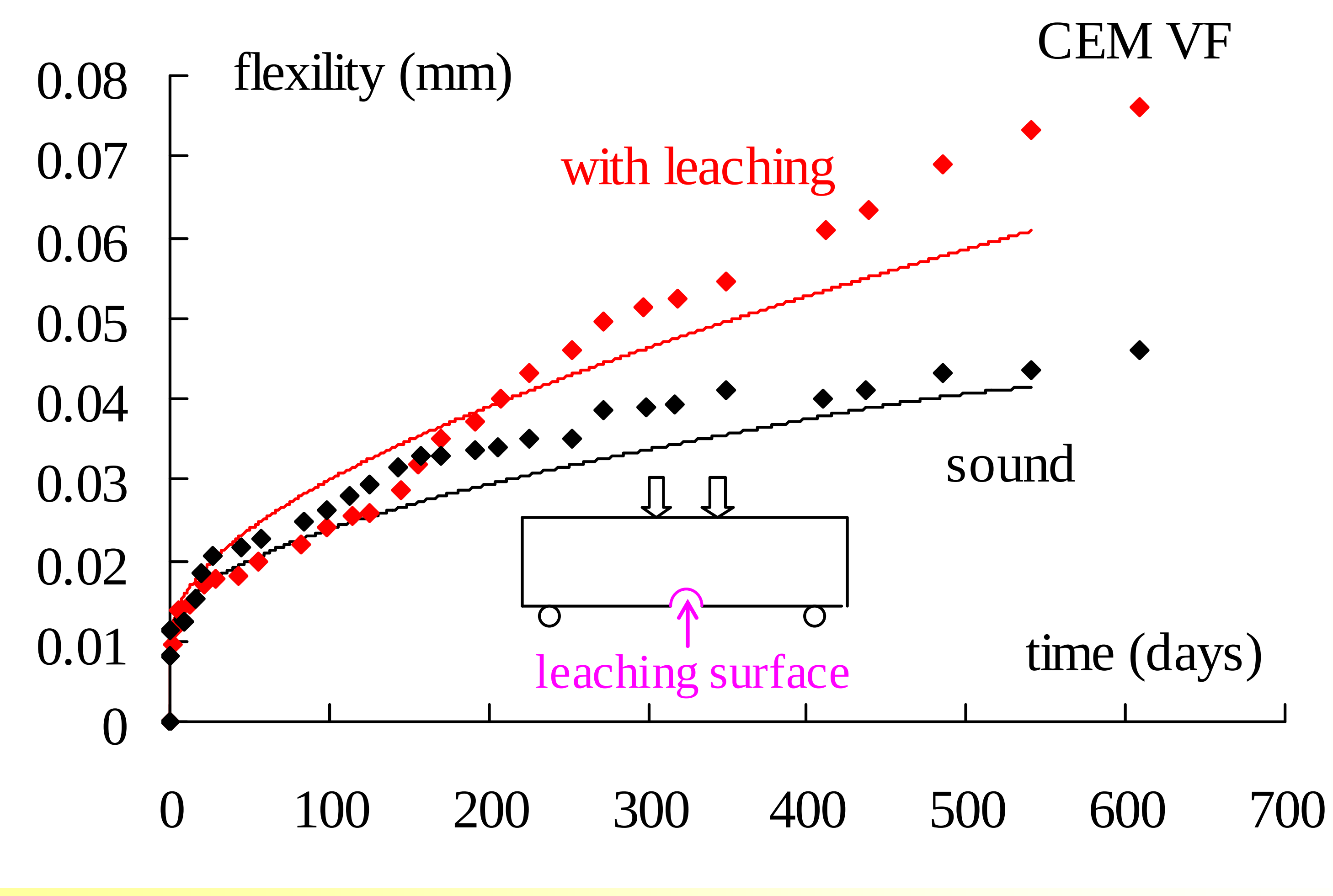
Longitudinale strain



Creep flexion test with degradation (data after Camps 2008)

Coupling Model

2) Leaching-creep simulation



Creep flexion test with degradation
(data after Camps 2008)

Conclusions and perspectives

Conclusions

- Elastoplastic damage model and creep model can describe the mechanical behavior of concrete in short and long term.
- The coupling of mechanical and leaching can describe the mechanical behavior subjected to chimic degadation in long term .

Perspectives

- Temperature-leaching-mechanical coupling

Thank you for your attention!