Modeling of leaching-mechanical coupling in concrete

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Plan

• Background and problem
• Mechanical model
• Leaching
• Coupling model
• Conclusions and perspectives
Background

Where is the studied concrete?
- Structures;
- Seal material;
- Stock cell of nuclear waste B.

Which is the concrete subjected?
- Thermal load;
- Mechanical evolution;
- Chemical degradation.
Problem

Implemented models in COMSOL for concrete
✓ Mechanical
✓ Leaching
✓ Leaching-mechanical coupling
Mechanical model

1) Plastic damage modeling

- Plastic characterization

Criteron of Drucker-Prager

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

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

\[ \eta = \frac{1}{\sqrt{3}} \left( \frac{2R_c}{R_t + R_c} - 1 \right) \quad R_c : \text{Uniaxial compression strength} \]

\[ K = \frac{2}{\sqrt{3}} \left( \frac{R_t \cdot R_c}{R_t + R_c} \right) \quad R_t : \text{Tension strength} \]
Mechanical model

1) Plastic damage modeling

• Associated plasticity

\[ d\varepsilon_p^{ij} = d\lambda \frac{\partial f_p}{\partial \sigma_{ij}} \]

• Damage characterization

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

• Effective modulus

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

\[ \alpha(\gamma^P, d_m) \]
2) Creep characterization

• Creep strain
  in compression
  \[ \dot{\varepsilon}^{cpc} = A_c \left( A_1 t^{m-1} + A_2 \right) \sigma, \quad 0 < m < 1 \]

  First creep
  Second creep

  In tension
  \[ \dot{\varepsilon}^{cpt} = A_t \left( A_1 t^{m-1} + A_2 \right) \sigma, \quad 0 < m < 1 \]

• 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

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

- Diffusion coefficient of calcium ion

- Hydric source of calcium ion

- Diffusion coefficient with ammonium nitrate

\[
D(Ca(NO_3)_2) = \lambda D_e(Ca^{2+}) \nabla^2 Ca^{2+}
\]

- Acceleration parameter

- Diffusion coefficient of calcium ion
Leaching model

1) Leaching characterization

- Diffusion module for leaching

\[ \frac{\partial C_{\text{solid}}}{\partial t} + \nabla (-D \nabla c) = R, \ c = \text{concentration} \]
Leaching model

2) Leaching-plastic damage coupling

• Chemical damage

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

• Chemical damage-mechanical parameters

\[
\begin{align*}
E &= E_0 \left( 1 - d_c \right) \\
R_c &= R_{c0} \left( 1 - d_c \right) \\
R_t &= R_{t0} \left( 1 - d_c \right)
\end{align*}
\]

Test of micro indentation
2) Leaching-plastic damage simulation

Leaching model

Directe tension test after different degradation times (data after Camps 2008)
2) Leaching-plastic damage simulation

Flexion test after different degradation times
(data after Camps 2008)
Coupling Model

1) Leaching-creep coupling characterization

- Variation of diffusion coefficient with plastic damage

\[ D(d_m) = \lambda D_e \left( 1 + \alpha_D d_m \right) \]

- Variation of creep strain rate with chemical damage

\[
\begin{align*}
\dot{\varepsilon}^{cpc} &= A_c \left( A_1 m t^{m-1} + A_2 \right) \left( 1 + \alpha_{dc} d_c \right) \sigma, \quad \text{compressive stress} \\
\dot{\varepsilon}^{cpt} &= A_t \left( A_1 m t^{m-1} + A_2 \right) \left( 1 + \alpha_{dc} d_c \right) \sigma, \quad \text{tensive stress}
\end{align*}
\]
Coupling Model

1) Leaching-creep coupling characterization

- Plane stress module
Coupling Model

1) Leaching-creep coupling characterization

- PDE module for creep
1) Leaching-creep coupling characterization

- Diffusion module for leaching
Coupling Model

2) Leaching-creep simulation

Creep compression test with degradation (data after Camps 2008)

- Ca$^{2+}$ concentration
- Axial strain
- Strain (10$^{-6}$)
- Time (days)
- CEM VF

With leaching

Sound

Leaching surface
2) Leaching-creep simulation

Concentration of calcium ion

Longitudinale strain

Creep flexion test with degradation (data after Camps 2008)
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 chemical degradation in long term.

Perspectives
• Temperature-leaching-mechanical coupling
Thank you for your attention!