Experimental investigation of the delayed behaviour of the unsaturated argillaceous rocks by means of Digital Image Correlation techniques

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Argillaceous rocks of Meuse/Haute Marne

Depth: -420 et -550 m (130 m thick)
Mineralogy: clay minerals (~45%); carbonates (~20%); quartz (~30%)

Total porosity: 15%
Permeability: $<10^{-20}$ m$^2$
Introduction

Hydromechanical behavior of argillaceous rocks

Shrinking and Swelling: strain related to RH
E and Rc ↓, when RH ↑
Creep: more significant, when RH ↑

Microstructure induces heterogeneous mechanical response at various scales

Reversible, irreversible, elastic, plastic, creep, hydration …:
at which scale? RVE?

10^{-4} / ° RH
10^{-2} \varepsilon_{rupture}
10^{-4} / week
Introduction

Object

**Study of the mechanisms of delayed behavior of the argillaceous rocks under coupled HM conditions**

*By means of DIC technique*
Multiscale full-field strain measurements

Experimental setup

Uniaxial compression under controlled moisture with multiscale full-field strain measurements

- Loading device
- Macroscopic measurements: strain gauges, LVDT
- Suction control
- Optical multiscale full-field strain measurements during hydric-mechanical loading

Macroscopic optical setup (24x36 mm)
&
Microscopic optical setup (1.5x1.5 mm)
Digital image correlation (DIC) and associated errors

Digital image correlation
Identify the position of each object point in two images by correlation algorithm

$$\Phi_D \approx \operatorname{Argmin}_{\Phi_0 \in V} C(f, g, D, \Phi_0)$$

Example::

$$C(\Phi_0) = \int_D \left[ f(u) - g(\Phi_0(u)) \right]^2 \, du \approx \sum_{i \in D} \left[ f(u_{ij}) - g(\Phi_0(u_{ij})) \right]^2$$

Determination of the local (full-field) or average strains
Average the transformation gradient over domains of interest

Various sources of random or systematic errors
Noise, image quality, contrast, interpolation method, out-of-plane motion, etc.

Multiscale full-field strain measurements

Reference image

Image after deformation

$\Phi$ transformation in subpixel accuracy

f(X) g(x) = g(\Phi(X))
Multiscale full-field strain measurements

**Improvement of the system** (Yang and Michel *et al.* 2010)

Optimal aperture minimizes the systematic errors
Minimizing the effect of global out-of-plane motion

\[ \varepsilon = \varepsilon_a - \frac{\Delta g}{g} \quad (\Delta g/g = -\frac{dZ}{OC} \quad \Delta \frac{Z_{macro}}{Z_{micro}} = \Delta \varepsilon_{zz}) \]

**Strain measurement \( \varepsilon \) accuracy**

- **Macro DIC**
  - Local accuracy \( \sim 10^{-5} \)
  - Global accuracy \( <10^{-5} \)
  - (suitable for creep test)

- **Micro DIC**
  - \( 0.135 \text{ mm} \)
  - \( 1.5 \text{ mm} \)
  - \( <5 \times 10^{-5} \)
Characterization of the heterogeneity

Hydromechanical behavior of argillaceous rocks

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Hydromechanical behavior of argillaceous rocks

Hydration and dehydration under uniaxial stress (Yang and Michel et al. 2011, in preparing)

The test lasted 10 months
Hydromechanical behavior of argillaceous rocks

Hydration and dehydration under uniaxial stress

The test lasted 10 months

- σ controlled 8.5MPa-0.3MPa
- σ controlled 2MPa-8.5MPa

1st cycle
2nd cycle
3rd cycle

Dehydration(initial->RH45%_1.5MPa)
In rehydration_2MPa
In dehydration_2MPa
In loading(2MPa->8MPa)
In rehydration_8MPa
In dehydration_8MPa
In unloading(8MPa_1MPa)
In rehydration_0.3 MPa
In dehydration_0.3 MPa
Hydromechanical behavior of argillaceous rocks

Hydration and dehydration under uniaxial stress

\( \varepsilon \) vs RH quasi-linear, reversible under low \( \sigma \) and irreversible under high \( \sigma \)

\( E \) vs RH quasi-linear

\( \nu \) vs RH quasi-constant for RH < 85%
Hydromechanical behavior of argillaceous rocks

Dehydration under RH = 25% at 1 MPa

\[ \varepsilon_{\text{axial}} \approx 0.3 \] at 1 MPa

\[ \varepsilon_{\text{lateral}} = -0.18\% > \varepsilon_{\text{axial}} = -0.13\% \] at 10 MPa during rehydration

Shrinkage and swelling strongly depend on the applied stress

The classical Biot theory is not relevant

Dehydration under RH = 40% at 18 MPa

\[ \varepsilon_{\text{lateral}} = 0.08\% < \varepsilon_{\text{axial}} = 0.83\% \] at 18 MPa during dehydration
Hydromechanical behavior of argillaceous rocks

Hydration and dehydration under uniaxial stress

ε vs RH quasi-linear, reversible under low σ and irreversible under high σ

E vs RH quasi-linear

ν vs RH quasi-constant for RH < 85%
Hydromechanical behavior of argillaceous rocks

Strain at various scales

Local zone with high clay content (200 µm)

Zone 1 (millimetric scale)

\[ \Delta \varepsilon \text{ (local zone)} \approx 10 \times \Delta \varepsilon \text{ (Zone 1)} \]

Subjected to \( \Delta \text{RH} \)
Creep behavior under controlled HM (Yang and Michel et al. 2011)

Loading paths:
- Axial stress: 10 MPa; 15 MPa; 20 MPa
- RH: 25%; 65%; 75%; 80%
Hydromechanical behavior of argillaceous rocks

Characterization of strain rate

Correction of the strain using the linear relation between $\varepsilon$ and RH
Hydromechanical behavior of argillaceous rocks

Strain rate over time

![Graph showing strain rate over time with a peak at around 10 days and gradual decrease thereafter.]

2 weeks
last 4 days
Strain at various scales

- RH and/or $\sigma$ → strain rate ↑

Strain rate $10^{-9}$ S$^{-1}$ (18 MPa) - $10^{-11}$ S$^{-1}$ (9 MPa)
Hydromechanical behavior of argillaceous rocks

Crack perpendicular to the stress direction

Map of $\varepsilon_{eq} \sigma$ from 1 MPa to 7 MPa

Map of $\varepsilon_{eq} \sigma = 18$ MPa (30th – 35th day)
Hydromechanical behavior of the unsaturated clayey rocks

Mechanical behavior

\[ \sigma - \varepsilon \text{ linear } \sigma < 10\text{MPa} \]
\[ E - \text{HR linear, reversible under RH} < 85\% \]
\[ \text{Poisson’s ratio constant } = 0.13 \]

Shrinkage and swelling

\[ \varepsilon - \text{HR linear and reversible } < 85\%, \text{ irreversible at high } \sigma \]
\[ \text{Small damage } > 85\% \]

Shrinkage and swelling strongly depend on the applied stress

Classical Biot model is not relevant
Creep behavior under controlled RH

HR and/or $\sigma$ \quad \Rightarrow \quad \text{Strain rate}$

Strain rate $10^{-9}$ s$^{-1}$ (18 MPa) $- 10^{-11}$ s$^{-1}$ (9 MPa)

Areas with cracks perpendicular to the applied loads had a strain rate similar to that of intact zones.

Cracks parallel to the applied stress developed and opened over time and could lead to fracture.
Thank you for your attention