X-ray tomographic study of wetting bentonite

Tero Harjupatana
Department of Physics, University of Jyväskylä
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Goal

To develop and apply experimental techniques based on X-ray tomography (CT) in order to

- provide data for finding the relevant hydromechanical and transport properties of wetting bentonite
- provide a data bank for validating hydromechanical models of bentonite buffer

→ Utilize CT to measure water content of wetting and swelling bentonite in 3D as a function of time (4D imaging)
**X-ray tomography**

A non-invasive 3D imaging method

**Parts**
- X-ray source (a)
- Sample (b)
- Detector (c)
- Computer

**Procedure**
- X-ray images from different angles (scan)
- Reconstruction (~ 3D density map)
- Data analysis and visualization
CT device and measuring principle

- Skyscan 1172 micro-CT
  - Table top device
  - Best resolution ~ 2 µm
  - Max practical sample size
    ~ 3.0 x 1.5 cm
  - Scanning time 1 h – 1 day

- Measuring principle:
  - Sequential CT imaging of bentonite sample during wetting (2 days – 2 weeks)
  - 3D displacement due to swelling found by image correlation technique
  - Water content analyzed using difference images
Requirements

- Stability
- Optimal selection of measuring parameters
- Careful calibration and compensation of imaging artefacts
  - Latest development: “Dynamic Flat-field correction”

Al plates with different thickness are used in Dynamic Flat-field correction.
Samples and sample holder

- Compacted cylindrical bentonite sample doped with small marker particles (hollow glass spheres)
- Sample is held in a constant volume (2.3 cm$^3$) and wetted through one end
Measurement details

- Reference scan of dry sample
- Wetting initiated
- Scans at appropriate times, typically 10 times in 1-2 weeks. Duration of one scan ~ 45 min
- The total mass of water in the sample is achieved by weighings

X-ray image  Reconstructed slice  3D visualization
Deformation analysis

- Block-matching (BM) algorithm in 3D
- Rubber sample and COMSOL were used to test BM
Water content analysis

- Water content can be calculated if the partial densities of water and bentonite are known \( (\eta = \frac{\rho_w}{\rho_b}) \)
- Linear equation for bentonite-water system is \( \mu \approx a_b \rho_b + a_w \rho_w \)
- Constants \( a_b \) and \( a_w \) are determined by calibration samples
- The initial and the new density of bentonite can be calculated from dry image and deformations respectively

![Dry sample (\( \mu_0 \))](image1)
![Wetted sample (\( \mu_1 \))](image2)
![Difference (\( \Delta \mu = \mu_1 - \mu_0 \))](image3)
Method validation

- Sample preparation, reference scan and wetting were done as before
- The sample was scanned at some intermediate time
- The sample was removed and cutted into slices
- Water content of the slices was determined by drying in oven
- Water content was also calculated with the CT method
Water content and deformations
Water content in 1D

Measured water content

Ideal diffusion
Swelling pressure

Bentonite: MP Biomedicals (purified)
Dry density: 1.23 g/cm$^3$
Water: Allard-pH-7 (TDS ~ 0.26 g/L)

Bentonite: CaMT (27%), NaMT (73%)
Dry density: 1.31 g/cm$^3$
Water: Posiva ref. 2 (TDS = 10 g/L)
Conclusions

- 4D X-ray tomographic imaging method for monitoring deformation and water transport in swelling bentonite completed (finally)
- The method allows measuring
  - 3D displacement field
  - 3D water content distribution ($\rho_b$ and $\rho_w$) and
  - swelling pressure from both ends

as a function of time

- Next step: application to MX-80 bentonite
Thank you
Effect of wetting pressure