X-ray tomographic study of wetting bentonite

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Goal

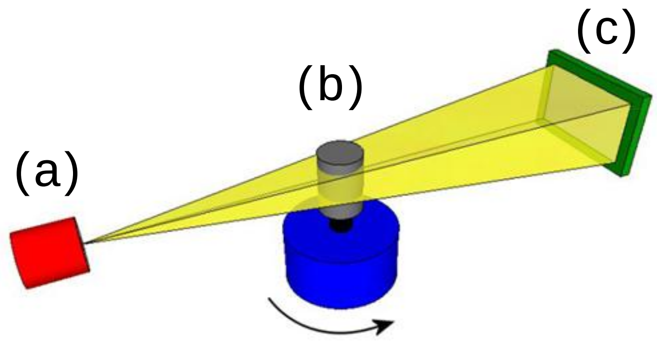
To develop and apply experimental techniques based on X-ray tomography (CT) in order to

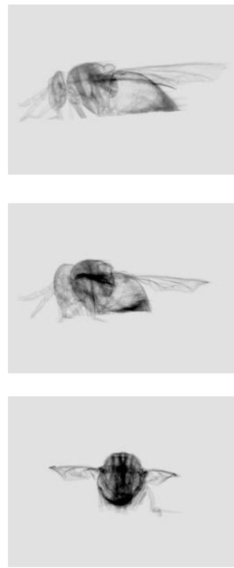
- provide data for finding the relevant hydromechanical and transport properties of wetting bentonite
- provide a data bank for validating hydromechanical models of bentonite buffer

→ 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



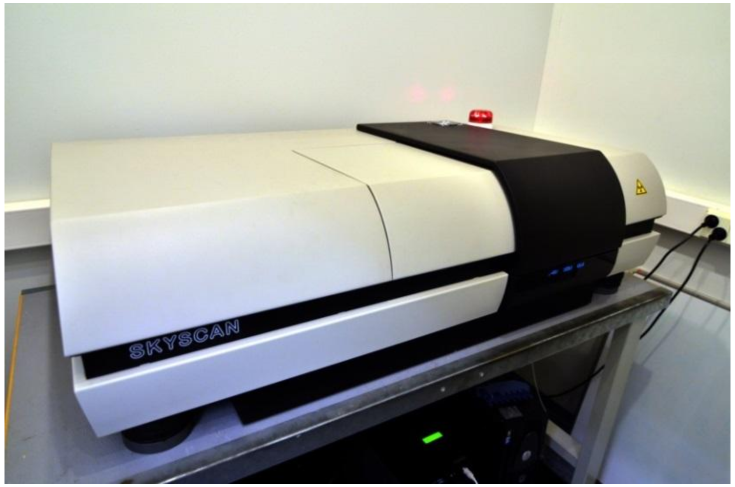


X-ray images

3D visualization

CT device and measuring principle

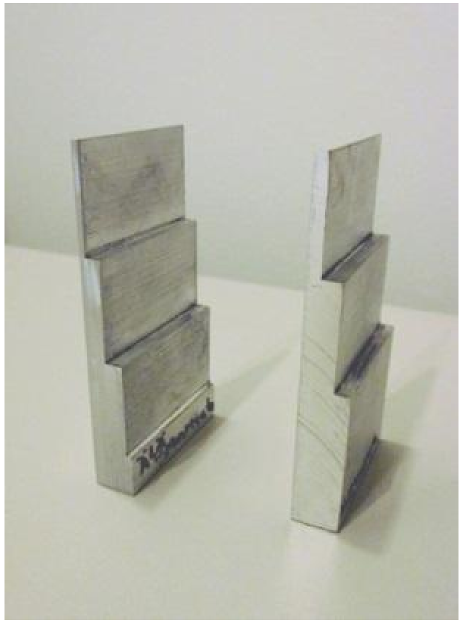
- Skyscan 1172 micro-CT
  - Table top device
  - Best resolution ~ 2 µm
  - Max practical sample size ~ 3.0 x 1.5 cm
  - Scanning time 1 h – 1 day



- 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

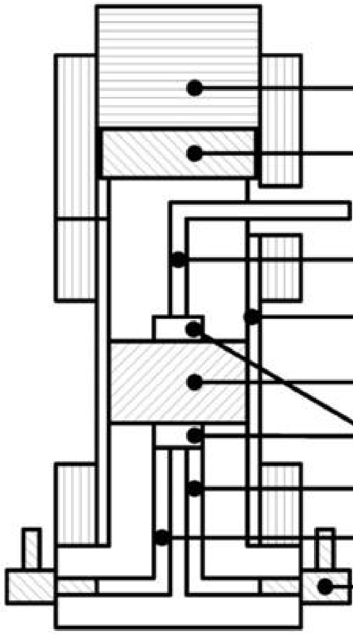
- Stability
- Optimal selection of measuring parameters
- Careful calibration and compensation of imaging artefacts
  - Latest development: ”Dynamic Flat-field correction”



Al plates with different thickness are used in Dynamic Flat-field correction

Samples and sample holder

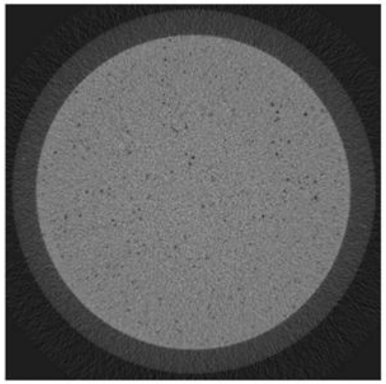
- Compacted cylindrical bentonite sample doped with small marker particles (hollow glass spheres)
- Sample is held in a constant volume (2.3 cm^3) and wetted through one end

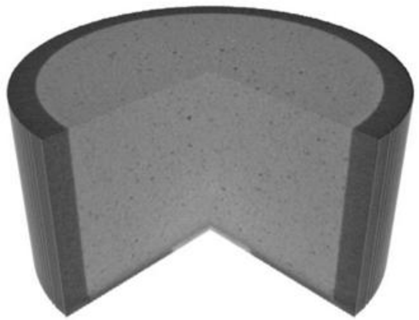


Measurement details

- 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

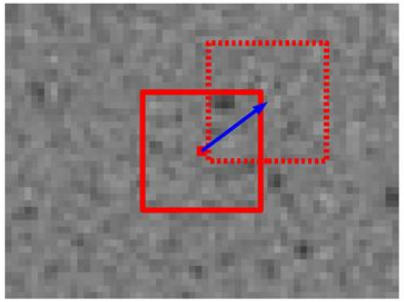

X-ray image

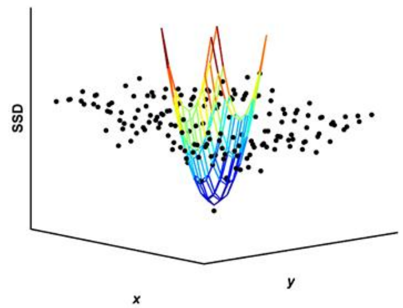

Reconstructed slice


3D visualization

Deformation analysis

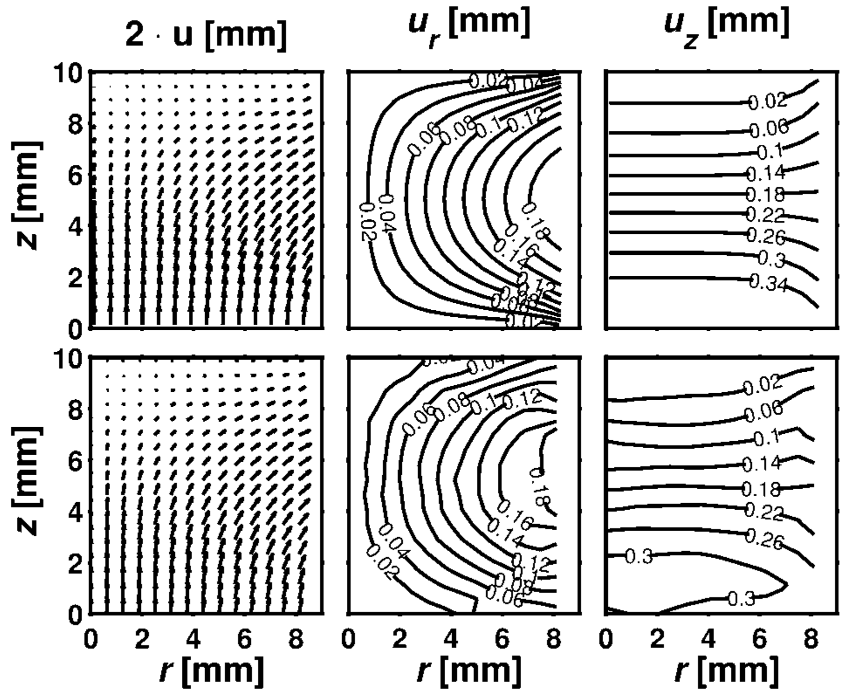
- Block-matching (BM) algorithm in 3D
- Rubber sample and COMSOL were used to test BM





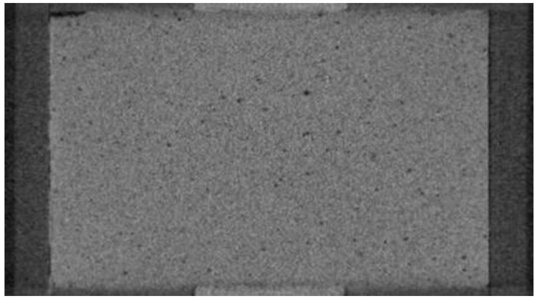
COMSOL

BM

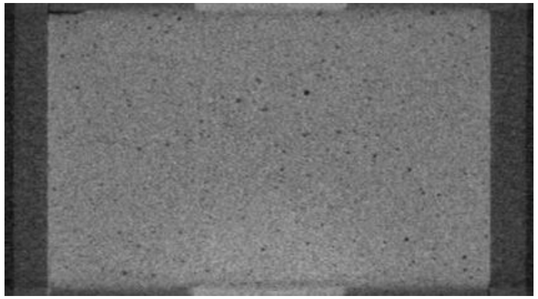


Water content analysis

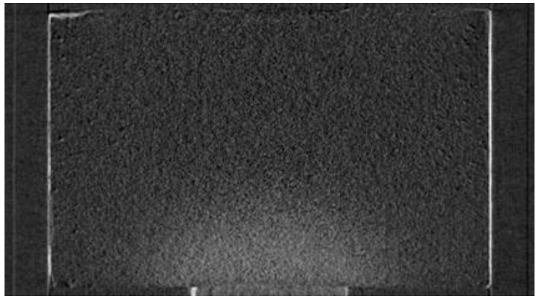
- Water content can be calculated if the partial densities of water and bentonite are known ($\eta=\rho_w/\rho_b$)
- Linear equation for bentonite-water system is $\mu \approx a_b\rho_b + a_w\rho_w$
- Constants a_b and a_w are determined by calibration samples
- The initial and the new density of bentonite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



Dry sample (μ_0)



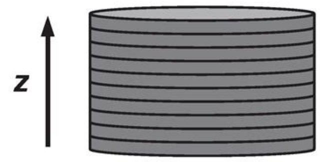
Wetted sample (μ_1)

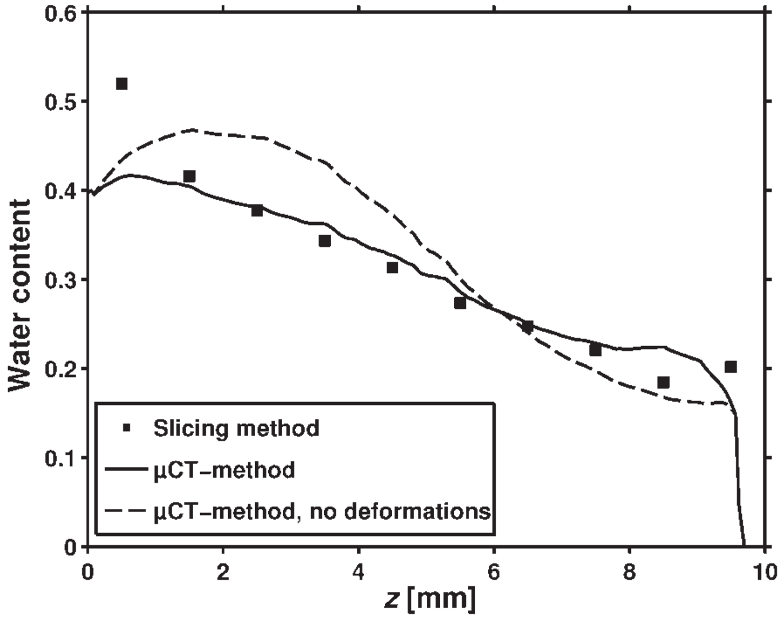


Difference ($\Delta\mu=\mu_1 - \mu_0$)

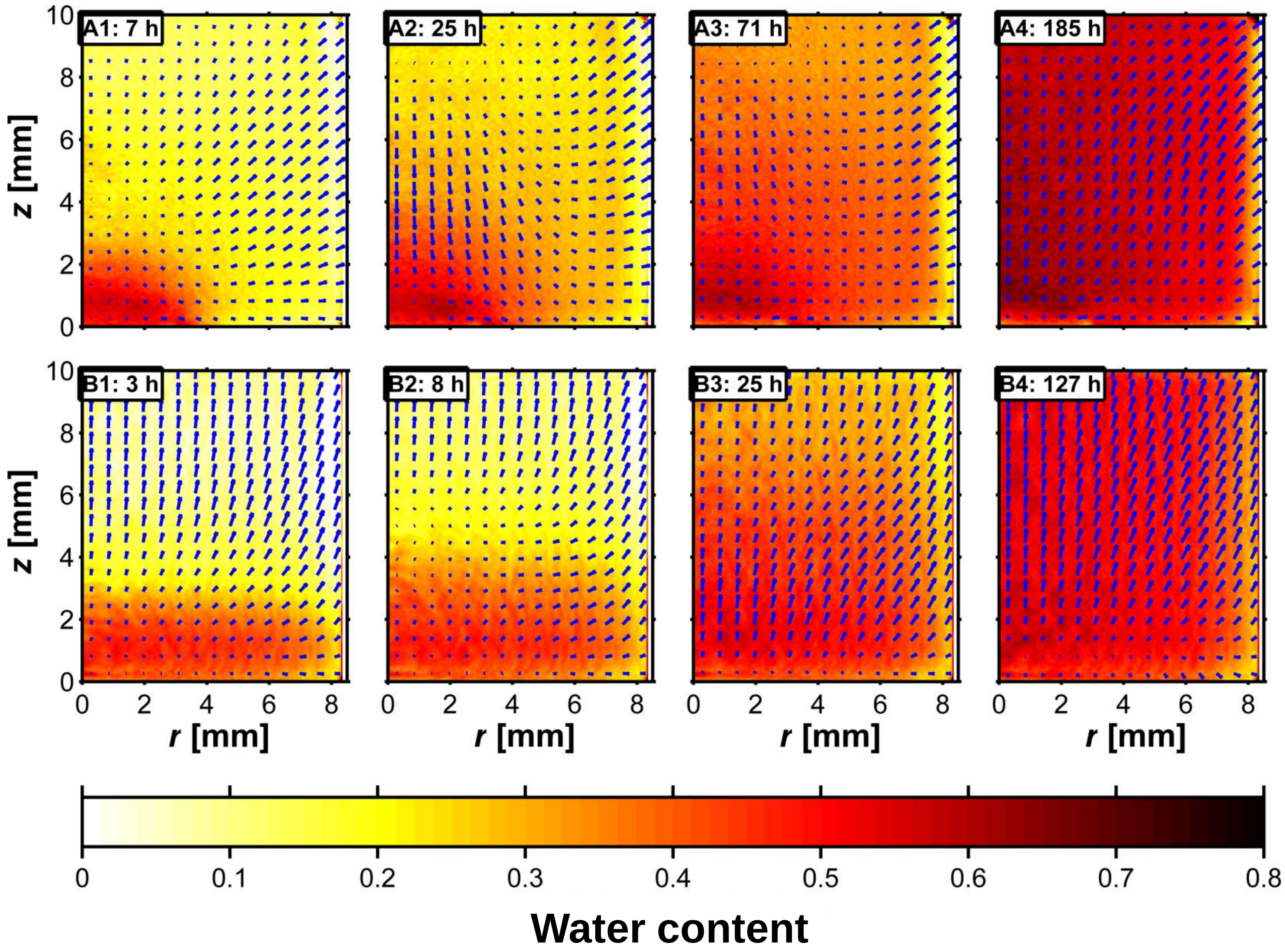
Method validation

- 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

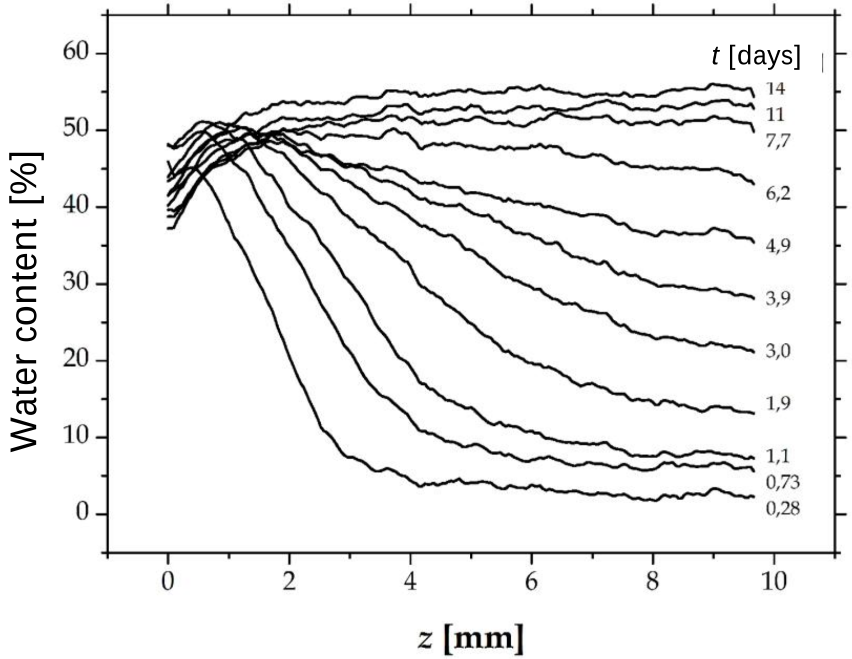




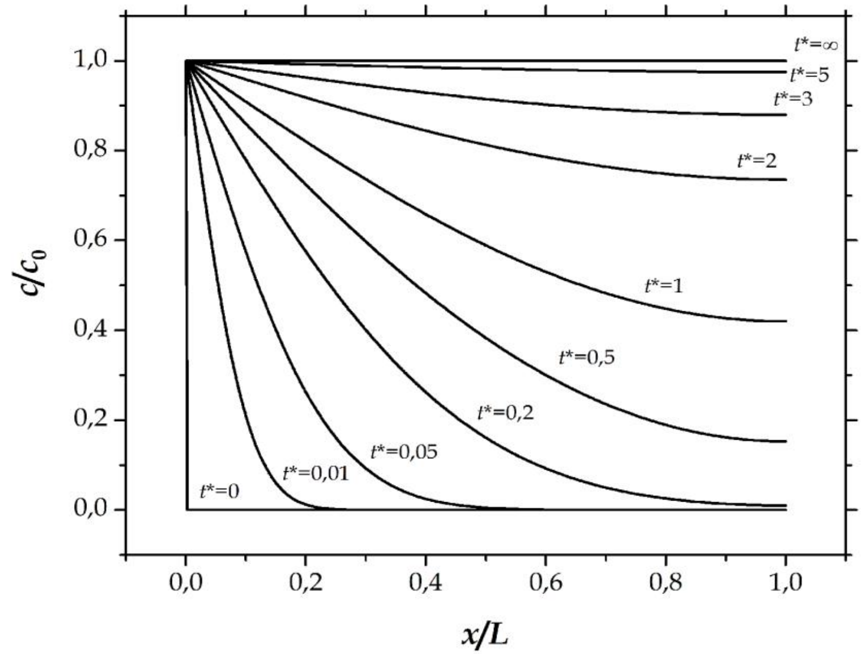
Water content and deformations



Water content in 1D

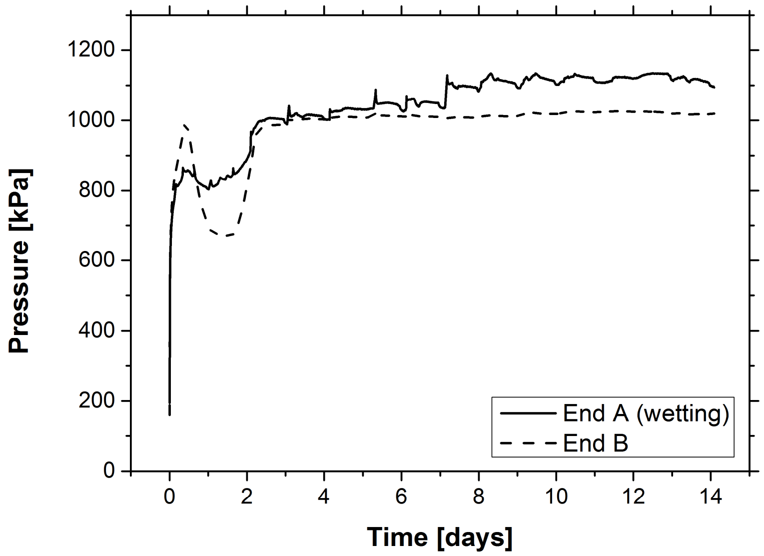


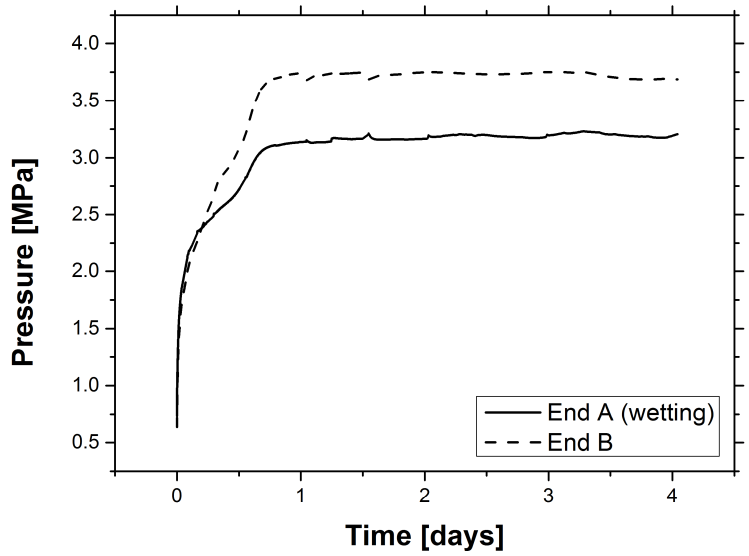
Measured water content



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 (ρ_b and ρ_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