Hydraulic behaviour of bentonite

Introduction to the hydromechanical processes

Beacon training course
Barcelona – January 2018
F. Collin, A-C Dieudonné & R. Charlier
Deep geological disposal constitutes one of the most promising solutions for the safe isolation of high-level and intermediate-level radioactive wastes
Deep geological disposal constitutes one of the most promising solutions for the safe isolation of high-level and intermediate-level radioactive wastes.

**French CIGEO concept for ILW**
(Andra)

**Swiss concept for HLW**
(Nagra)

**MULTI-BARRIER CONCEPT**

- Bentonite
- Bentonite blocks
- Bentonite pellets
- Canister

---

**Contents**

- Introduction
- Microstructure
- Saturated
- Unsaturated
- Conclusions
• Bentonite = clay material that primarily consists of \textit{montmorillonite}

1) Significant swelling upon hydration = \textit{swelling capacity}
2) Very low \textit{permeability} (~ \(10^{-20} - 10^{-21} \text{ m}^2\) in saturated conditions)
3) Important radionuclides retardation capacities
• Bentonite = clay material that primarily consists of **montmorillonite**

1) Significant swelling upon hydration = **swelling capacity**
2) Very low **permeability** (~ $10^{-20} - 10^{-21} \text{ m}^2$ in saturated conditions)
3) Important radionuclides retardation capacities

• Different bentonites: FoCa7, Febex, GMZ, Kunigel, MX-80…

---

**Introduction**

**Microstructure**

**Saturated**

**Unsaturated**

**Conclusions**
• Bentonite = clay material that primarily consists of montmorillonite

1) Significant swelling upon hydration = swelling capacity
2) Very low permeability (\(\sim 10^{-20} - 10^{-21} \ m^2\) in saturated conditions)
3) Important radionuclides retardation capacities

• Different bentonites: FoCa7, Febex, GMZ, Kunigel, MX-80…

• Different forms: powder, compacted blocks, pellets
• Bentonite = clay material that primarily consists of montmorillonite

1) Significant swelling upon hydration = swelling capacity
2) Very low permeability (∼$10^{-20} – 10^{-21}$ m² in saturated conditions)
3) Important radionuclides retardation capacities

• Different bentonites: FoCa7, Febex, GMZ, Kunigel, MX-80…

• Different forms: powder, compacted blocks, pellets
- Introduction
- Microstructure and swelling behaviour
- Water Transfer in saturated conditions
- Unsaturated conditions
- Conclusions
Hierarchical structure of bentonite

Unit layer

~nm

Interlayer

Clay layer

Aggregate

10^2 - 10^4 nm

Width [nm]

Particle

8 - 10 nm

Introduction  Microstructure  Saturated  Unsaturated  Conclusions
Swelling behaviour of bentonite

Water in compacted bentonite

Swelling behaviour of bentonite
Compaction of bentonite creates a **double-porosity structure**

MX-80 bentonite (Seiphoori 2014)
Compaction of bentonite creates a **double-porosity structure**

**Introduction**

**Microstructure**

- Saturated
- Unsaturated

**Conclusions**
Hydration of bentonite modifies the **double-porosity structure**

MX-80 bentonite (Seiphoori 2014)
Aging of bentonite modifies the **double-porosity structure**

MX-80 bentonite (Delage et al. 2006)
- Introduction
- Microstructure and swelling behaviour
- Water Transfer in saturated conditions
- Unsaturated conditions
- Conclusions
Permeability in saturated conditions

Mixture MX-80/sand (Wang et al., 2013), Kunigel and Fourges clay (Marcial et al., 2002)
Permeability in saturated conditions: influence of sand content

Kunigel V1 bentonite and sand (JNC, 2000)
Permeability in saturated conditions: influence of sand content

Kunigel V1 bentonite and sand (JNC, 2000)
- Introduction
- Microstructure and swelling behaviour
- Water Transfer in saturated conditions
- Unsaturated conditions
- Conclusions
• Water retention curve: \[ \text{amount of water stored} = f(\text{suction} \ldots) \]

(generally a unique relationship in the models!)

• Classical approaches for modelling the water retention behaviour: parameters to be fit using experimental data

![Water retention curve diagram](image)

Modified after Nuth and Laoui, 2008

1. Residual saturation
2. Partially saturated
3. Quasi-saturated
4. Saturated
Relative permeability curve:

Permeability in Cox as a function of the degree of saturation
Limitations of existing models

1) Saturation kinetics

PGZ2 Experiment
(de la Vaissière 2013)

2) Development of swelling pressure

3) Existence of technological gaps

FEBEX Experiment
(Alonso et al. 2005)
Experimental observations: Effect of dry density on water retention curve

MX-80 water retention curves (Seiphoori et al., 2014)
**Experimental observations:** wetting under constant volume and free-swelling conditions

MX-80 bentonite/sand (7/3 in dry mass) (Gatabin et al. 2016)

### Degree of saturation

\[
S_r = \frac{V_w}{V_v} = \frac{e_w}{e}
\]

\[\rho_{d0} = 2.0 \text{ Mg/m}^3\]

**Competing effects** of
- Water uptake \((e_w)\)
- Swelling \((e)\)

---

**Introduction**

- **Microstructure**
- **Saturated**
- **Unsaturated**
- **Conclusions**

---

25
Experimental observations: wetting under constant volume and free-swelling conditions

Effect of a lower dry density

MX-80 bentonite/sand (7/3 in dry mass) (Wang et al. 2013)
• Water retention curve: \[ \text{amount of water stored} = f(\text{suction} \ldots) \]

(generally a unique relationship in the models!)

• Water retention behaviour: influence of the density

![Graph showing the relationship between degree of saturation and suction](image)
• Water retention curve: amount of water stored = f(suction…) (generally a unique relationship !)

• Water retention behaviour: influence of the density
• Water retention curve: amount of water stored = f(suction…)
  (generally a unique relationship !)

• Water retention behaviour: influence of the density

![Graph showing water retention curve](image)
• Water retention curve: \( \text{amount of water stored} = f(\text{suction} \ldots) \) 

( generally a unique relationship ! )

• Water retention behaviour: influence of the density
Development of a new water retention model

\[ e_w = S_r \cdot e = e_{wm} + e_{wM} \]

Dubinin model

\[ e_{wm}(s, e_m) = e_m \exp[-(C_{ads}s)^{n_{ads}}] \]

« Van-Genuchten » model

\[ e_{wM}(s, e, e_m) = (e - e_m) \left[1 + \left(\frac{s}{a}\right)^n\right]^{-m} \]

With \( a = \frac{A}{e - e_m} \)
Constant volume wetting paths

Free swelling wetting paths

**Experimental data**

- \( \rho_d = 1.69 \text{ Mg/m}^3 \) (Wang et al., 2013)
- \( \rho_d = 2.03 \text{ Mg/m}^3 \) (Gatabin et al., 2016)

**Model**

- \( \rho_d = 1.69 \text{ Mg/m}^3 \)
- \( \rho_d = 2.03 \text{ Mg/m}^3 \)
Permeability evolution

→ Extension of the formulation for simple porosity media to double porosity media

\[ K_w = K_{w0} \left( \frac{e_M^N}{(1 - e_M)^M} \right) \frac{(1 - e_{M0})^M}{e_{M0}^N} \]
Permeability evolution

\[ e = e_m + e_M \]

- Aggregate
- Intra-aggregate pore
- Inter-aggregate pore

- Experimental data (Gatabin et al. 2006)
- Extended Kozeny-Carman model

- Saturated water permeability, $K_w$ m$^{-1}$
- Dry density, $\rho_d$: Mg/m$^3$
- Macrostructural void ratio, $e_M$

**Introduction**

**Microstructure**

**Saturated**

**Unsaturated**

**Conclusions**
Introduction

Microstructure and swelling behaviour

Water Transfer in saturated conditions

Unsaturated conditions

Conclusions
• Many Hydro-mechanical couplings in Bentonite
• Many Hydro-mechanical couplings in Bentonite

• Influence of the Micro-macro interactions

• Be careful about Heterogeneity: interface, initial material state, induced by the loading during the transient period, erosion/piping in saturated condition
Interface = material **discontinuity** between bodies of same nature or of different nature, or between two different media

Sealex in situ test  
(Tournemire, France)

Compacted bentonite  
(engineered barrier)

Host rock  
(natural barrier)

Container with vitrified waste

Praclay Seal experiment  
(Mol, Belgium)
PGZ2 in situ test, Meuse Haute-Marne URL (France)

PGZ1013:
- Length: 20 m
- Diameter: 101.3 mm

MX-80 bentonite/sand buffer:
- Length: 400 mm
- Diameter: 94 mm

(de la Vaissière 2013)
PGZ2 in situ test, Meuse Haute-Marne URL (France)
PGZ2 in situ test, Meuse Haute-Marne URL (France)
Infiltration test

Diagram:
- Air outlet
- High-rigidity frame
- Porous disc
- Confining cell
- Bentonite plug
- Porous disc
- Water inlet

Graph:
- Distance from wetting end, y, mm vs. Void ratio, e
- Initial void ratio = 0.64
- Time: 50 days, 150 days, 250 days
- Conservation of the total porous volume

Sections:
- RH4
- RH3
- RH2
- RH1
• Many Hydro-mechanical couplings in Bentonite

• Influence of the Micro-macro interactions

• Be careful about Heterogeneity: interface, initial material state, induced by the loading during the transient period, erosion/piping in saturated condition

• AC Dieudonne thesis at the University of Liege: [http://orbi.ulg.ac.be/handle/2268/201397#ft](http://orbi.ulg.ac.be/handle/2268/201397#ft)