Hydraulic behaviour of bentonite

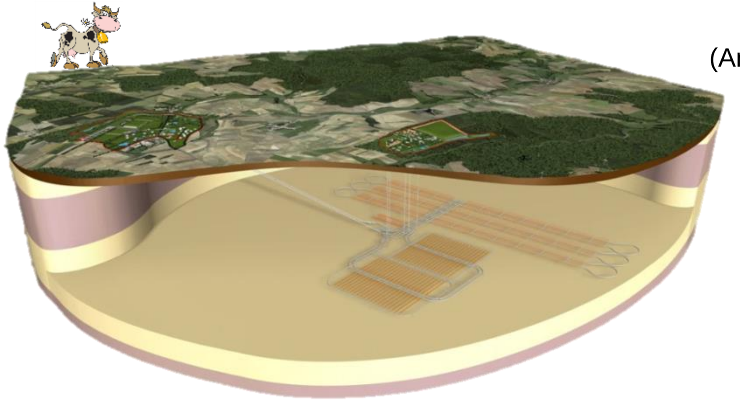
Introduction to the hydromechanical processes

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



(Andra)

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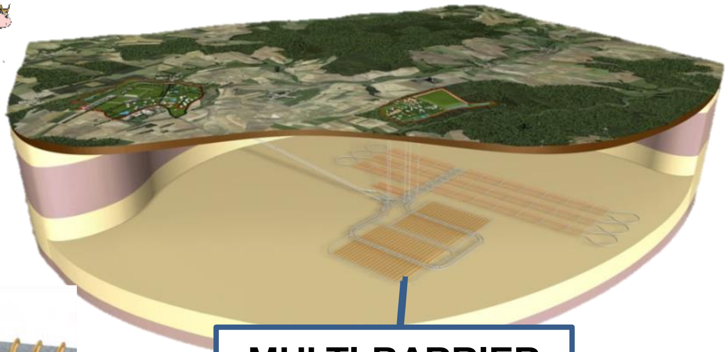
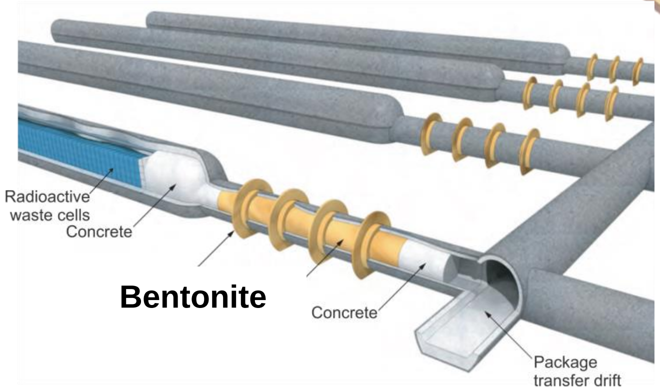


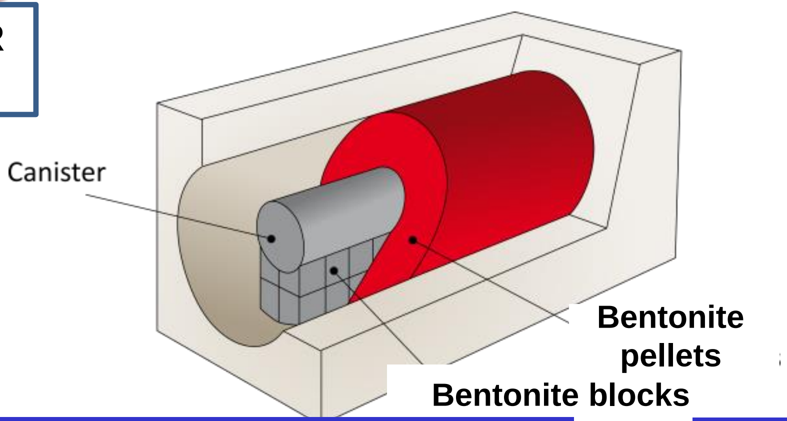
(Andra)

French CIGEO concept for ILW
(Andra)



MULTI-BARRIER CONCEPT

Swiss concept for HLW
(Nagra)



- Bentonite = clay material that primarily consists of **montmorillonite**

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

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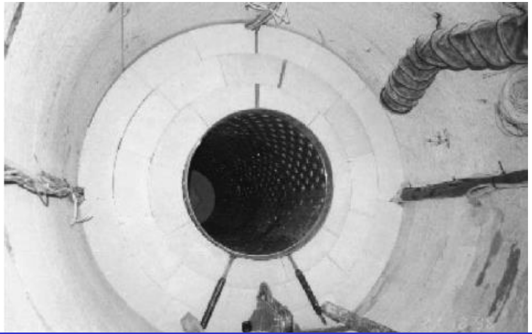
- Different forms: powder, compacted blocks, pellets

Febex Experiment
(Alonso et al. 2005)



REM Experiment
(Andra)

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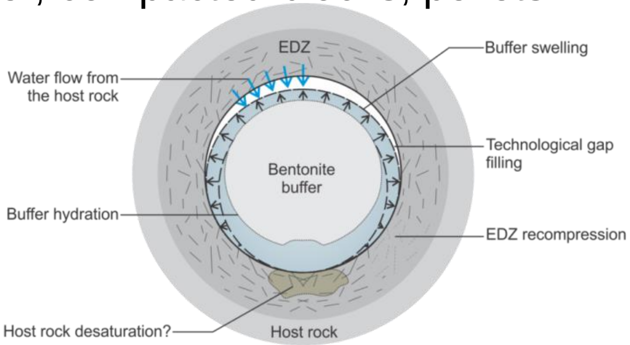

- Introduction
- Microstructure and swelling behaviour
- Water Transfer in saturated conditions
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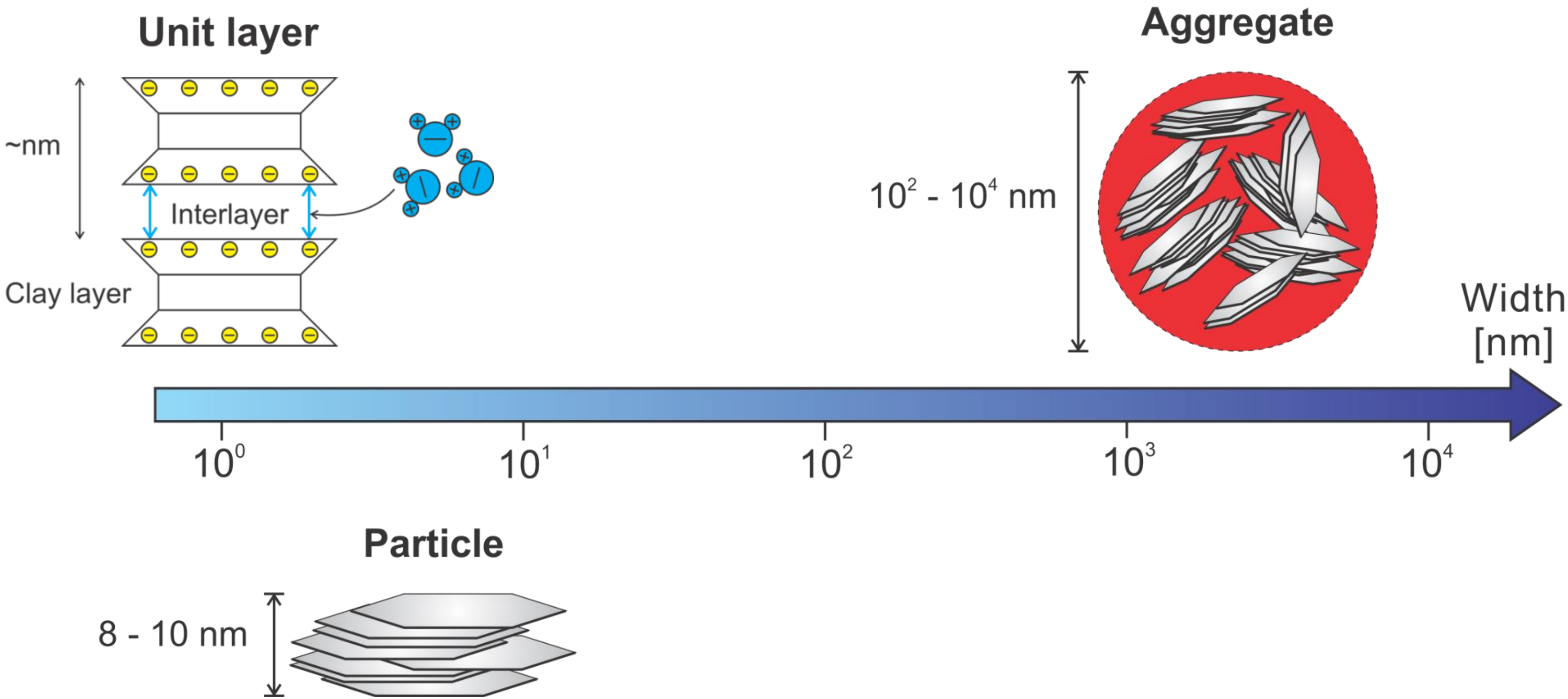
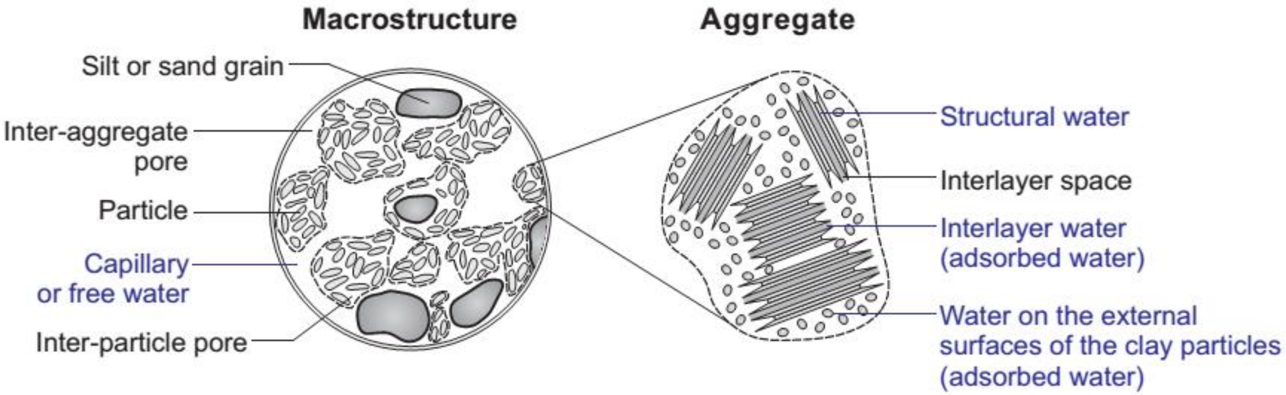
Hierarchical structure of bentonite



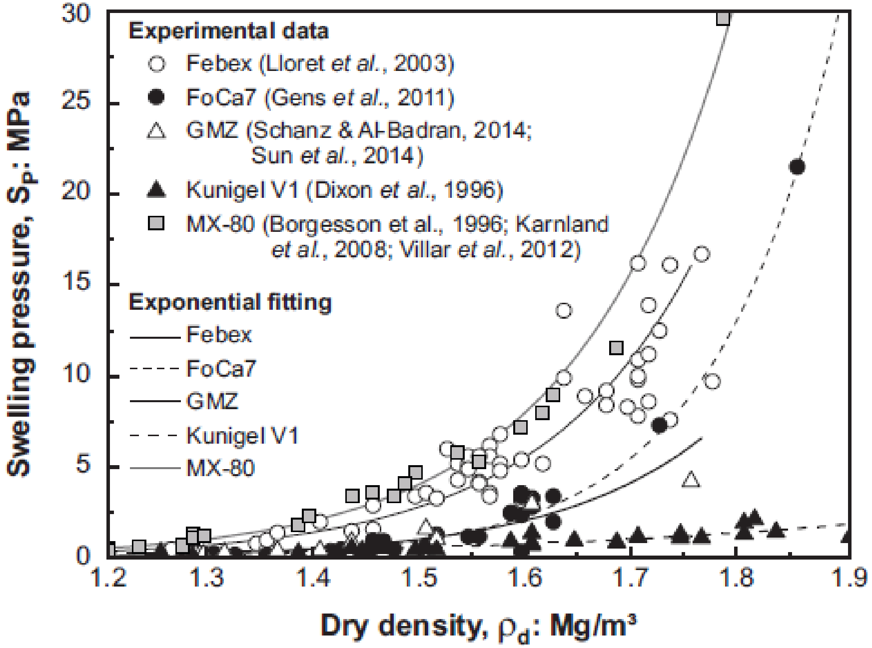
Swelling behaviour of bentonite



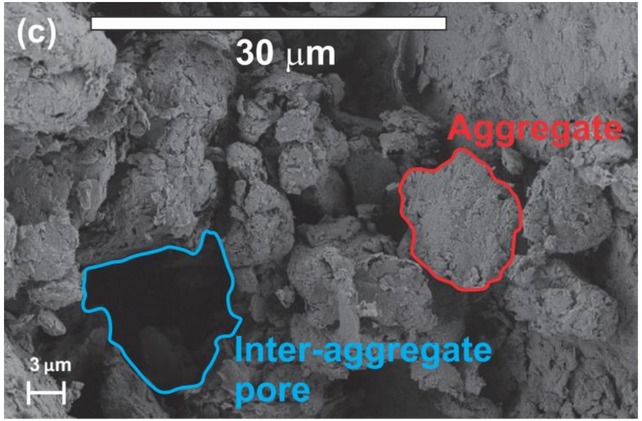
Water in compacted bentonite

Modified after Gens and Alonso 1992, Jacinto et al. 2012

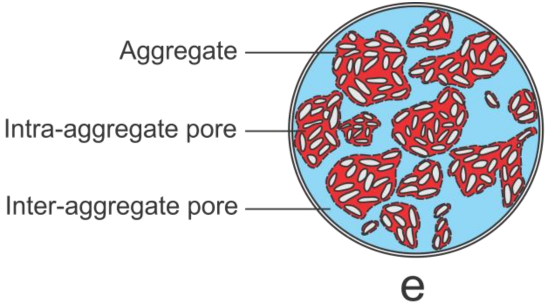
Swelling behaviour of bentonite

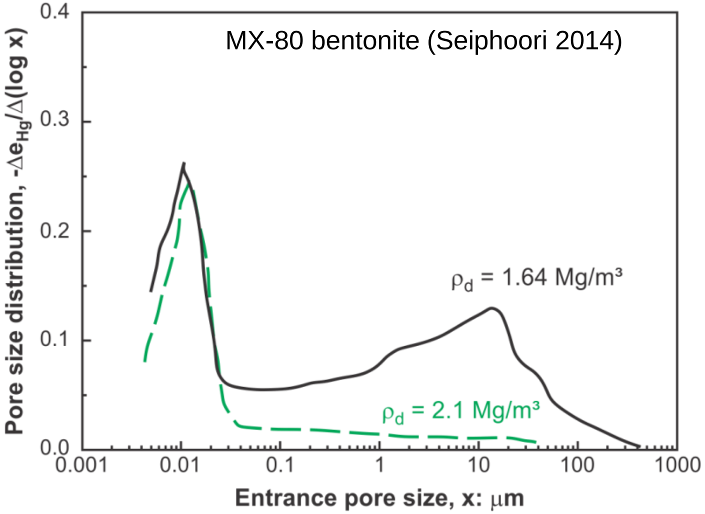


Compaction of bentonite creates a **double-porosity structure**



MX-80 bentonite (Seiphoori 2014)





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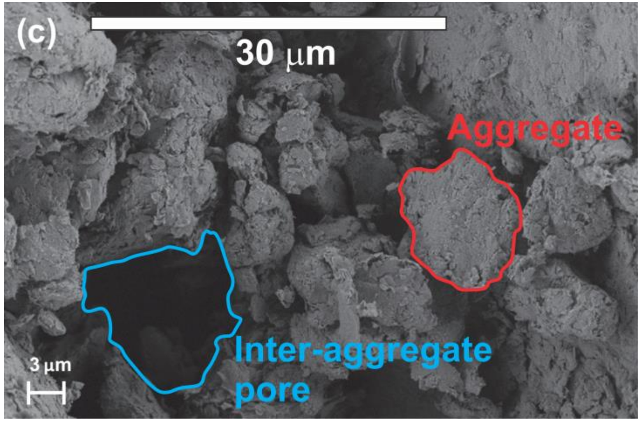

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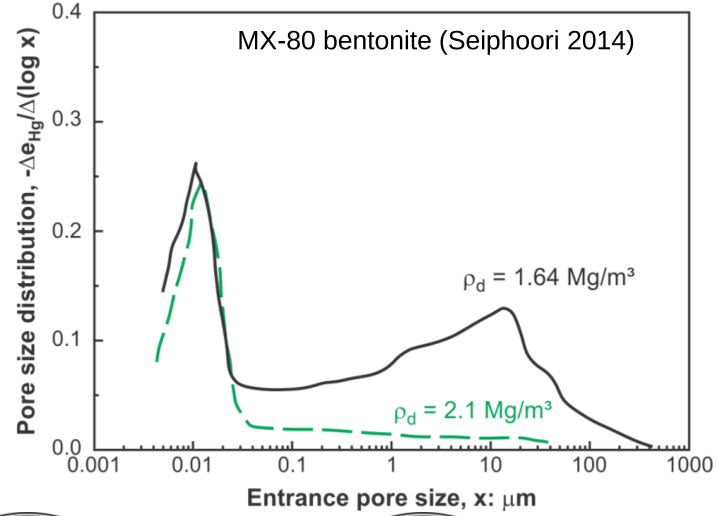
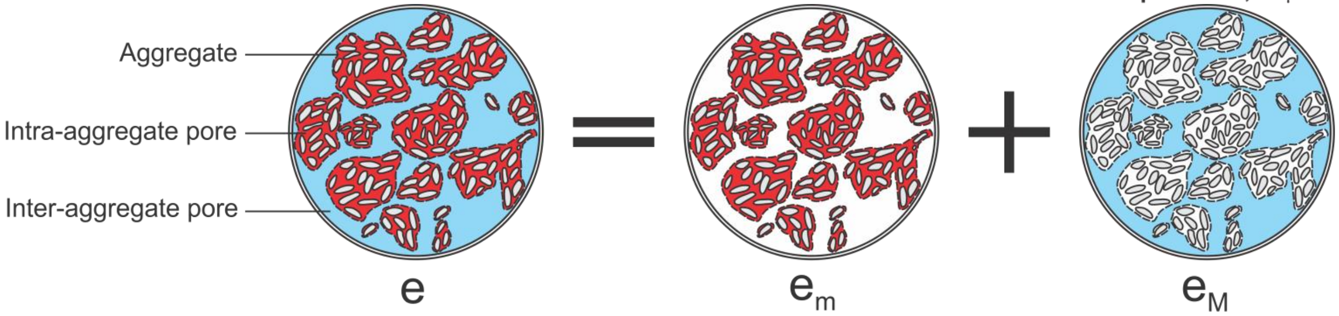
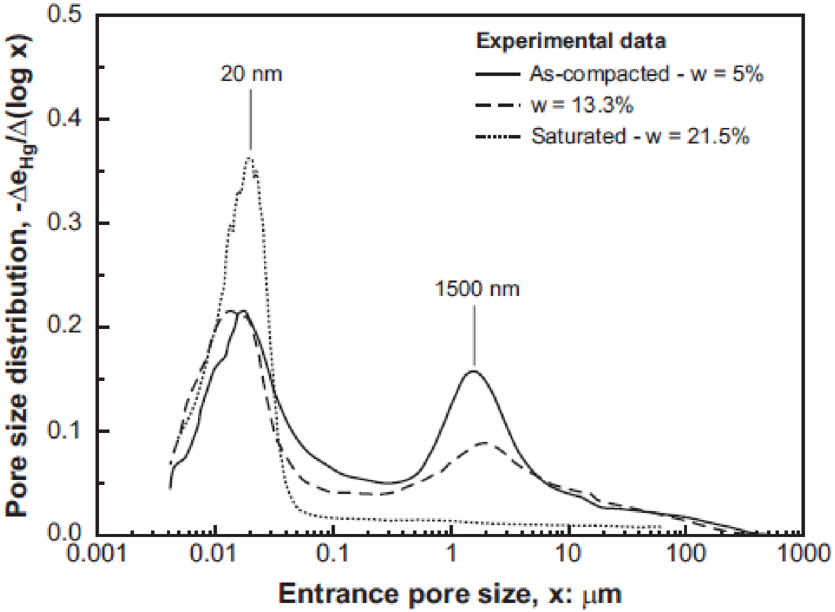


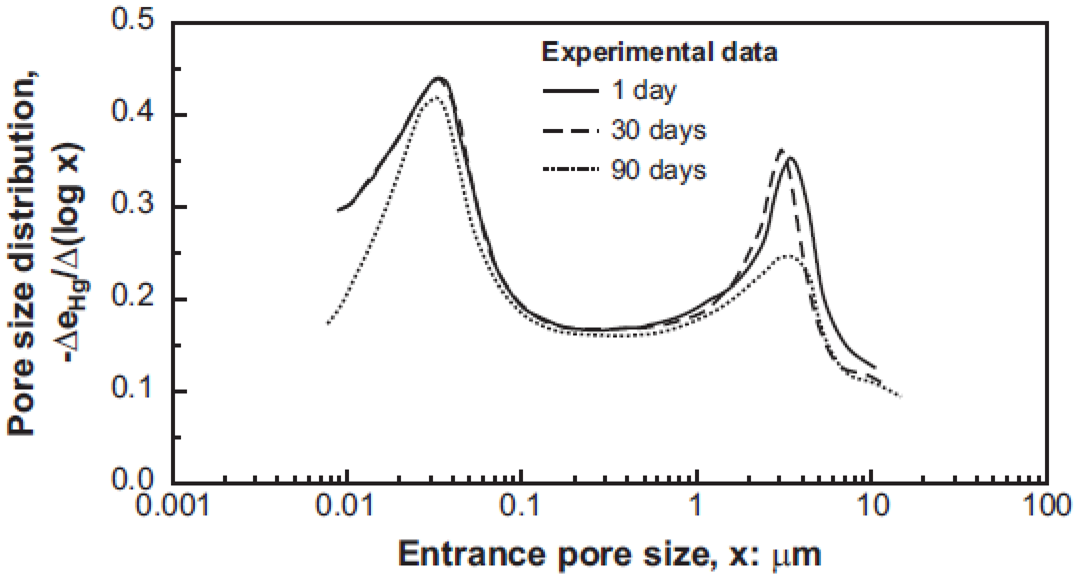


Hydration of bentonite modifies the **double-porosity structure**



MX-80 bentonite (Seiphoori 2014)

Aging of bentonite modifies the **double-porosity structure**



MX-80 bentonite (Delage et al. 2006)

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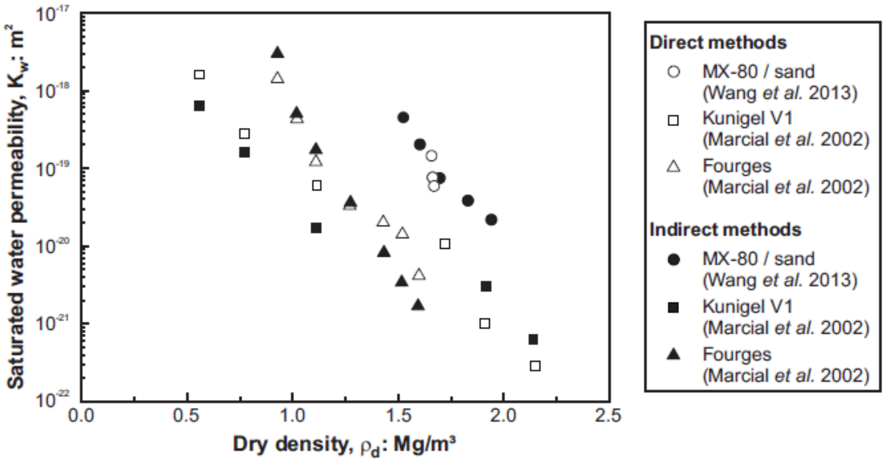
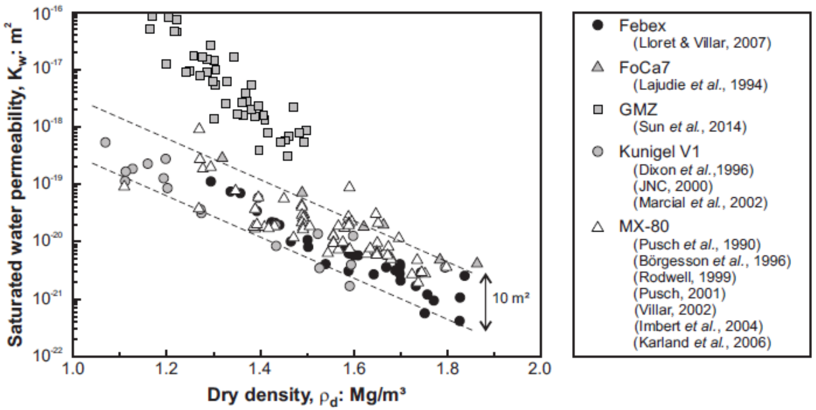
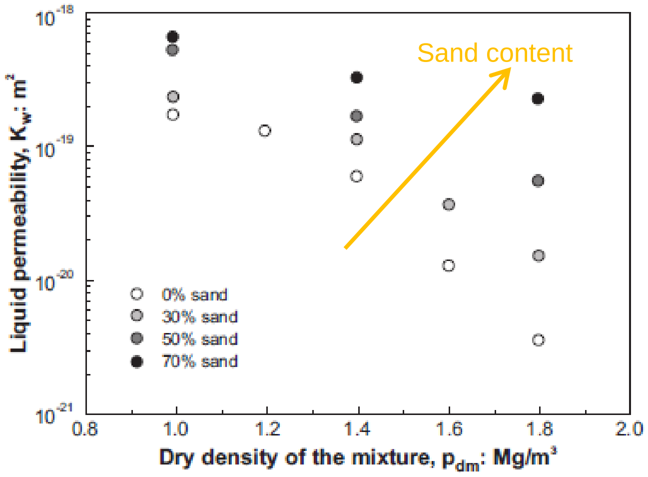
Permeability in saturated conditions





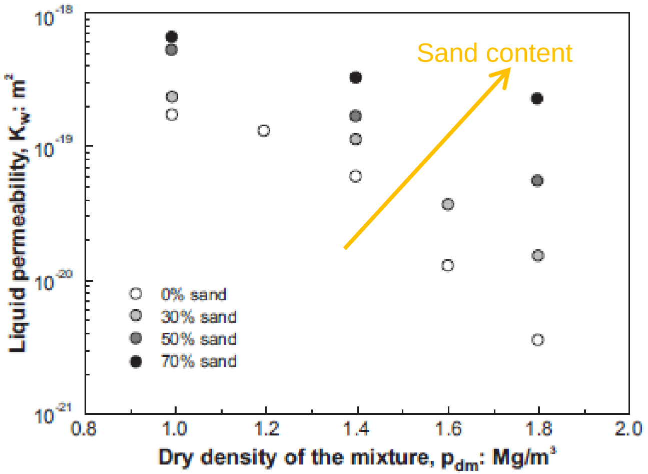
Mixture MX-80/sand (Wang et al, 2013), Kunigel and Fourges clay (Marcial et al., 2002)

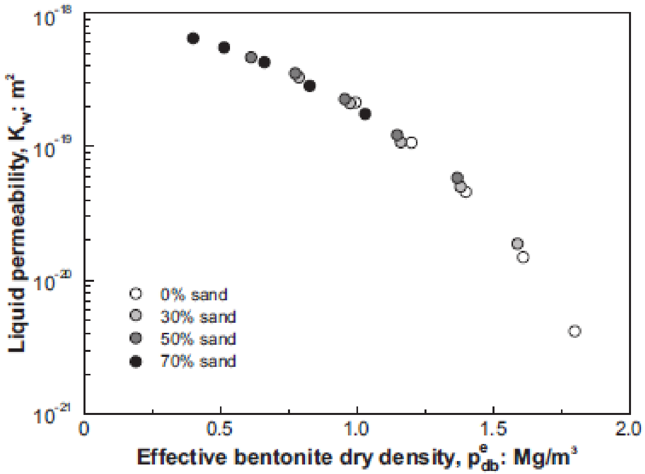
Permeability in saturated conditions: influence of sand content



Kunigel V1 bentonite and sand (JNC, 2000)

Permeability in saturated conditions: influence of sand content





$$\rho^e_{db} = \frac{m_{sb}}{\Omega_v + \Omega_{sb}} = \frac{f_b \rho_{sm}}{e + f_b \frac{\rho_{sm}}{\rho_{sb}}}$$

$$f_B = \frac{m_{sb}}{m_s}$$

$$\rho_{sm} = \left(\frac{f_b}{\rho_{sb}} + \frac{1 - f_b}{\rho_{ss}} \right)^{-1}$$

Kunigel V1 bentonite and sand (JNC, 2000)

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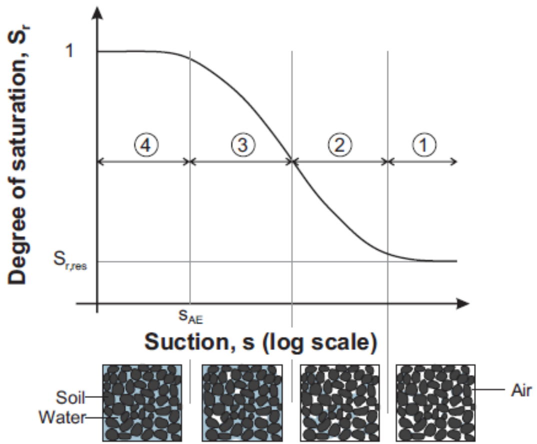
- Water retention curve: $\boxed{\text{amount of water stored = f(suction…)}}$

(generally a unique relationship in the models !)

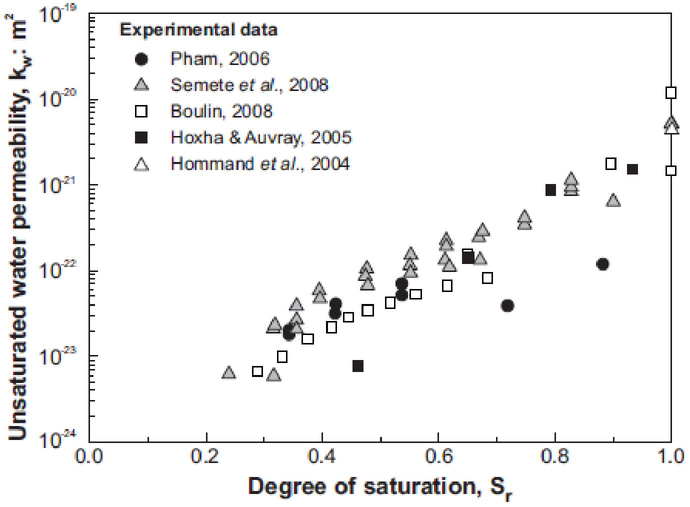
- Classical approaches for modelling the water retention behaviour: parameters to be fit using experimental data



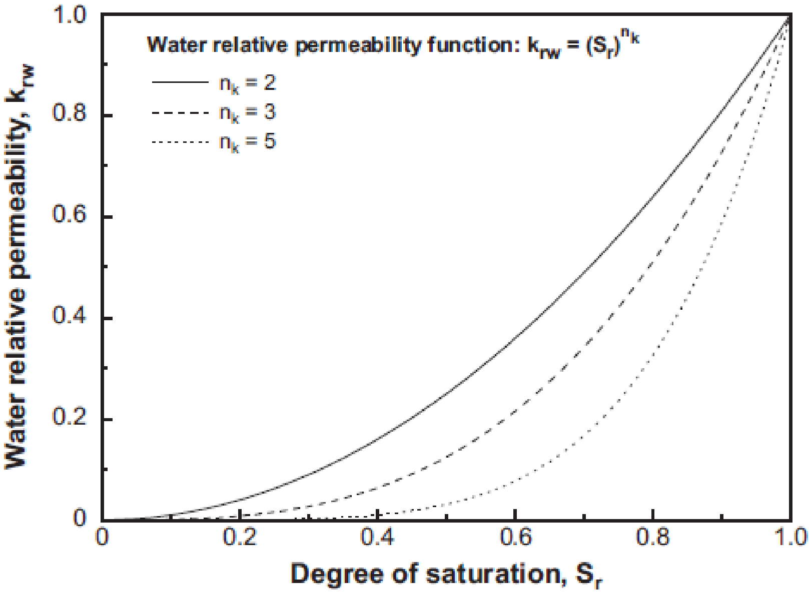
Modified after Nuth and Laoui, 2008

1. Residual saturation
2. Partially saturated
3. Quasi-saturated
4. Saturated

- Relative permeability curve:



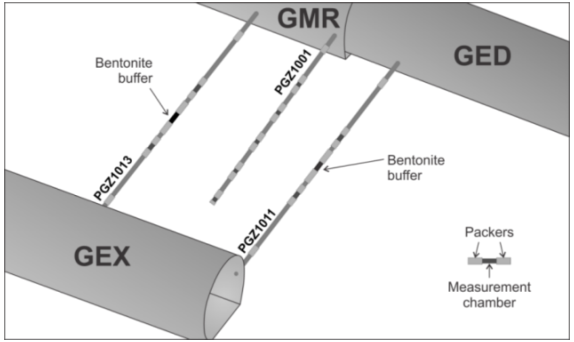
Permeability in Cox as a function of the degree of saturation

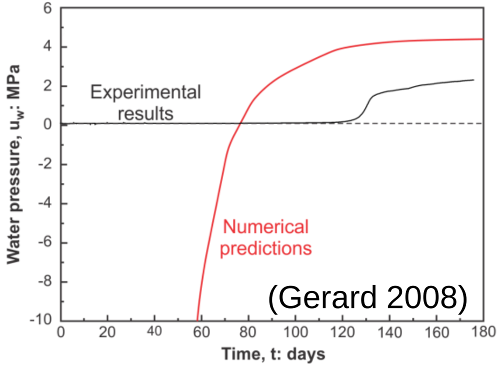


Limitations of existing models

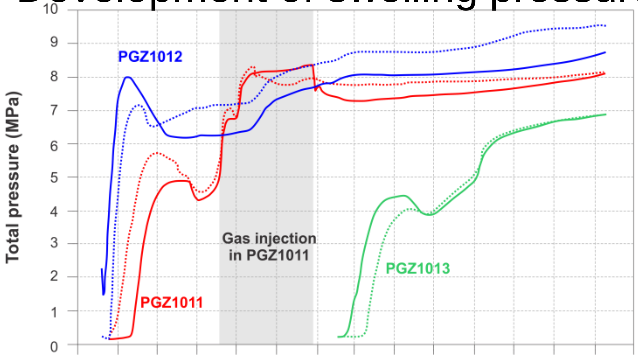
1) Saturation kinetics

PGZ2 Experiment
(de la Vaissière 2013)



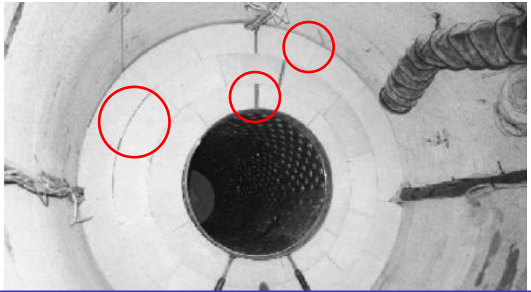


2) Development of swelling pressure

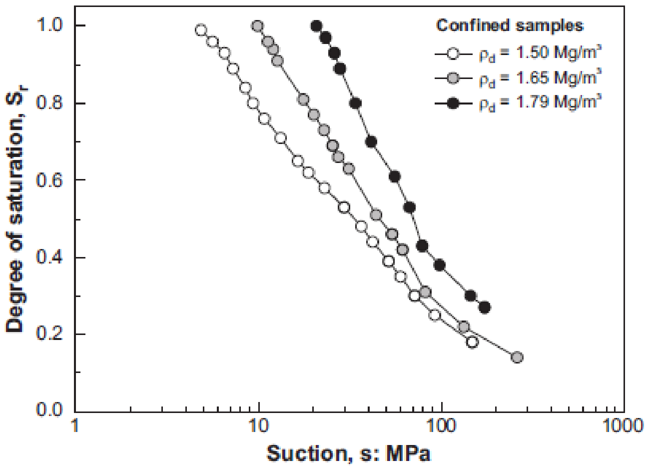


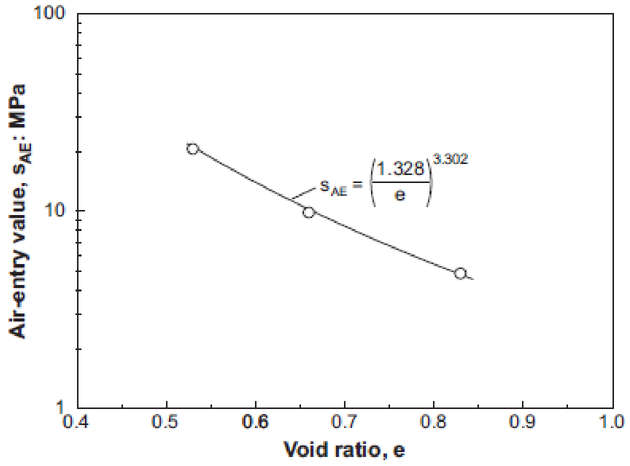
3) Existence of technological gaps

FEBEX Experiment
(Alonso et al. 2005)



Experimental observations: Effect of dry density on water retention curve





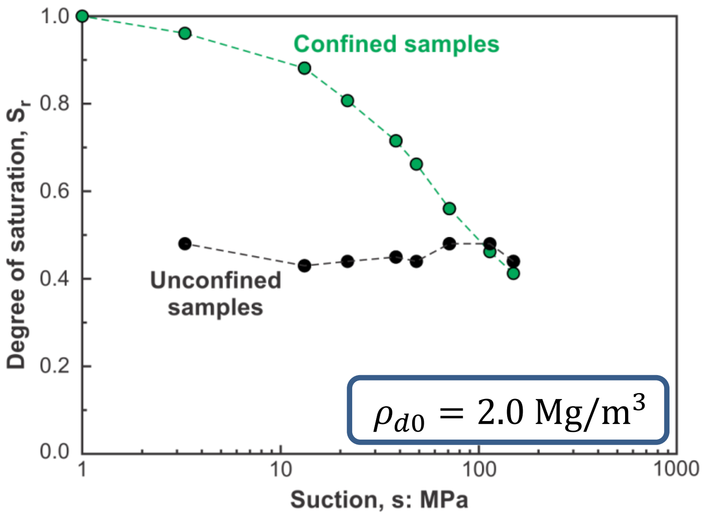
$$s_{AE} = \left(\frac{A}{e}\right)^{B}$$

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)

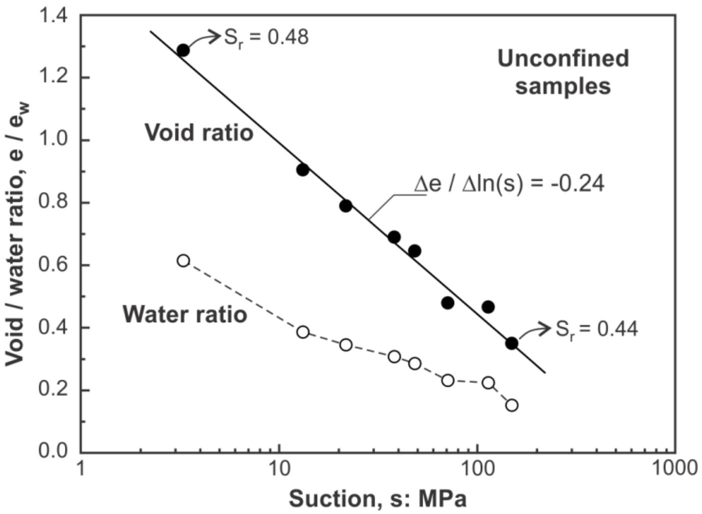
Degree of saturation



$$S_r = \frac{V_w}{V_v} = \frac{e_w}{e}$$

⇨ <u>Competing effects</u> of

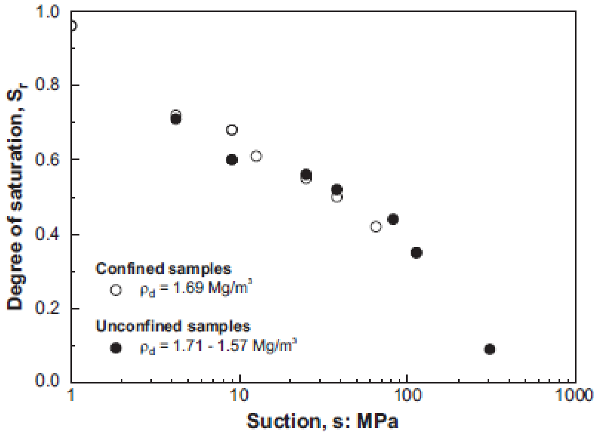
- Water uptake (e_w)
- Swelling (e)

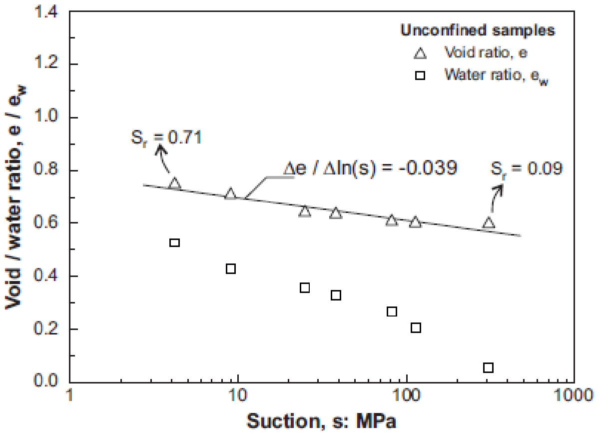


Experimental observations: wetting under constant volume and free-swelling conditions

Effect of a lower dry density

MX-80 bentonite/sand (7/3 in dry mass) (Wang et al. 2013)

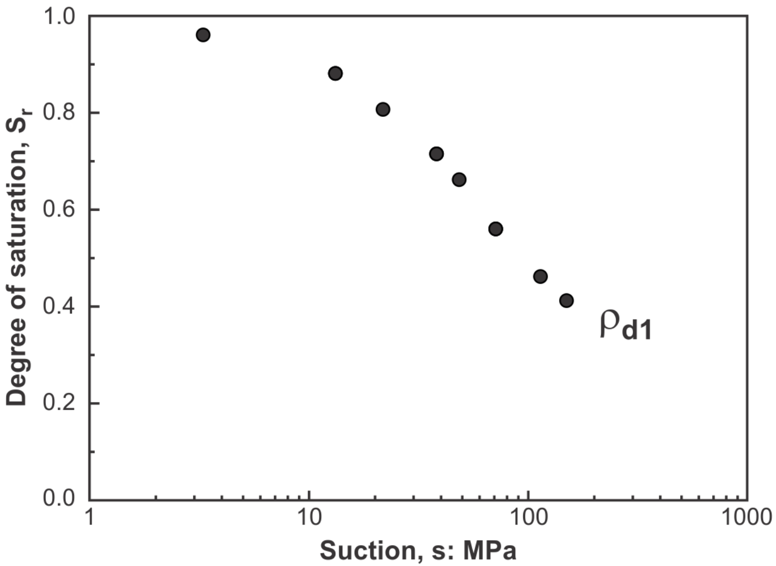




- Water retention curve: $\boxed{\text{amount of water stored = f(suction…)}}$

(generally a unique relationship in the models!)

- Water retention behaviour: influence of the density



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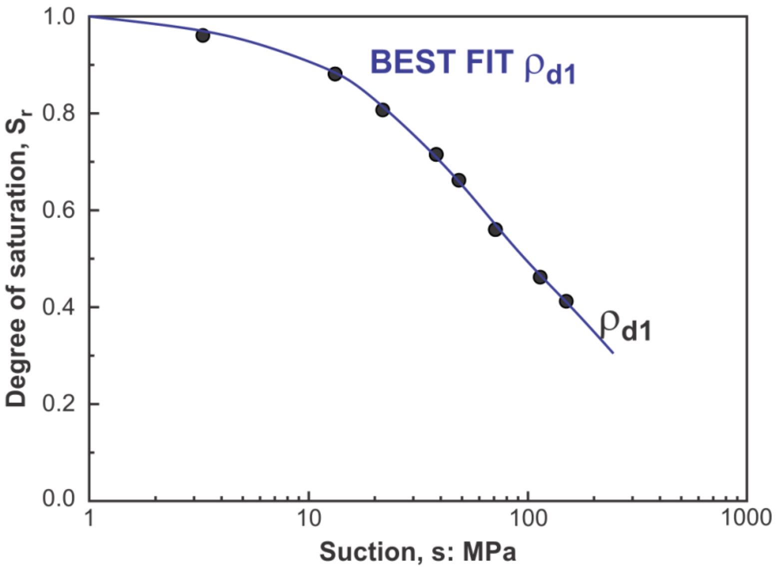

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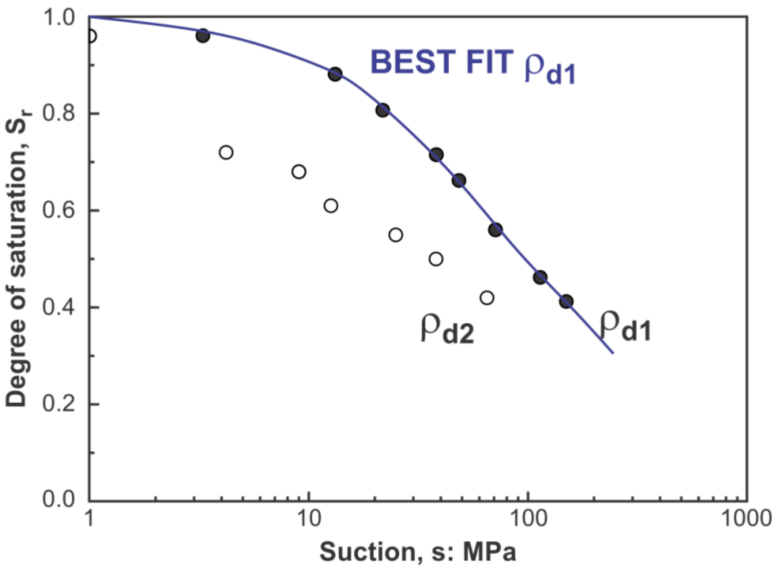

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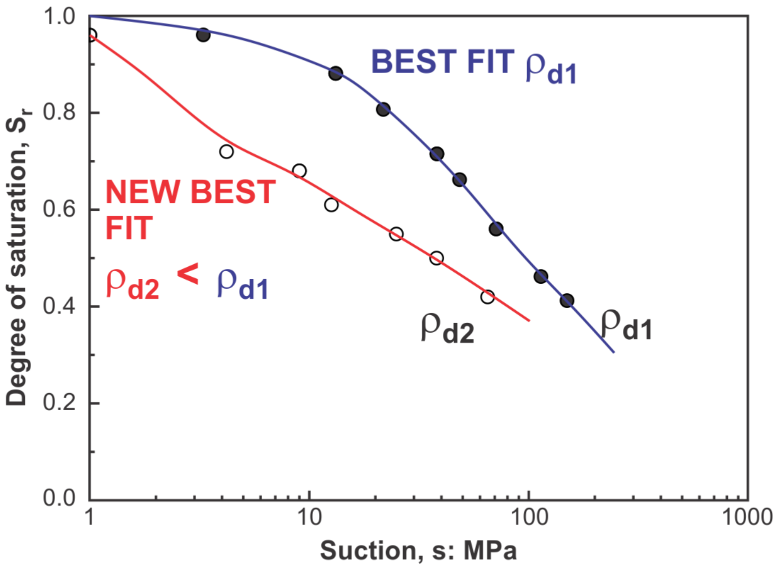
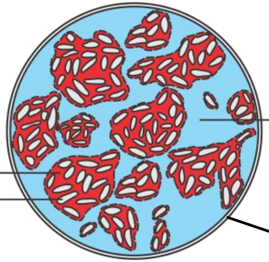


Development of a new water retention model

$$\boxed{e_w = S_r \,.\, e = e_{wm} + e_{wM}}$$



« Van-Genuchten » model

Dubinin model

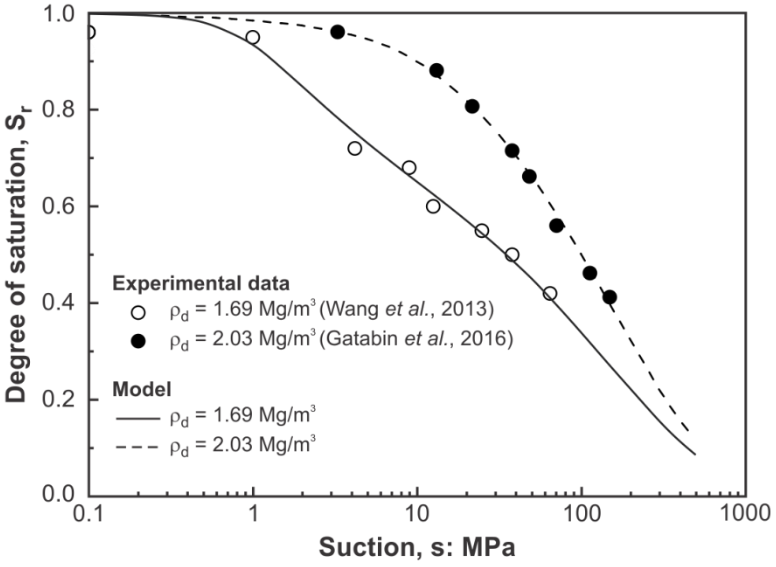
$$e_{wM}(s, e, e_m) = (e - e_m)\left[1 + \left(\frac{s}{a}\right)^n\right]^{-m}$$

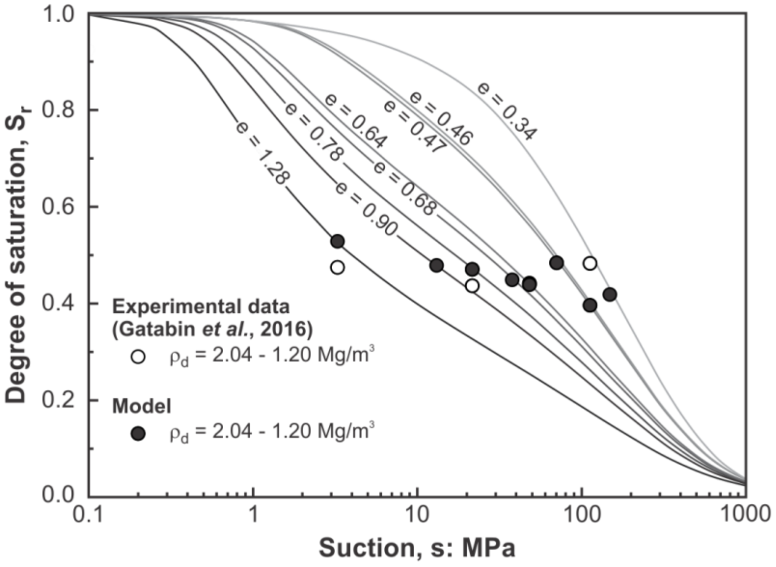
With $a = \frac{A}{e - e_m}$

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

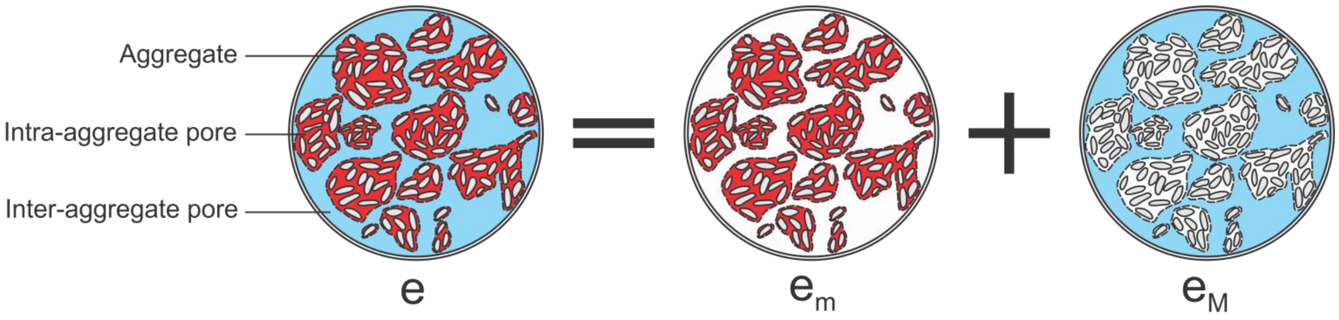
Constant volume wetting paths

Free swelling wetting paths





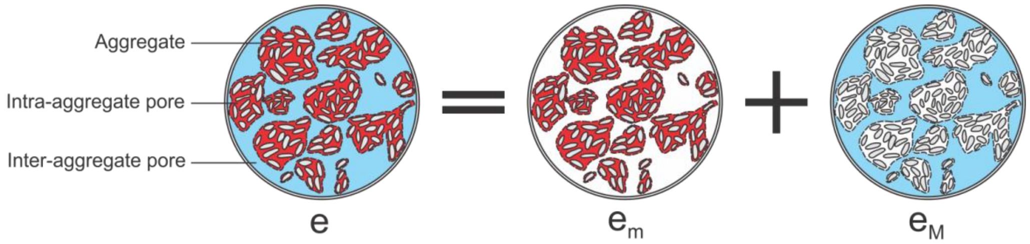
Permeability evolution

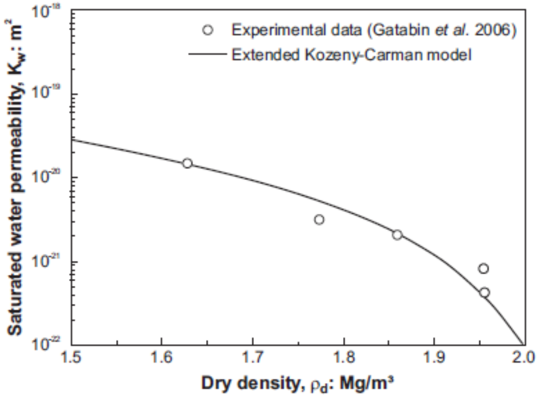


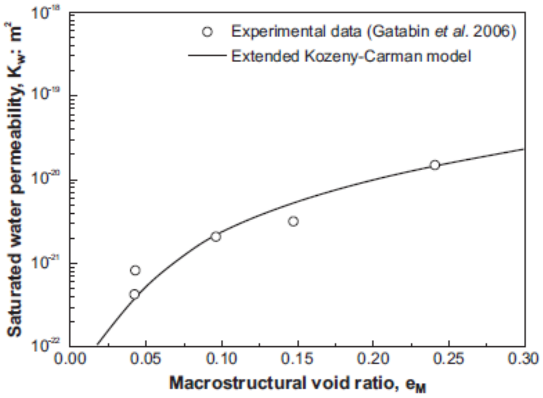
→ Extension of the formulation for simple porosity media to double porosity media

$$K_w = K_{w0} \frac{e_M^N}{(1-e_M)^M} \frac{(1-e_{M0})^M}{e_{M0}^N}$$

Permeability evolution







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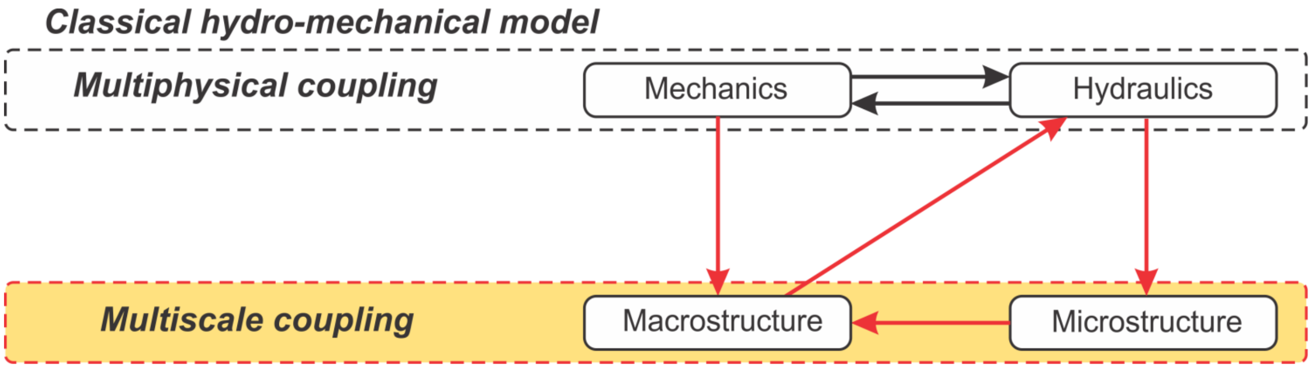
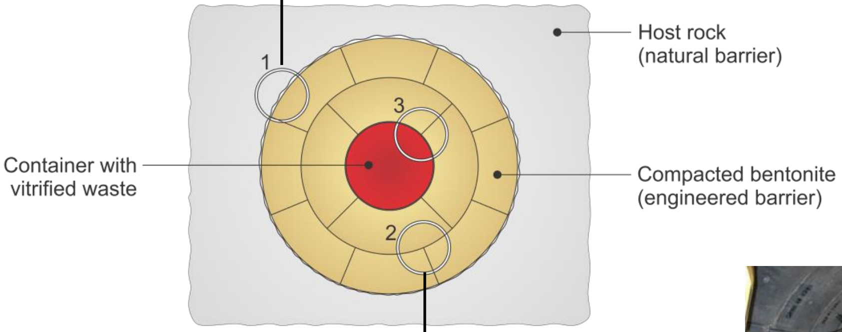
- Many Hydro-mechanical couplings in Bentonite



- 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

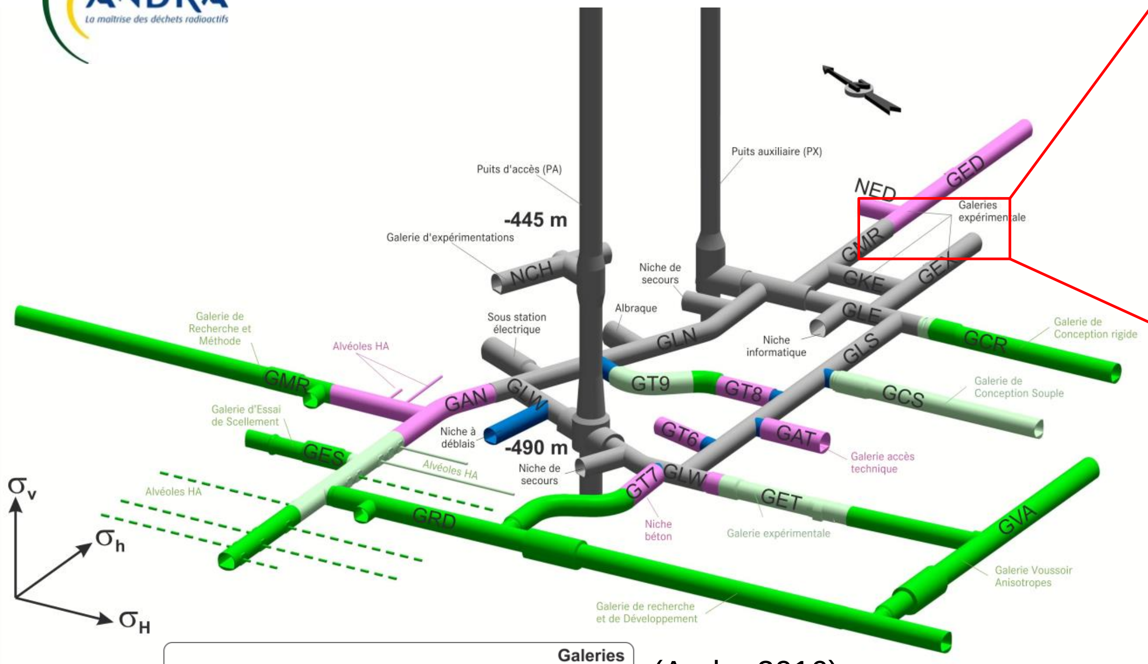
Interface = material **discontinuity** between bodies of same nature or of different nature, or between two different media

Sealex in situ test
(Tournemire, France)



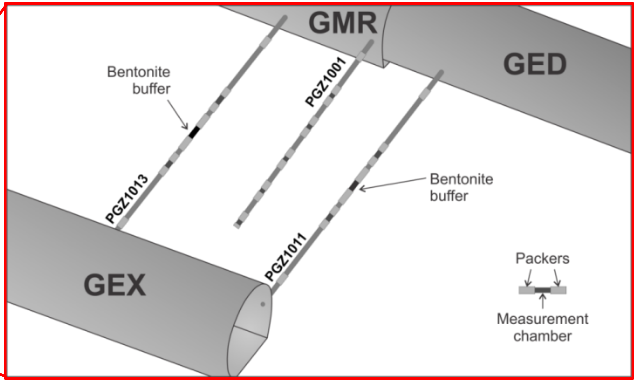
Praclay Seal experiment
(Mol, Belgium)

PGZ2 in situ test, Meuse Haute-Marne URL (France)



	Galeries length
Galeries excavated in 2007	485 m
Works 1 (November 2007 - June 2008)	560 m
Works 2 (April 2008 - June 2009)	780 m
Works 3 (November 2009 - December 2012)	900 m

(Andra 2016)

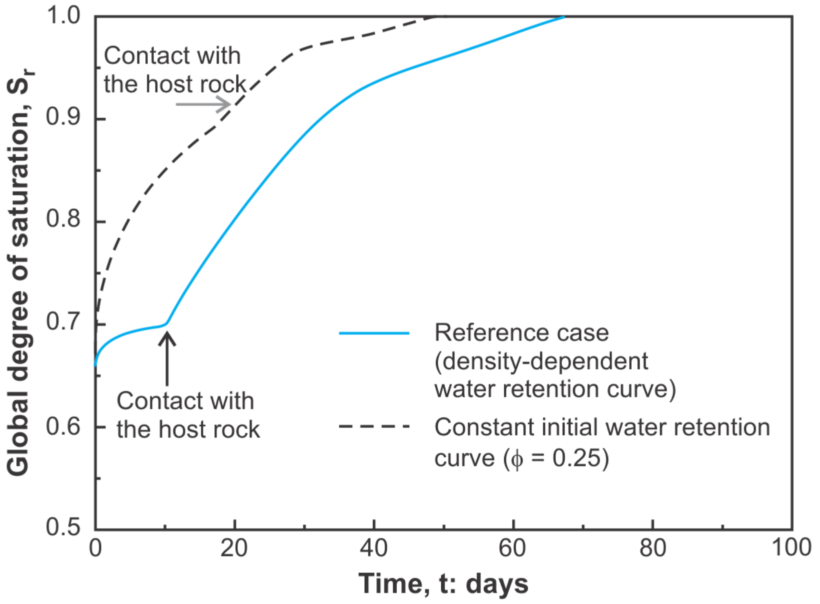


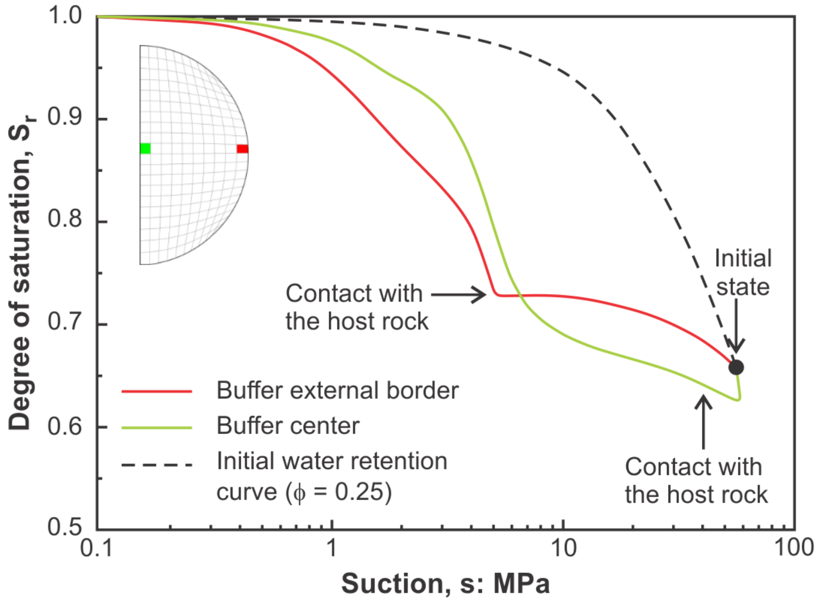
(de la Vaissière 2013)

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

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

PGZ2 in situ test, Meuse Haute-Marne URL (France)





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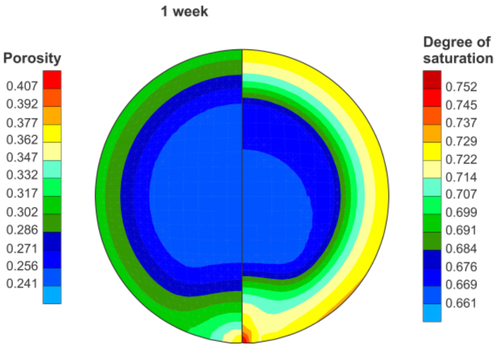
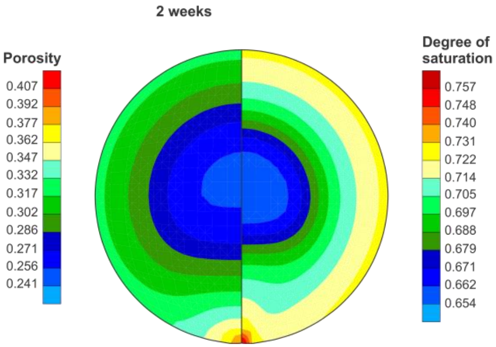
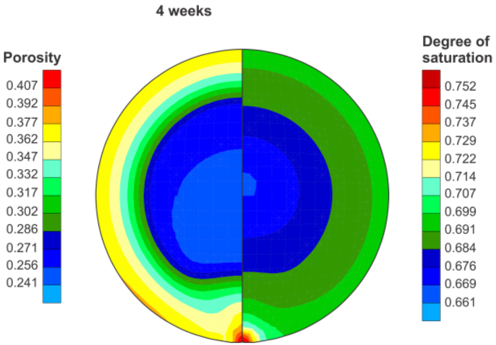
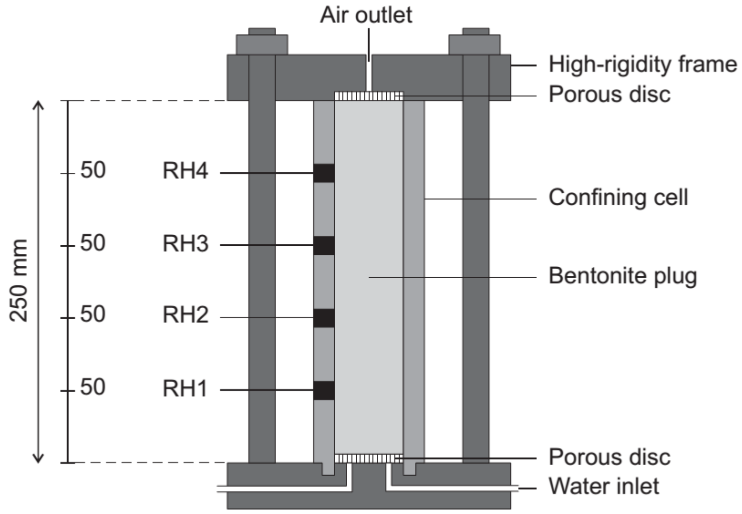
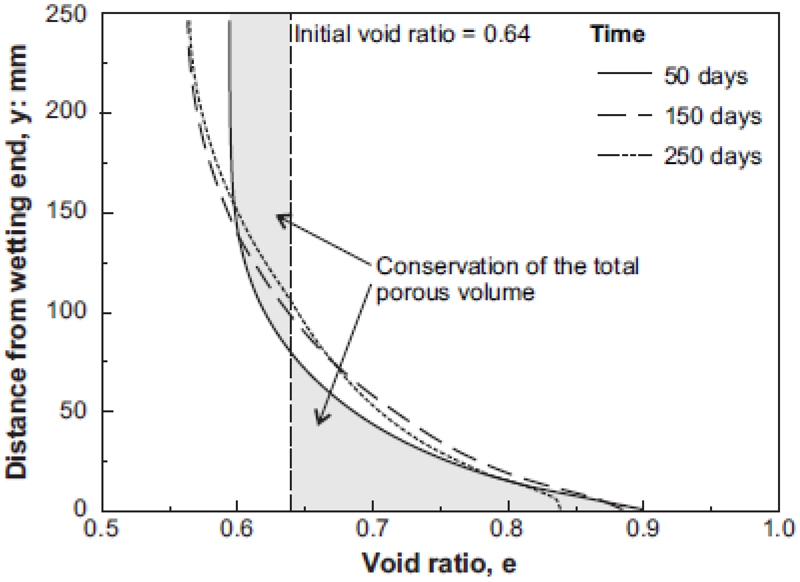






Infiltration test





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- 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