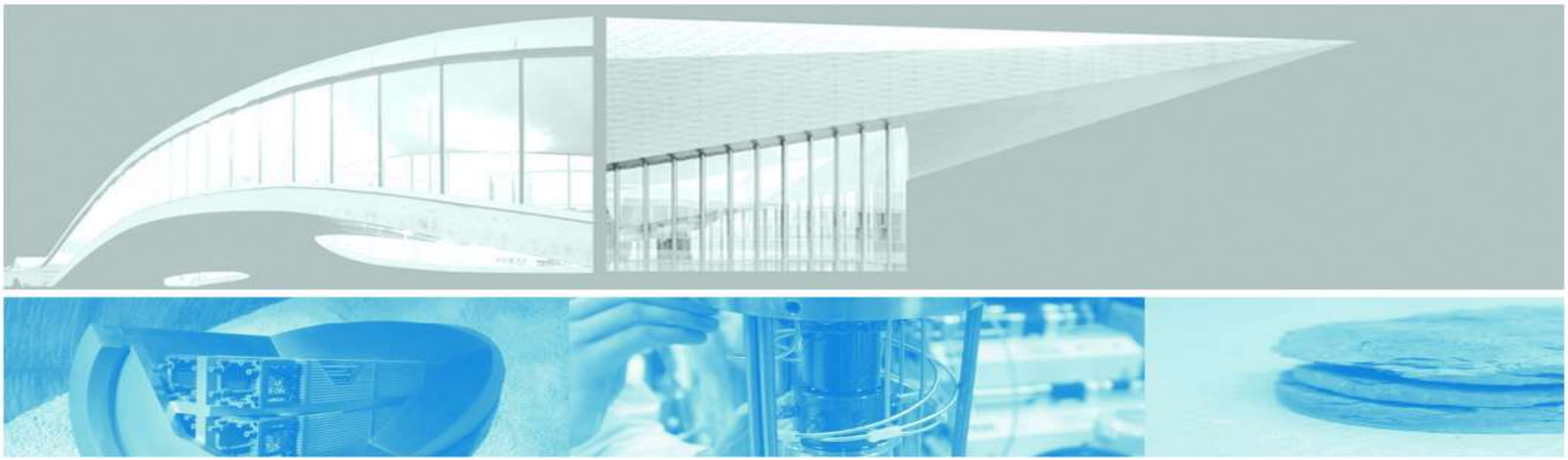
LABORATORY CHARACTERIZATION OF BENTONITE



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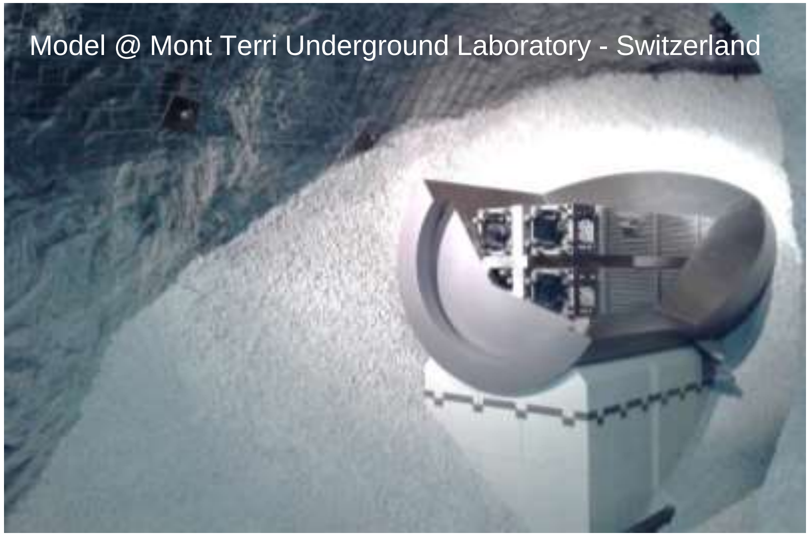
Mechanical Properties of Bentonite Barriers
Kaunas, 20 June 2017

Multi-barrier system (Swiss concept)

✓ **High Level Waste**

ENGINEERED BARRIER SYSTEM (EBS):

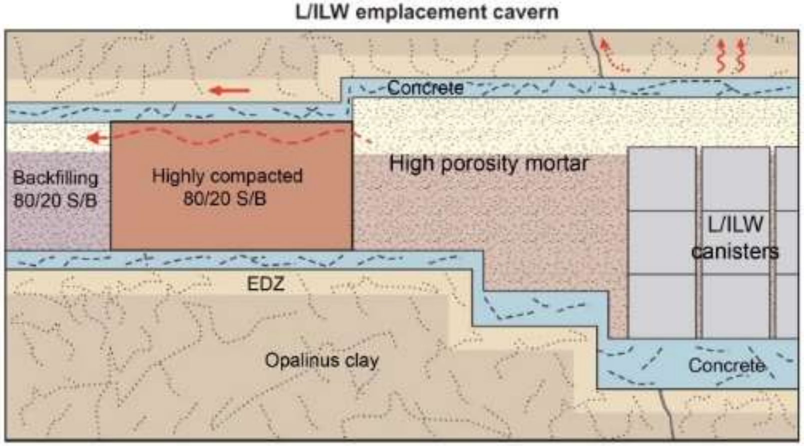
- Vitrified HLW
- Stainless steel container
- Compacted bentonite (**granular** + blocks)
- Low permeable Host rock (Opalinus Clay)



✓ **Low/Intermediate Level Waste**

ENGINEERED GAS TRANSPORT SYSTEM (EGTS):

- L/ILW Canister
- High porosity concrete
- Bentonite-based materials (**sand+bentonite**)
- Excavated Damage Zone in the Host rock



EPFL – LMS Laboratory Activity on Bentonite Characterization

In the last years the Laboratory of Soil Mechanics has been involved in a series of experimental projects to focus the hydromechanical behaviour of bentonite-based materials:

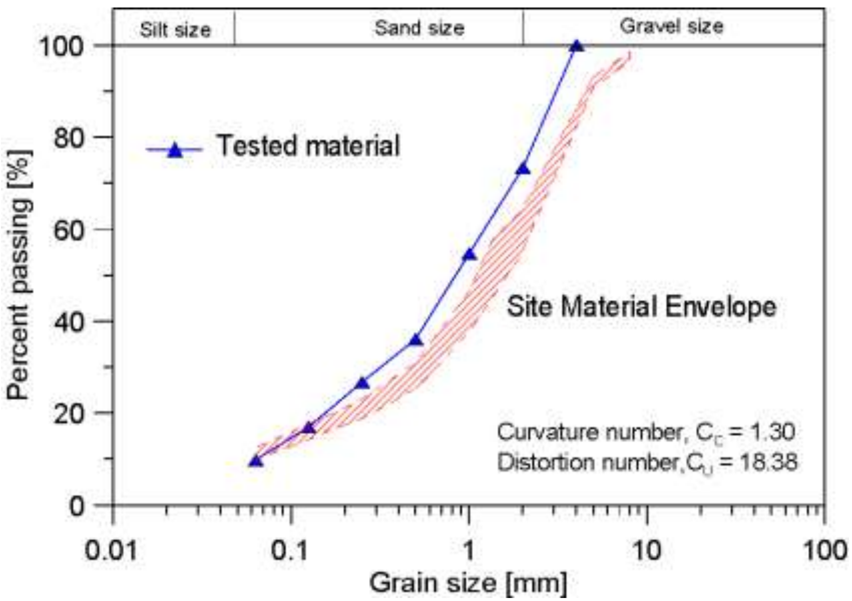
1. **MX-80 Granular Bentonite**
2. **MX-80 Granular Bentonite mixed with Quartz Sand**
3. **“Shot-clay” (Mx80 Bentonite)**

These materials have been subjected to an extensive laboratory testing program involving:

- ✓ Grain size distribution
- ✓ Microstructural and fabric characterization
- ✓ Swelling behaviour
- ✓ Water retention behaviour
- ✓ THM characterization using triaxial system

MX-80 Bentonite – Apparent Grain Size Distribution

- Mixture of different fractions of the broken and rounded bentonite units
- Grain size distribution (maximize the pourability)



Granular Bentonite

Bentonite fractions

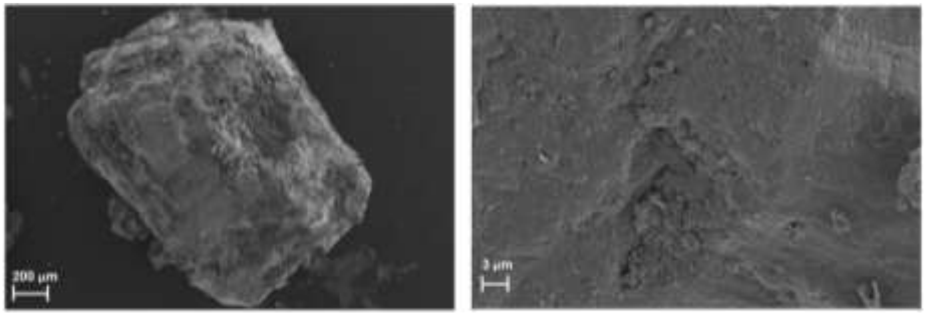
Smectite content† [%]	Specific surface area† s [m^2/g]	Specific gravity G_s	Liquid limit w_L [%]	Plastic limit w_p [%]	Hygroscopic water content (T = 22°C, RH = 34%) w_{hg} [%]
85	**523**	**2.74**	**420**	**65**	**5.4**

† Plötze and Weber (Nagra), 2007

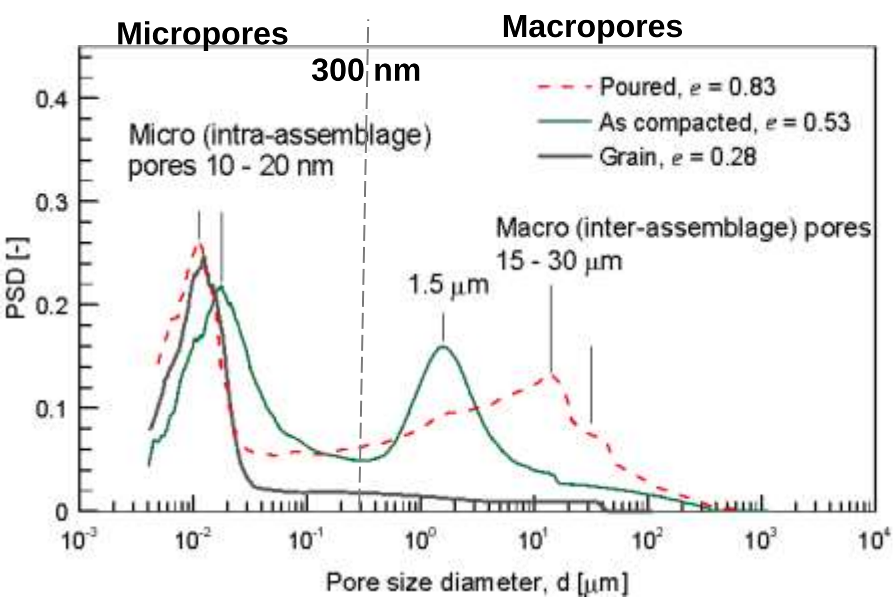
Microstructure at the as-compacted state

Seiphoori, Ferrari and Laloui (2014)

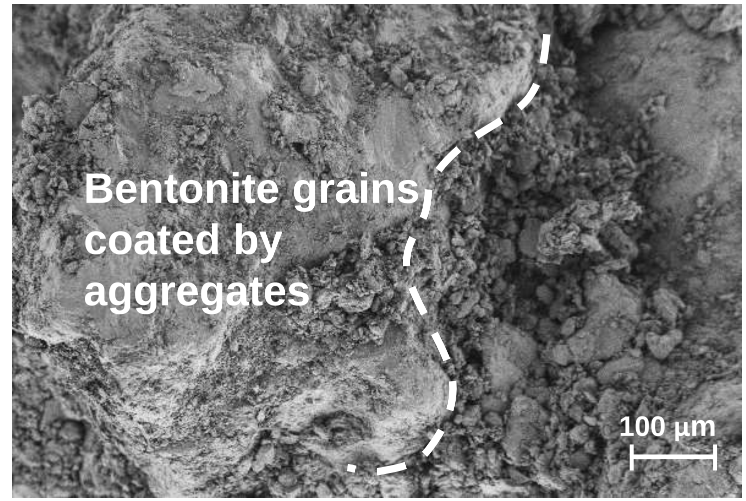
✓ **SEM of Single Grain**, e = 0.28, w = 5%

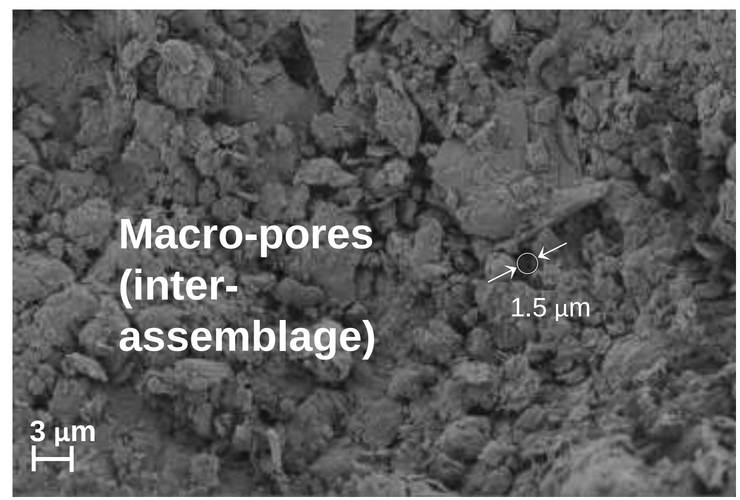


✓ **MIP**, double porosity structure

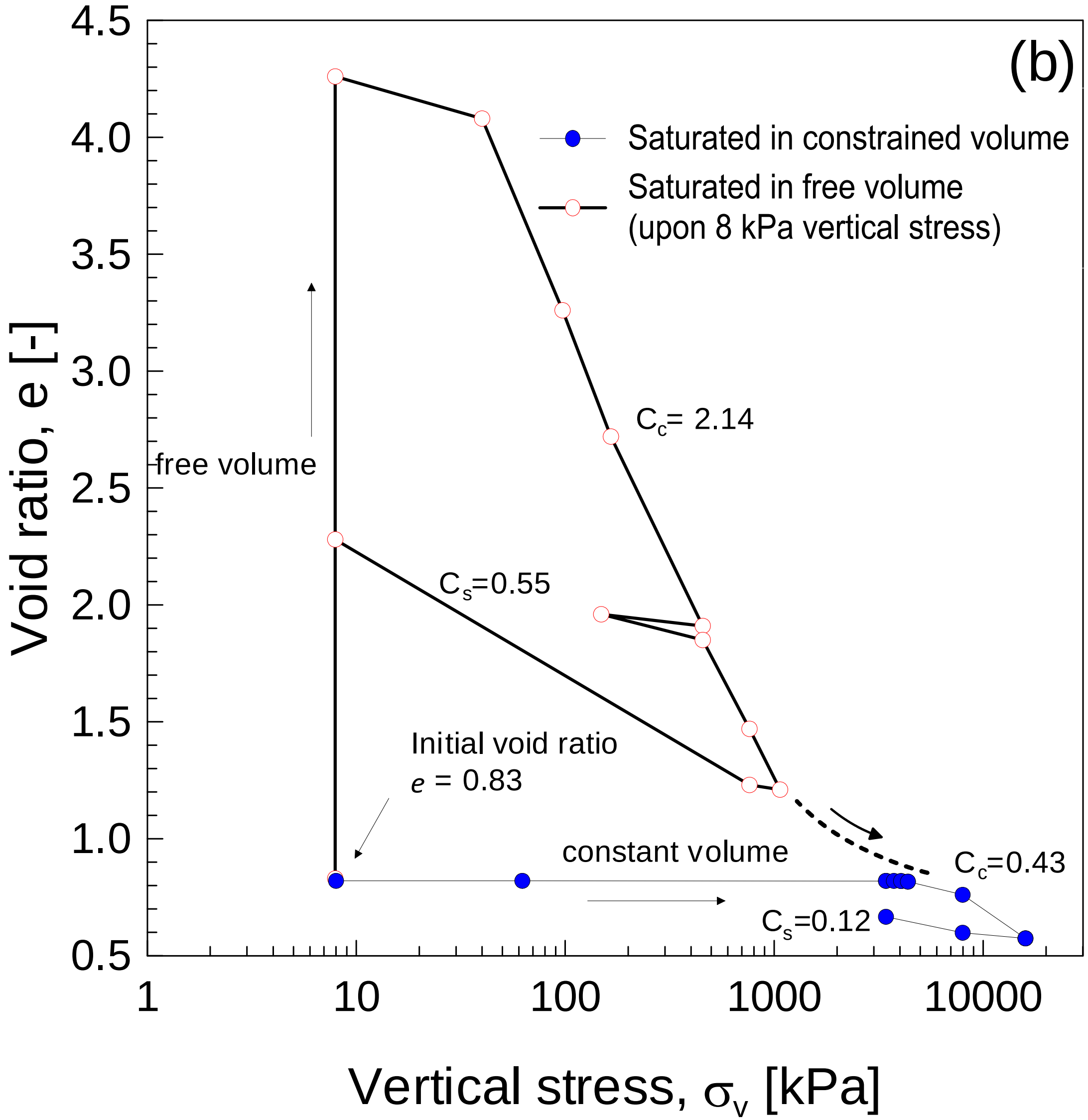


✓ **SEM**, e = 0.53, rd = 1.80 Mg/m3, w = 5%

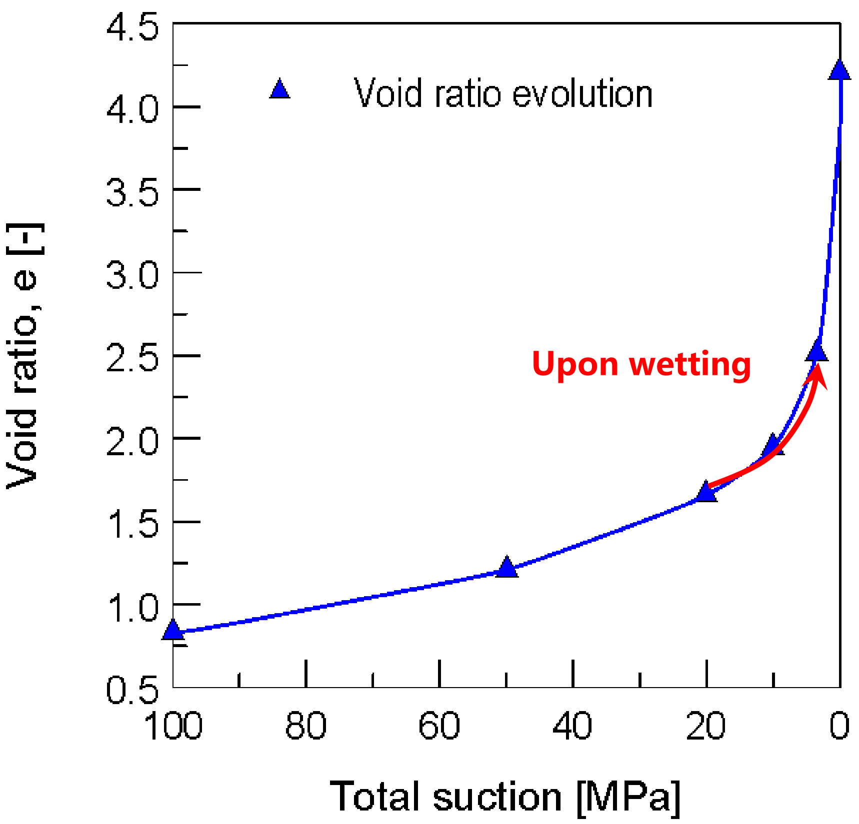




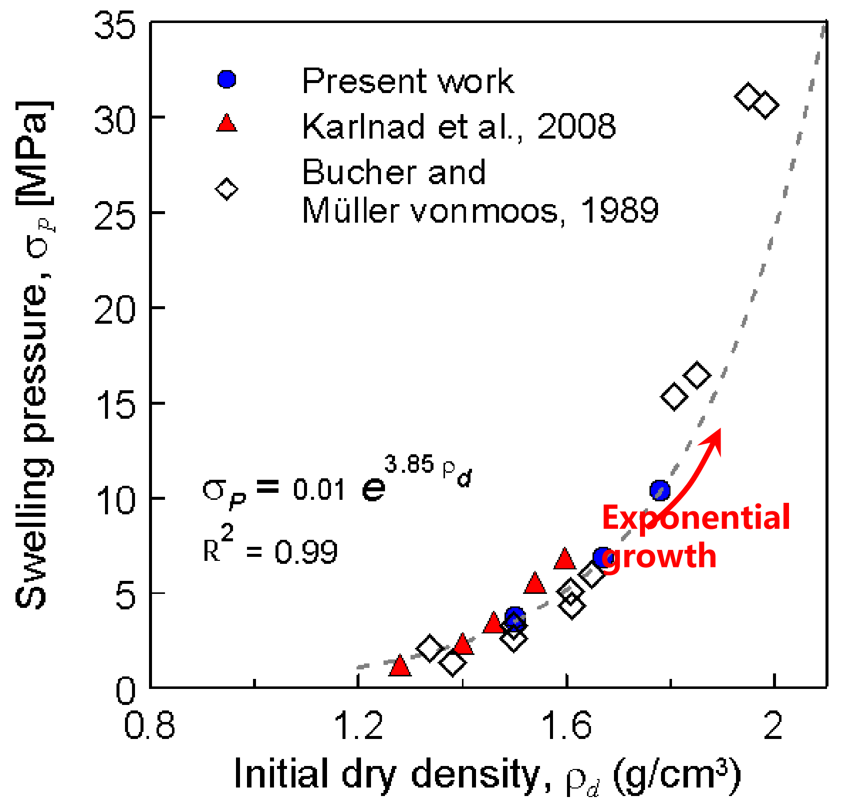
MX-80 Bentonite – Compaction and Swelling Behaviour



Free swelling test



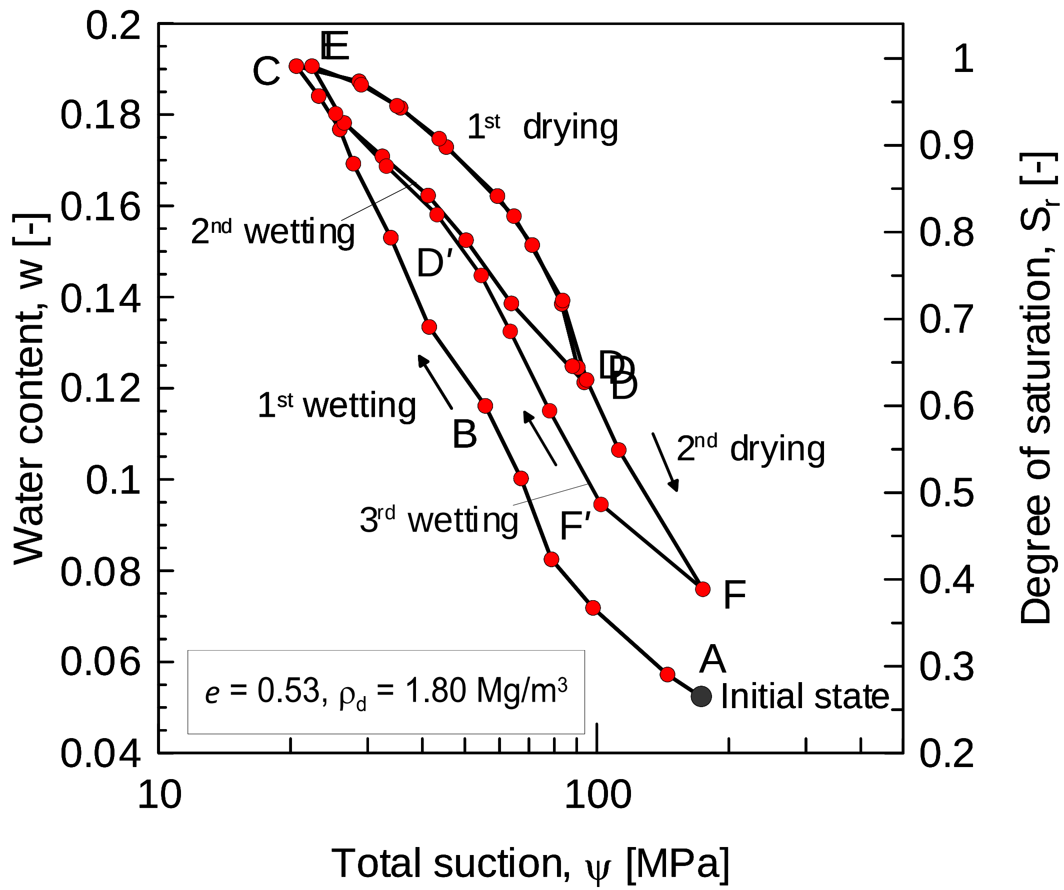
Constrained swelling test



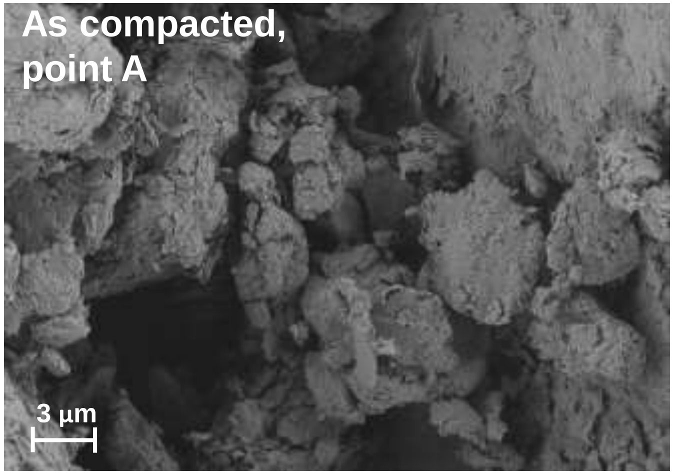
Swelling deformation up to **e = 4.2** and swelling pressures up to **10 MPa** at e = 0.53 (r_d = 1.80 Mg/m^3)

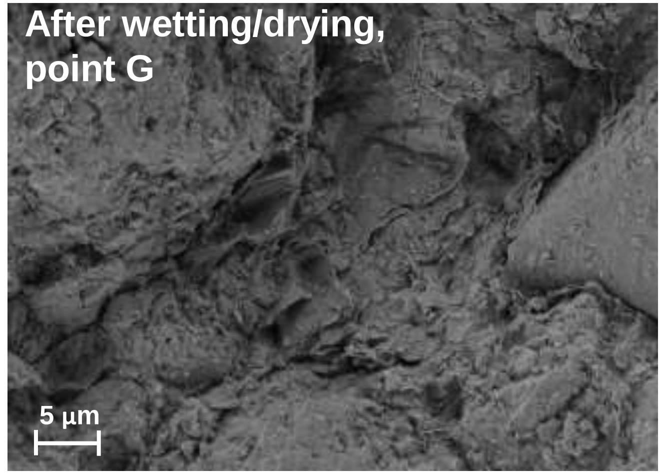
Wetting/drying cycles

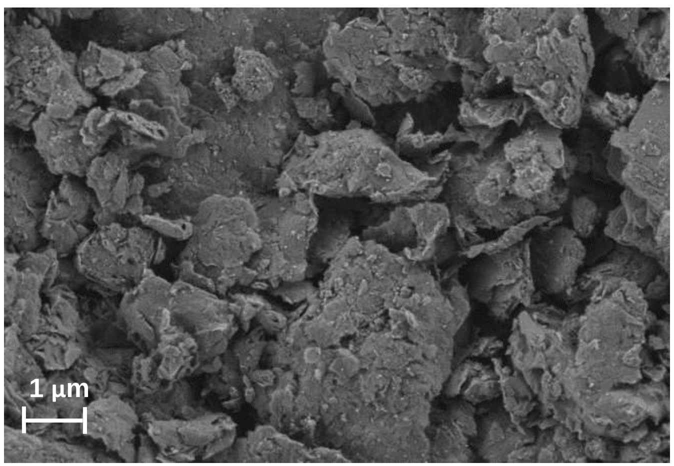
- ✓ Significant and irreversible change in water retention behaviour
- ✓ New hydraulic domain by creating a new wetting path
- ✓ Increase of the retention capacity

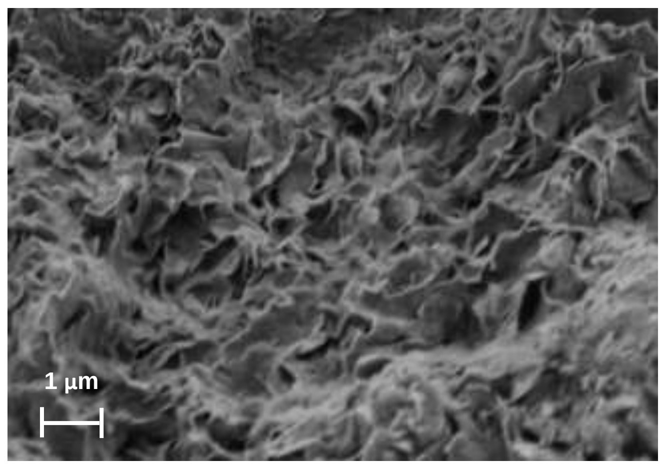


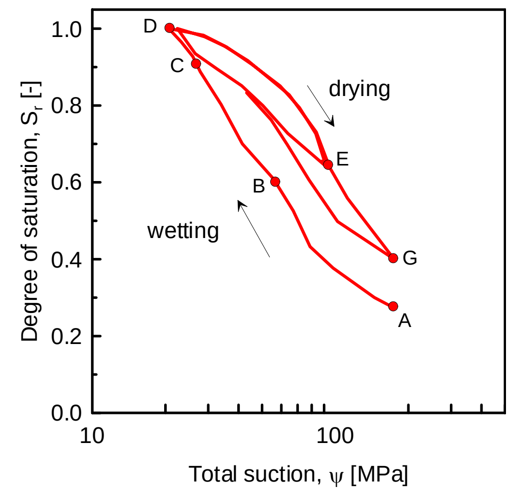
SEM analysis and the influence of wetting/drying on the fabric











Significant change of the fabric after wetting/drying cycle

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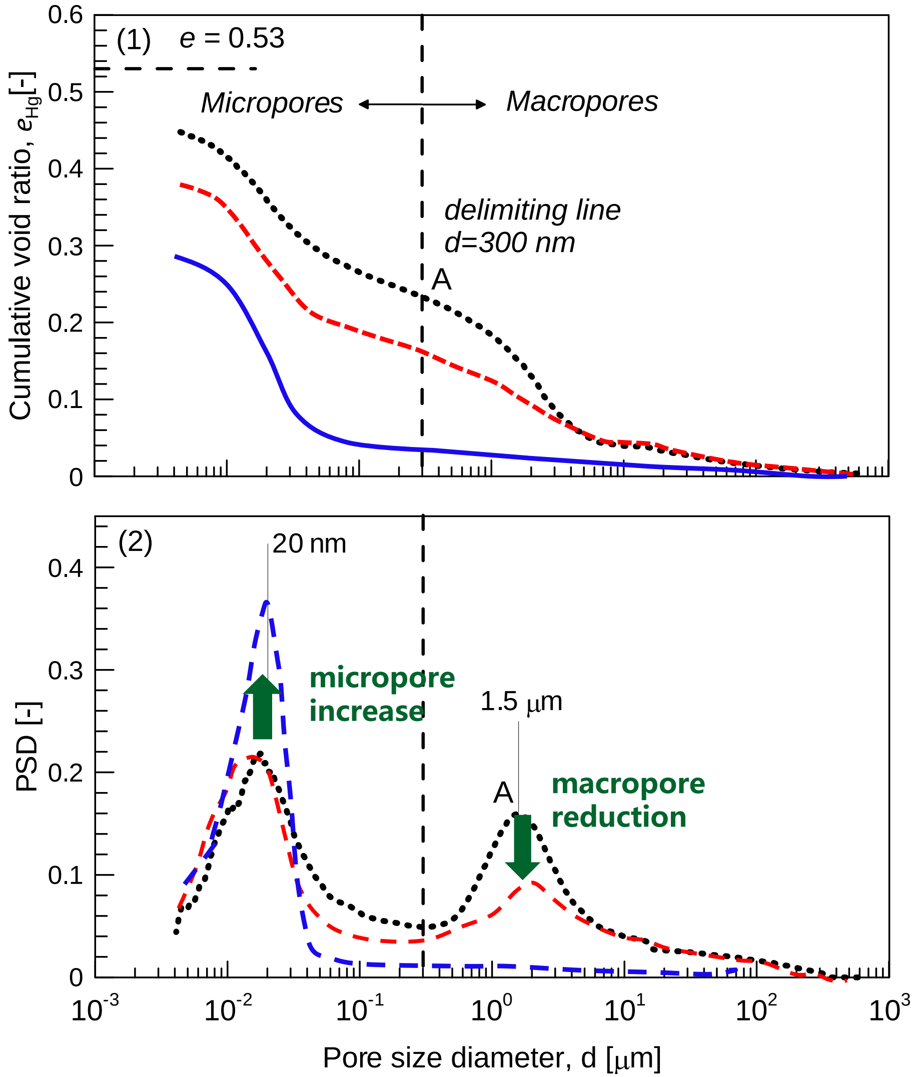
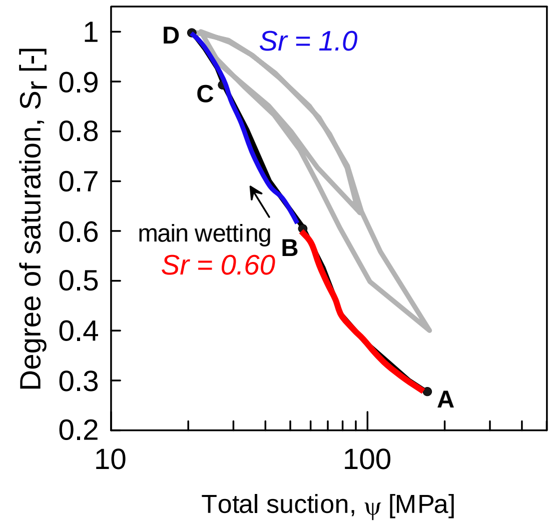
MIP analysis and the influence of wetting/drying on the fabric

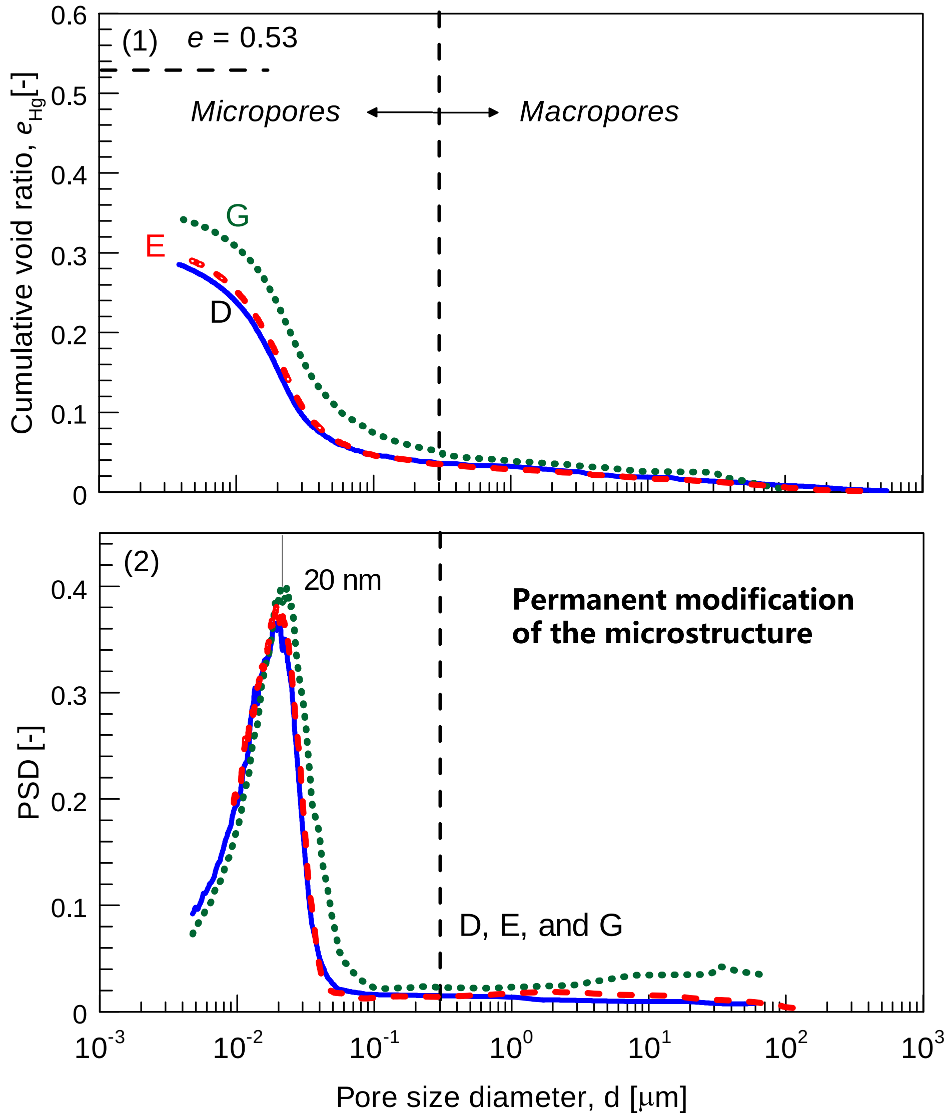


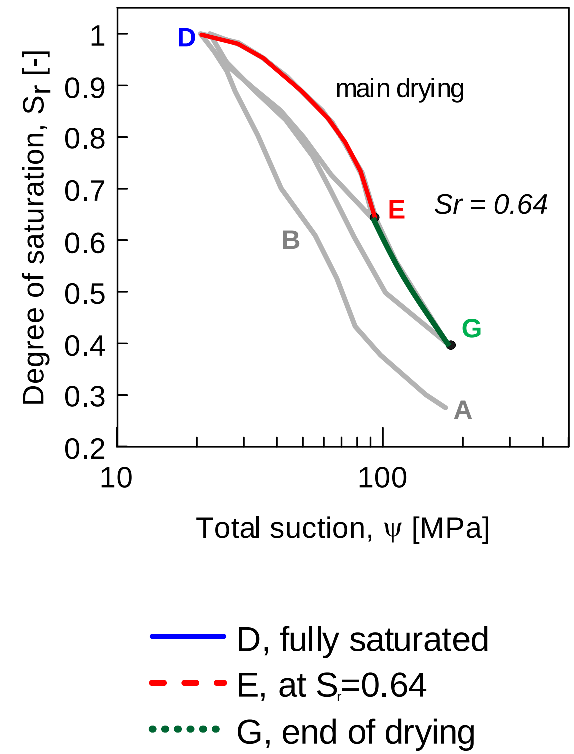


A, as compacted
B, at S_r = 0.60
D, fully saturated

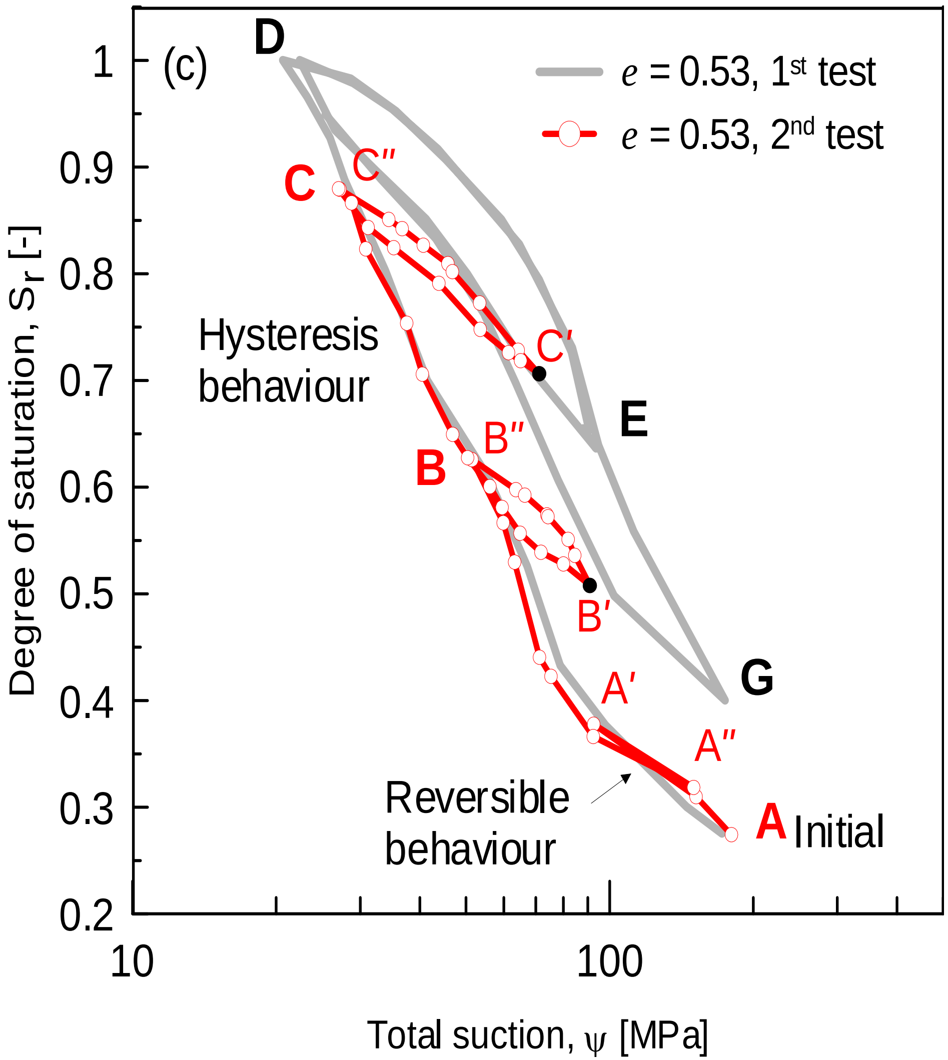
Decomposition of the total void ratio: $e = e_m + e_M$

MIP analysis and the influence of wetting/drying on the fabric





Wetting/drying before the fully saturation of the specimen



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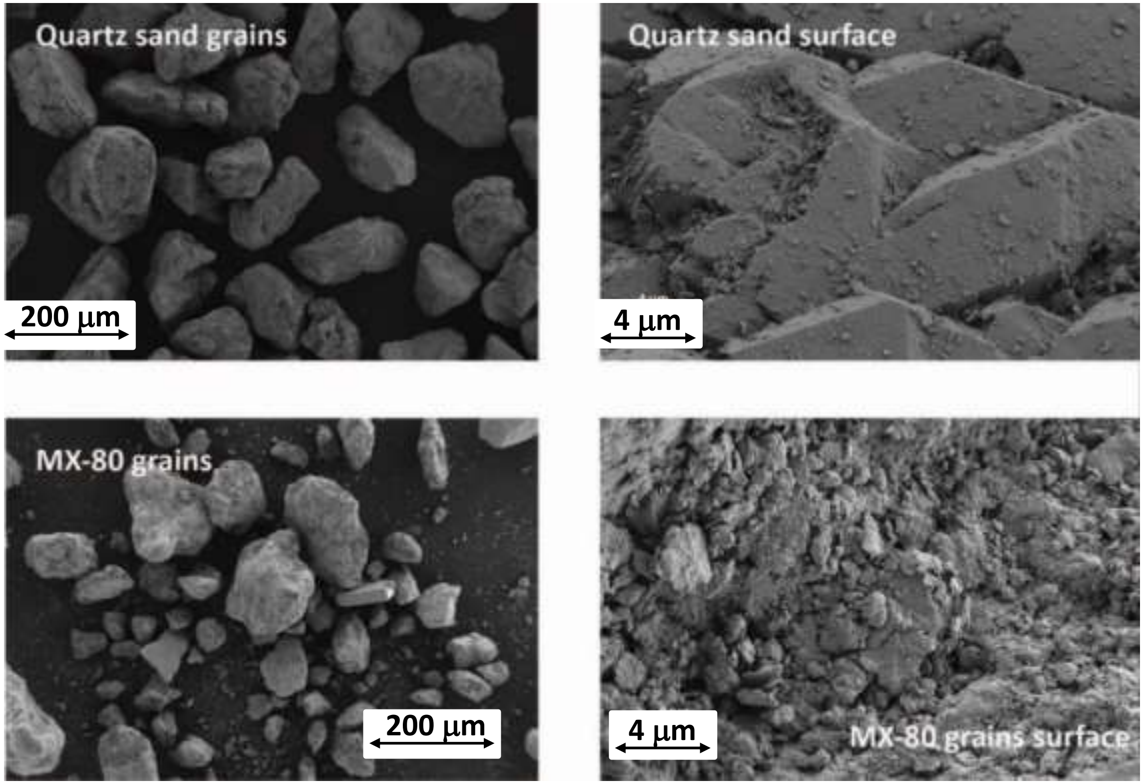
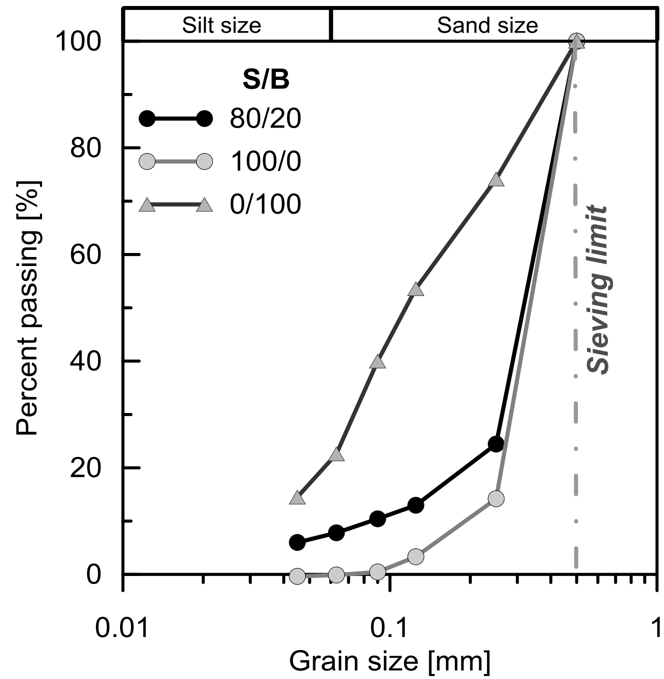
80/20 Sand/Granular Bentonite Mixture:



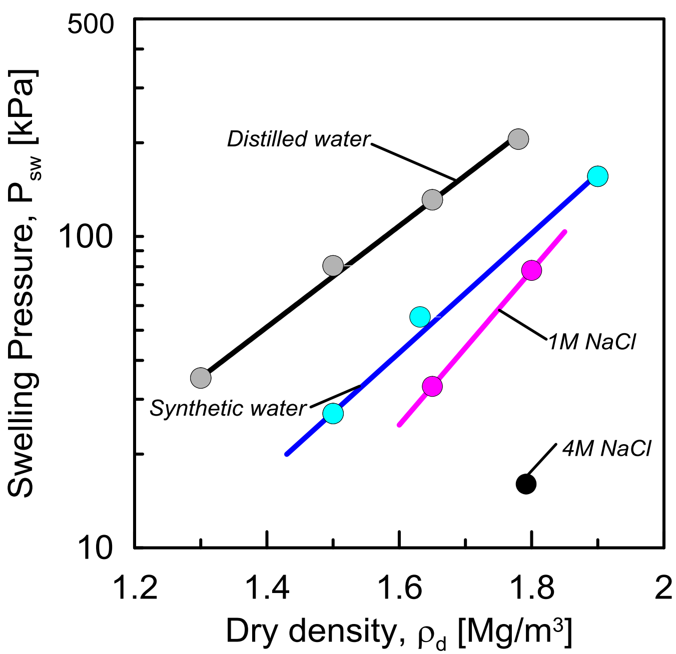


Properties	Sand	MX-80	80/20 S/B
Particle density, ρ_s [Mg/m^3]	2.65	2.74*	2.67
Liquid limit,	-	420*	81‡
Plastic limit,	-	65*	23.5‡
Smectite content	-	85%†	17%
Specific surface area, S [m^2/g]	0.003	523†	-

Manca, Ferrari and Laloui (2016)

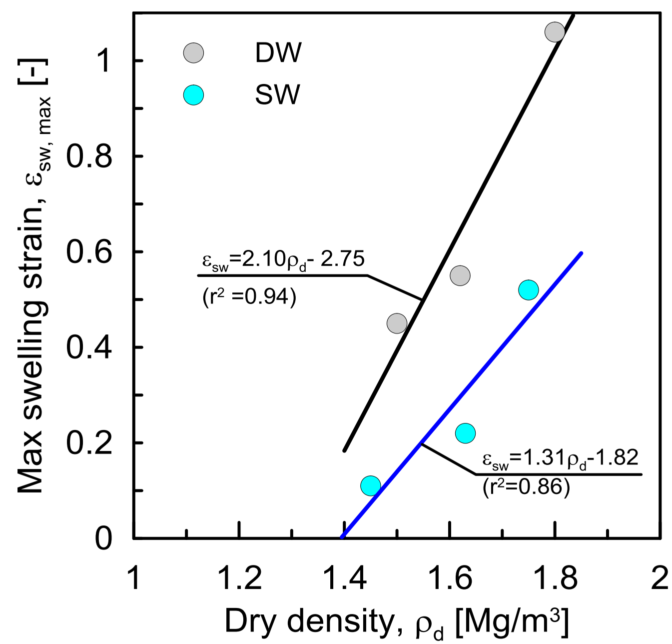
MX-80 Bentonite with Quartz Sand – Swelling Capacity

Constrained swelling test



- ✓ Exponential increment of P_{sw}
- ✓ P_{sw} reduction in the range of 67% - 45% for the dry density in the range of 1.3 - 1.9 g/cm^3 when the mixture is in contact with SW
- ✓ P_{sw} reduction in the range of 75% - 65% for the dry density in the range of 1.5 - 1.8 g/cm^3 when the mixture is in contact with sodium chloride 1M

Free swelling test



- ✓ Linear increment of the swelling deformation with dry density for both type of waters
- ✓ ε_{sw} reduction in the range of 80% - 40% for the dry density in the range of 1.3 - 1.9 g/cm^3 when the mixture is in contact with synthetic water

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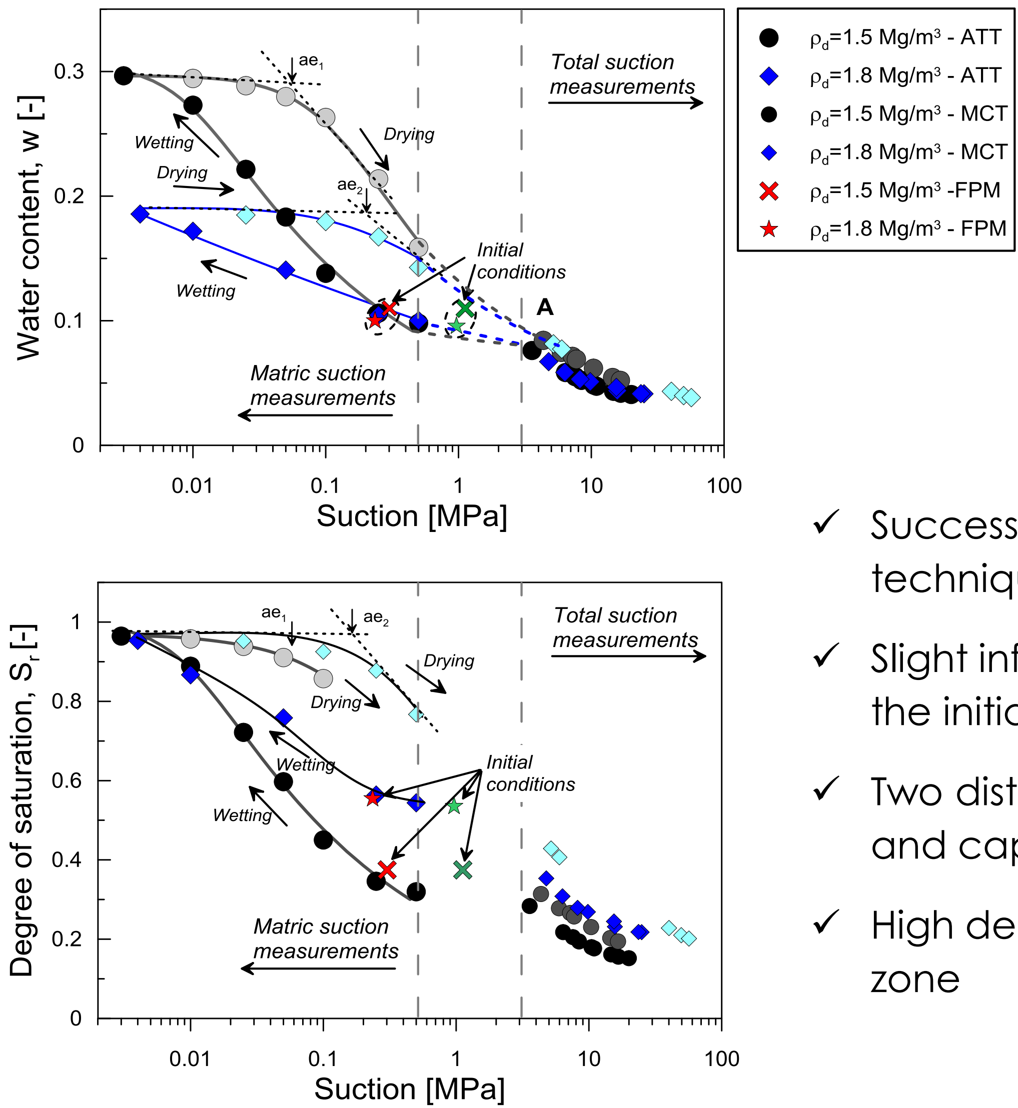
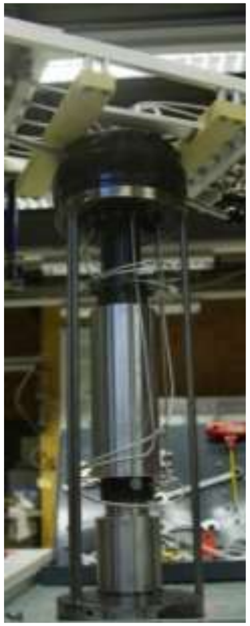
Water retention capacity with distilled water: two dry densities



- ✓ Successful combination of three experimental techniques
- ✓ Slight influence of the compaction density on the initial suction (as-compacted state)
- ✓ Two distinct regions of retention: Adsorption and capillary
- ✓ High density dependence on the low suction zone

THM characterization using triaxial system

Applications and features

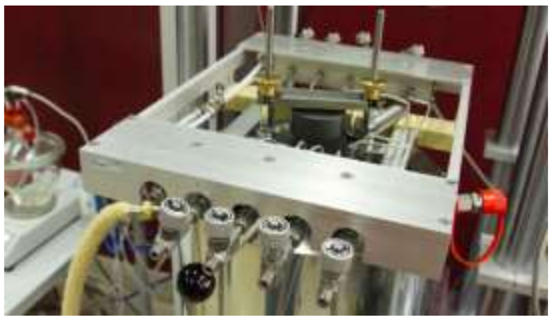


Inner cell system for specimen volume change assessment

At each base :
- Air flushing
- Water flushing
- Pore air pressure control
- Pore ***water pressure*** control
- ***water volume*** change measurement

Double PV controller for
- ***outer cell*** pressure control
- ***Inner cell*** pressure control
- inner cell ***volume change measurement***

2 PV controllers for the independent control of the pwp at the two bases



- ✓ Temperature control (4 – 150°C)
- ✓ Maximum confining pressure up to 30 MPa
- ✓ Maximum axial force up to 450 kN (orresponding to 230 MPa axial stress on sample 100x50 mm)
- ✓ Integrated system for matric and total suction control (0 – 1.5 MPa, 4 – 400 MPa)
- ✓ Independent volume/pressure controllers for top and bottom of the sample (permeability measurement)
- ✓ Swelling pressure measurement in constant volume condition
- ✓ Possibilty of installation of several loacal LVDTs inside the cell

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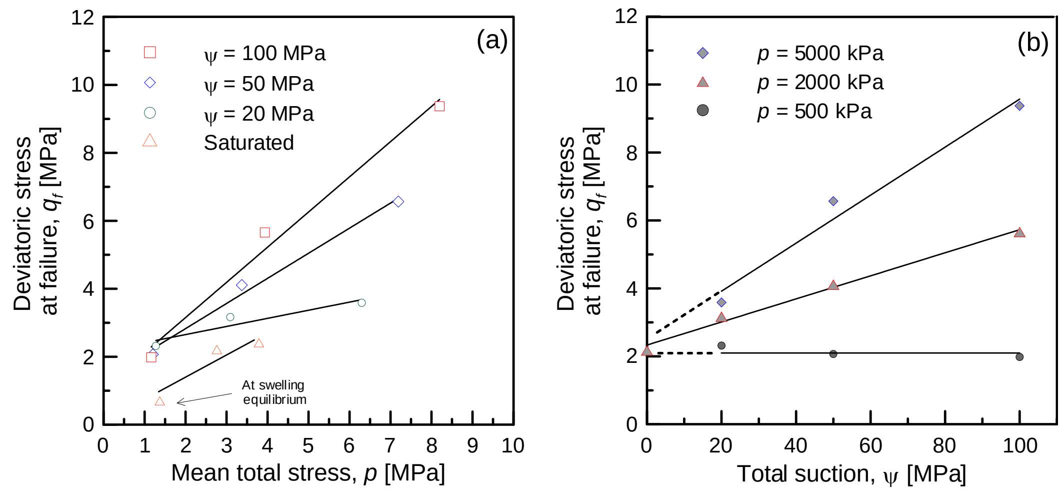
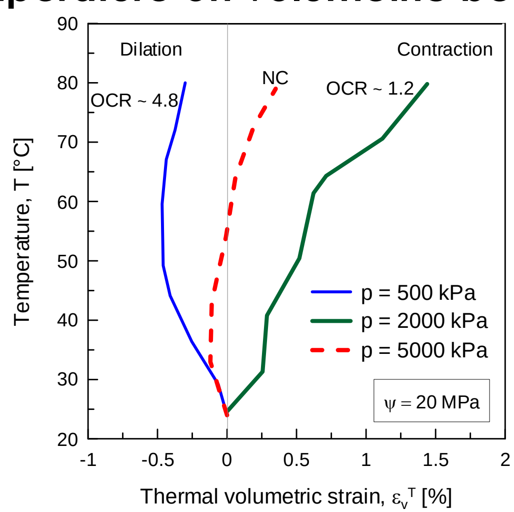
Deviatoric response for saturated and unsaturated conditions

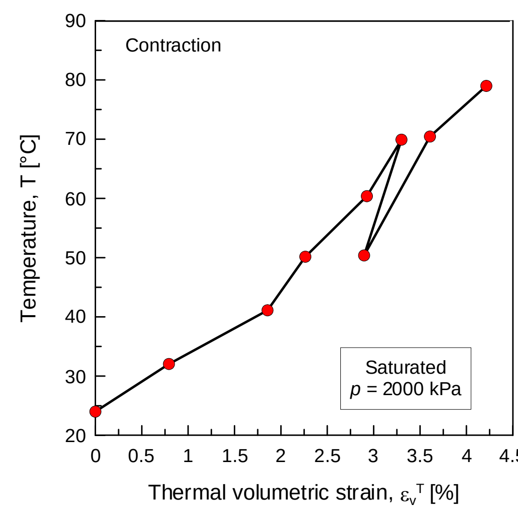
Seiphoori (2014)



Influence of temperature on volumetric behaviour of unsaturated and saturated material



† Unsaturated condition after isotropic mechanical compaction



† Saturated condition after isotropic mechanical consolidation

Summary and conclusion

- LMS-EPFL performed detailed characterization studies on different bentonite-based materials (MX-80 Granular Bentonite, MX-80/Sand mixtures, Shot-clay)
- The experimental work focused a wide range of tests including microstructure analysis, water retention response and coupled Thermo-Hydro-Mechanical aspects.
- Some interesting outcomes:
  - ✓ Microstructural observations at different points along the water retention domain provide insights on the behaviour of active clays. Significant change in water retention behaviour of compacted bentonite after first saturation due to the pore structure evolution
  - ✓ The swelling properties of sand-bentonite mixture can be defined from bentonite properties and bentonite fraction.

Thank you for your attention

- A. Seiphoori, A. Ferrari and L. Laloui. *Water retention behaviour and microstructural evolution of MX-80 granular bentonite during wetting and drying cycles,* in Geotechnique, vol. 64(9), p. 721-734, 2014.
- L.M. Keller, A. Seiphoori, P. Gasser, F. Lucas, L. Holzer and A. Ferrari. *The pore structure of compacted and partly saturated MX-80 bentonite at different dry densities*, in Clays and Clay Minerals, vol. 62(3), p. 174-178, 2014.
- A. Seiphoori, A. Ferrari, J. Rüedi, and L. Laloui. *Shot-clay MX-80 bentonite: An assessment of the hydro-mechanical behavior,* in Engineering Geology, vol. 173, p. 10-18 (2014).
- A. Seiphoori, *Thermo-hydro-mechanical characterisation and modelling of MX-80 granular bentonite*, PhD Thesis, EPFL n° 6159, 2014.
- D. Manca, A. Ferrari and L. Laloui. *Fabric evolution and the related swelling behaviour of a sand/bentonite mixture upon hydro-chemo-mechanical loadings,* in Geotechnique, vol. 66, num. 1, p. 41-57, 2016.