Effects of heterogeneities on the hydromechanical behaviour of bentonite-based engineered barriers: Results and current works at Laboratoire Navier

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I – Context

Radioactive waste disposal:

French concept (ANDRA):

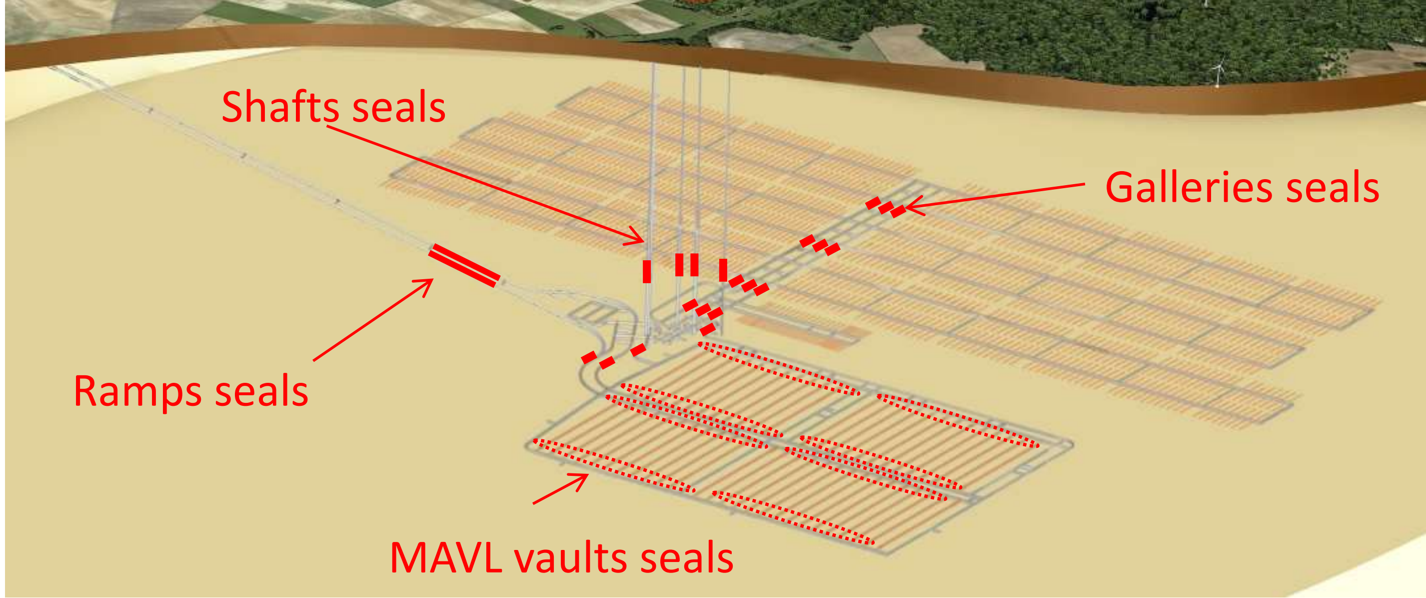
Compacted bentonite-based materials used as engineered barrier (swelling potential, retention capacity, low permeability)

Saturation from the host rock pore water:

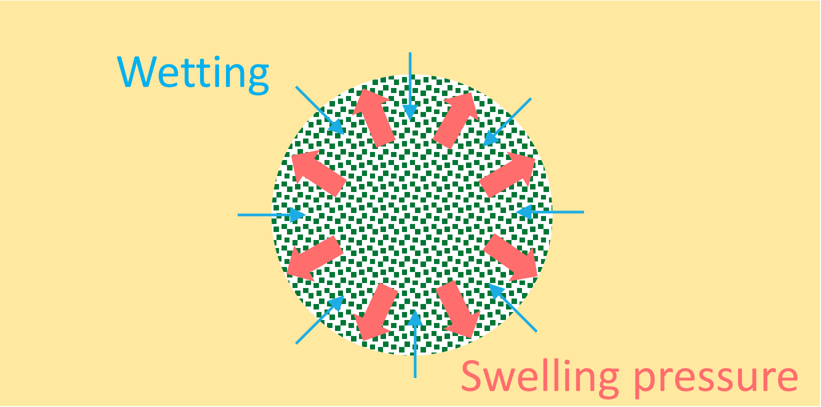
Swelling pressure develops against host rock

Study of hydromechanical behaviour upon hydration (suction decrease) at laboratory scale:

Hydration tests



French radioactive waste disposal concept. In red: sealing plugs made of bentonite-based materials (ANDRA).



Swelling of bentonite-based engineered barrier upon hydration

Contents

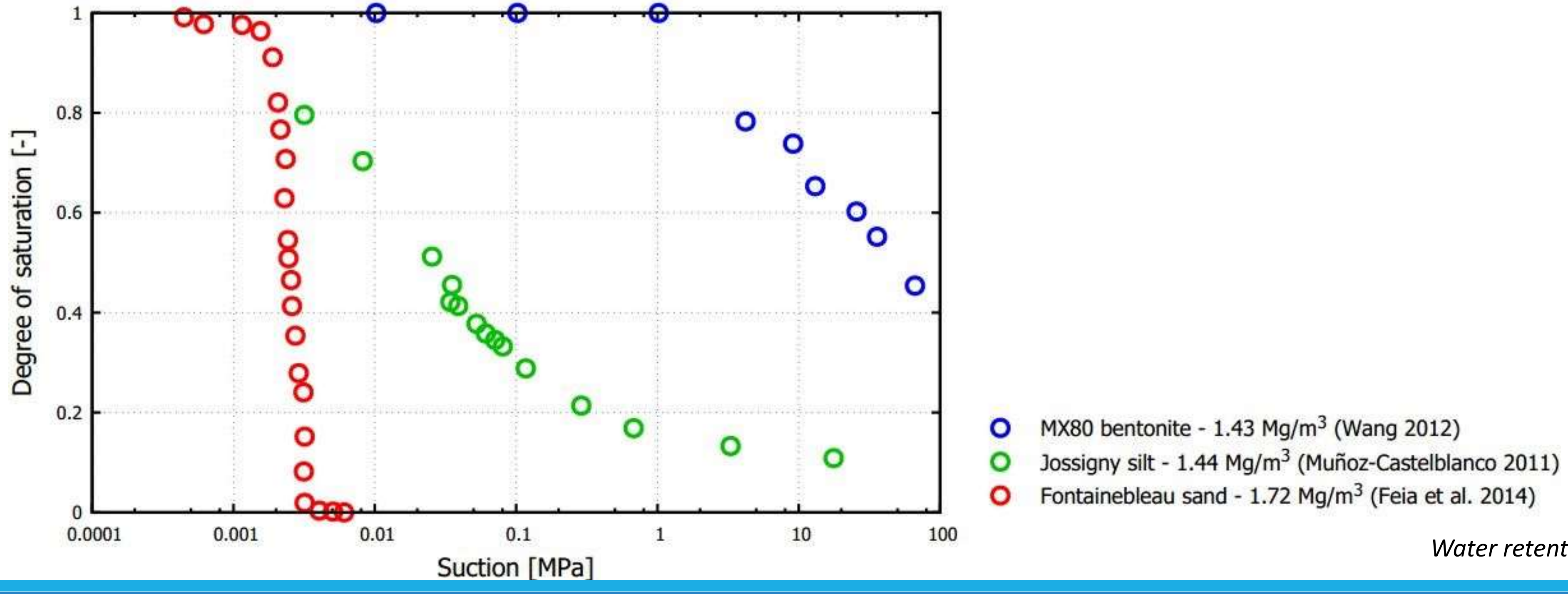
II – Control of suction

Hydration at laboratory scale:

Hydration: vapour phase

Controlling suction allows the material behaviour to be studied during hydration transient stages

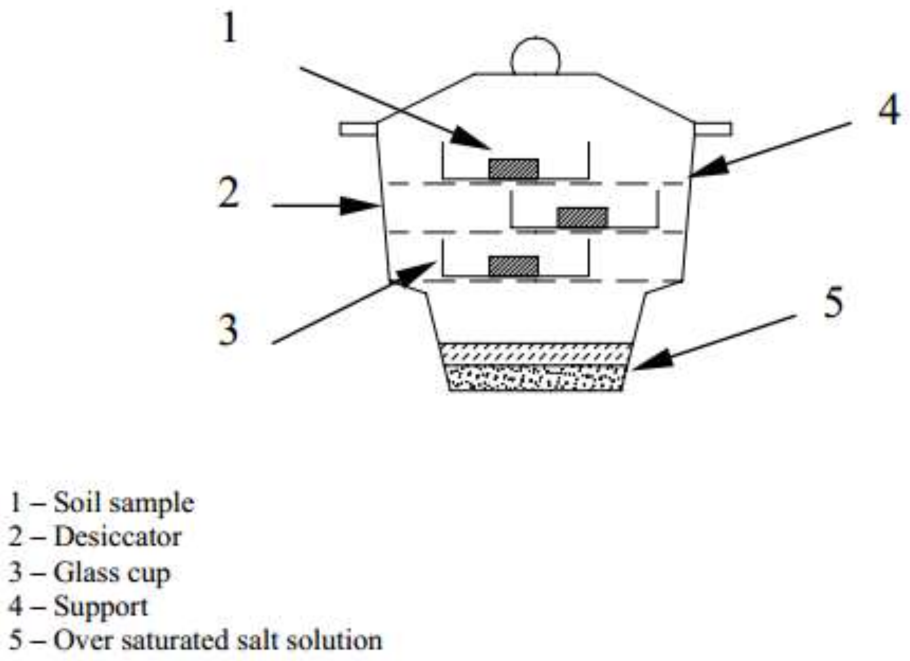
Highly compacted bentonite: Saturated at high suction values in constant volume conditions



Water retention curves of three soil samples.

II – Control of suction

Vapour equilibrium technique:



Imposing suction by imposing relative humidity in a dessiccator (Tang, 2005)

Soil sample in a dessiccator

Salt	Relative humidity (%)
$Mg(NO_3)_2$	55
NH_4NO_3	65
$NaNO_2$	66
$NaNO_3$	75
NaCl	76
Na_2CO_3	91
KNO_3	93
K_2SO_4	97

Relative humidity imposed by some salts at T = 20°C. After Delage et al., 1998.

II – Control of suction

Kelvin's law:

$$s = \frac{\mathrm{RT}}{\mathrm{Mg}} \ln(\mathrm{RH})$$

Relates the relative humidity to suction, at constant temperature

Salt	Relative humidity (%)	Suction (MPa)
$Mg(NO_3)_2$	55	82
NH_4NO_3	65	59
$NaNO_2$	66	57
$NaNO_3$	75	40
NaCl	76	38
Na_2CO_3	91	13
KNO_3	93	9
K_2SO_4	97	4

- s: suction;

- R: constant of perfect gases;

- T: absolute temperature;

- M: molar mass of water;

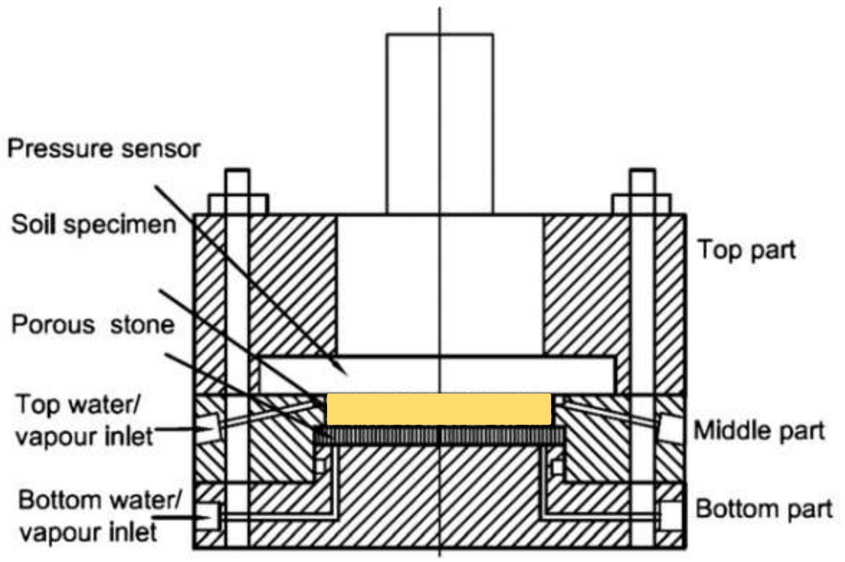
- g: gravity acceleration;

- RH: relative humidity

II – Control of suction

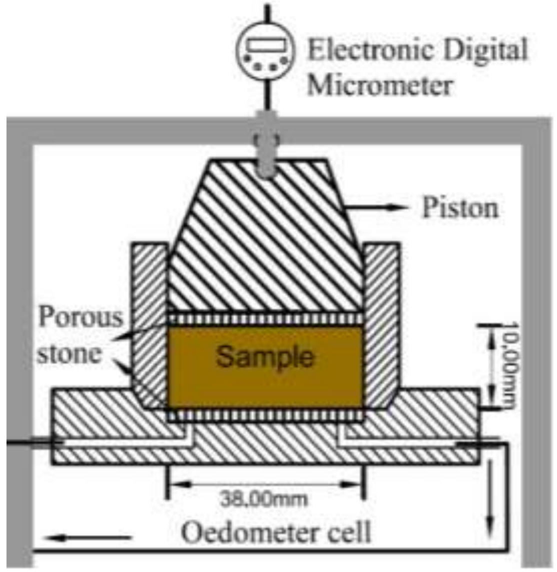
Examples of application :

Constant-volume cell:



Wang, 2012

Suction-controlled oedometer:



Wang, 2012

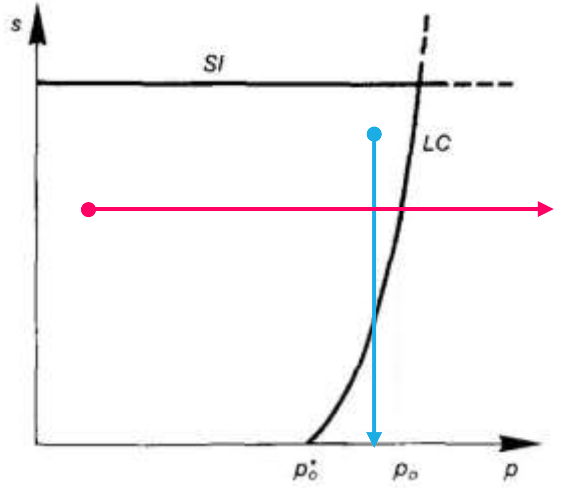
II – Control of suction

Examples of application :

Hydromechanical behaviour of soils:

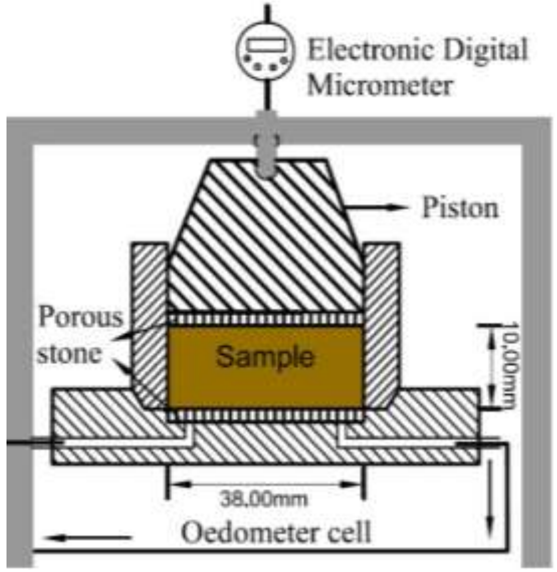
Mechanical loading at constant suction

Wetting/Drying at constant load



Barcelona Basic Model (after Alonso et al. 1990)

Suction-controlled oedometer:

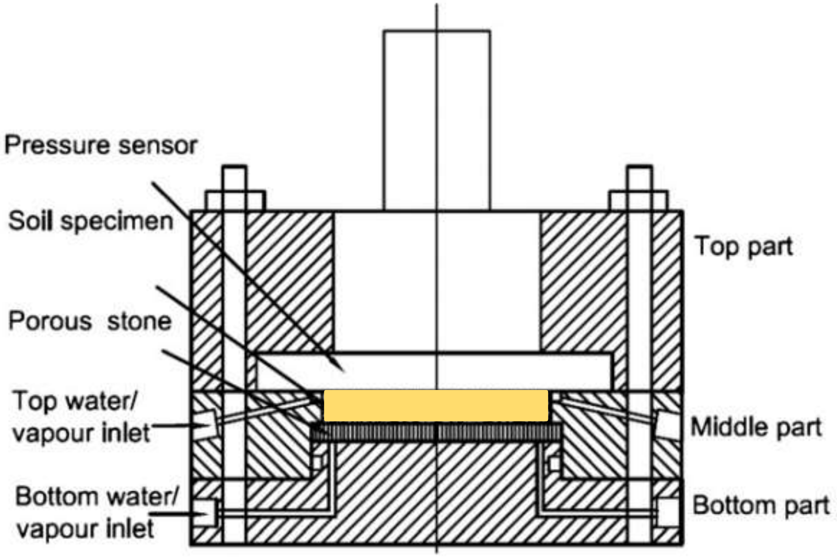


Wang, 2012

II – Control of suction

Examples of application :

Constant-volume cell:



Wang, 2012

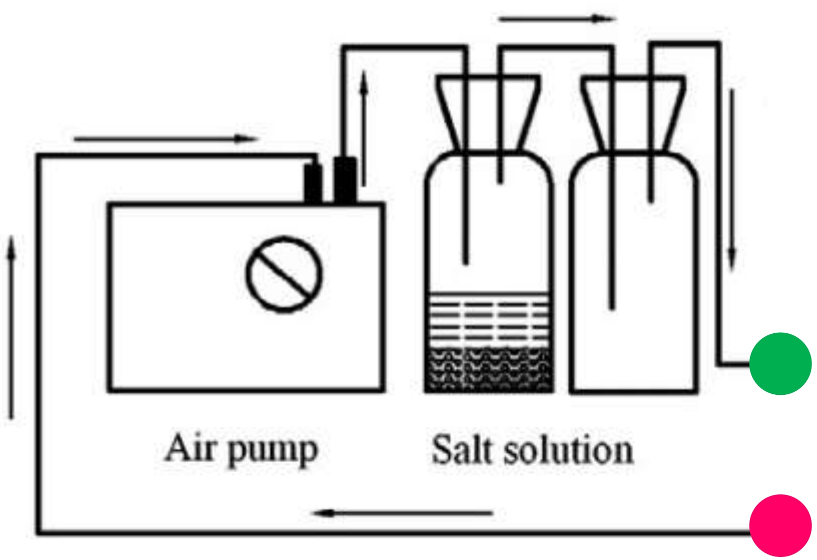
Hydration: Swelling prevented

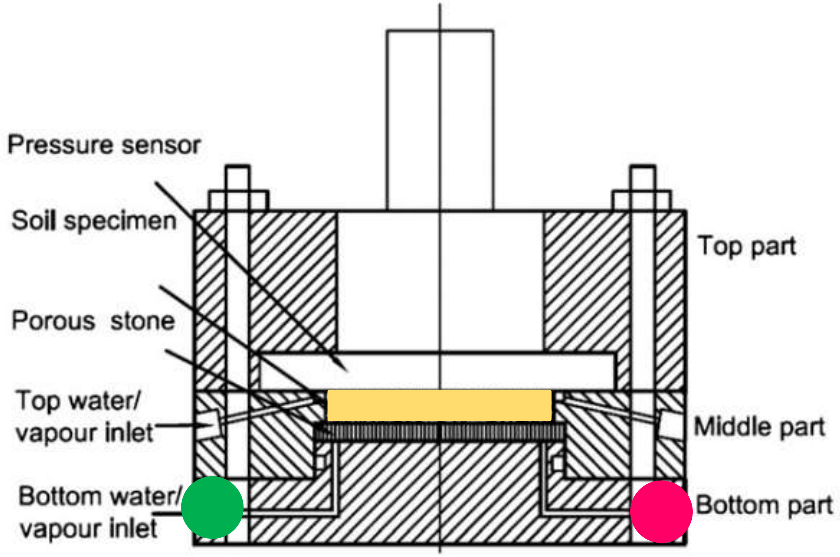
Axial pressure sensor: Swelling pressure measurement

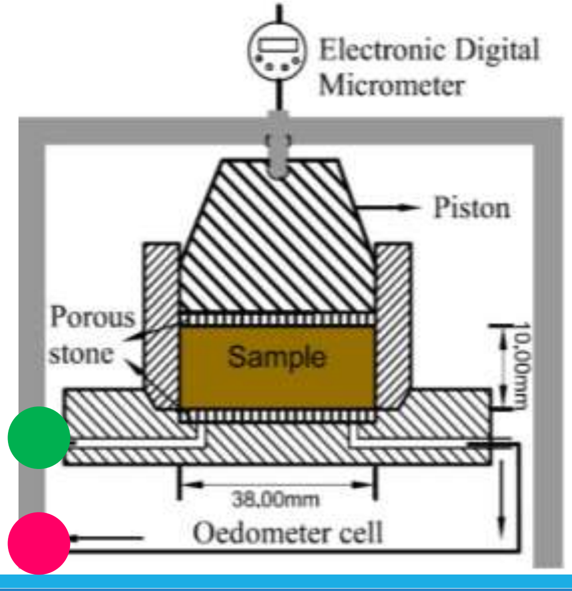
II – Control of suction

Examples of application :

Vapour equilibrium technique: Suction control







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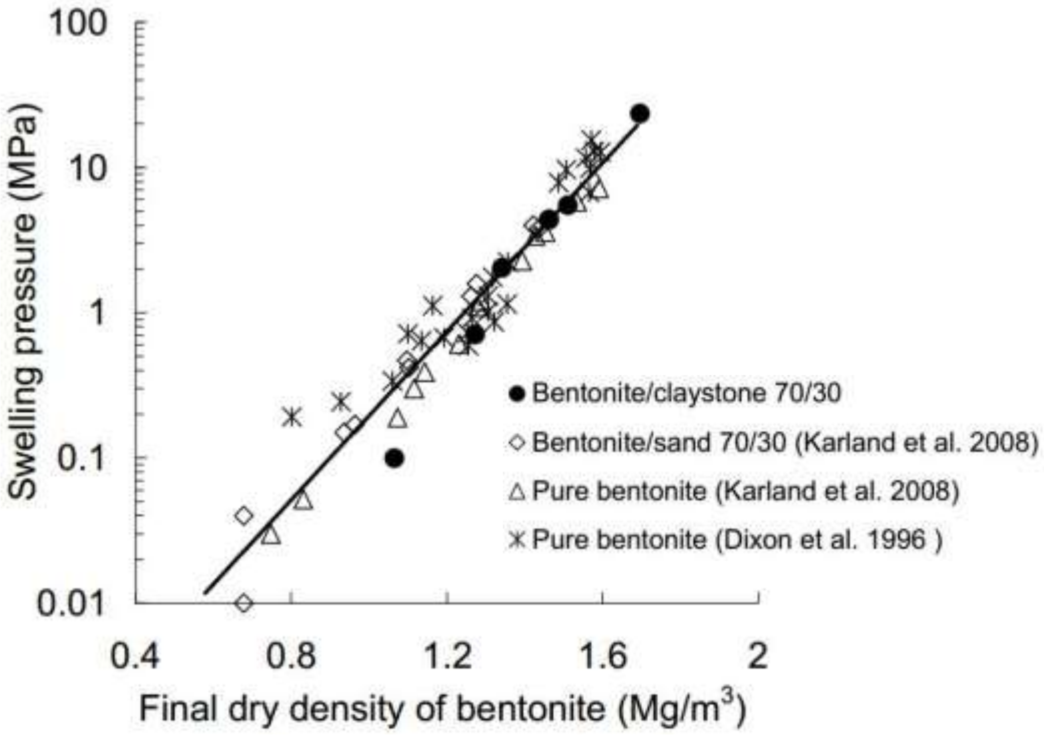
III – Swelling pressure of bentonite

Swelling pressure :

Same relationship for pure bentonite, sand/bentonite mixtures; claystone/bentonite mixtures



$$\rho_{db} = \frac{B\ \rho_m G_{si} \rho_w}{G_{si}\rho_w(1 + w_m) - \rho_m(1 - B)}$$

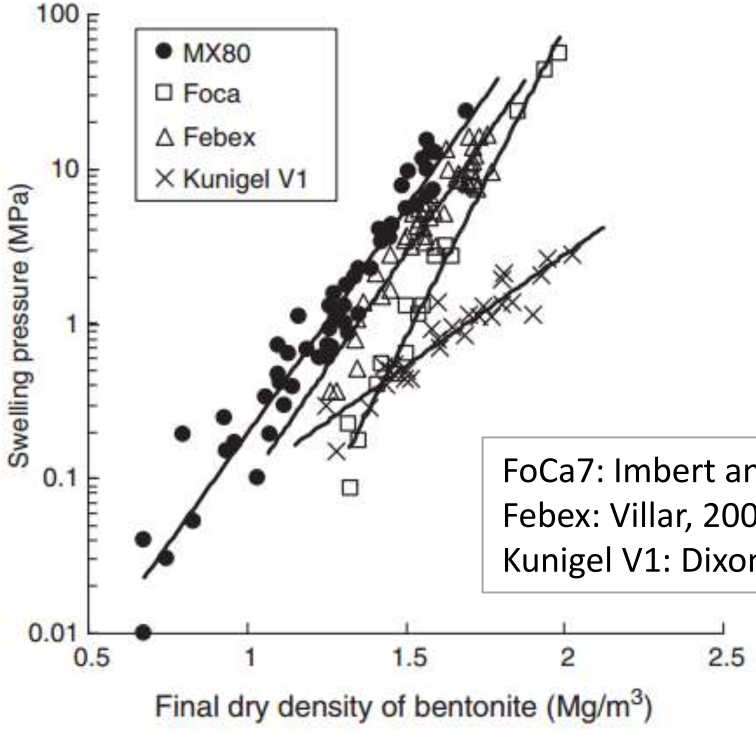
ρ_{db}: final dry density of bentonite
B: bentonite content in dry mass
ρ_m: unit mass of the mixture
G_{si}: specific gravity of material i (sand, claystone…)
w_m: water content of the mixture
ρ_w: water unit mass

Relationship between swelling pressure and bentonite final dry density (Wang, 2012)

III – Swelling pressure of bentonite

Swelling pressure :

Relationship between swelling pressure and final bentonite dry density



FoCa7: Imbert and Villar, 2006
Febex: Villar, 2002
Kunigel V1: Dixon et al., 1996

$$\sigma_s = \alpha \exp(\beta \rho_{db})$$

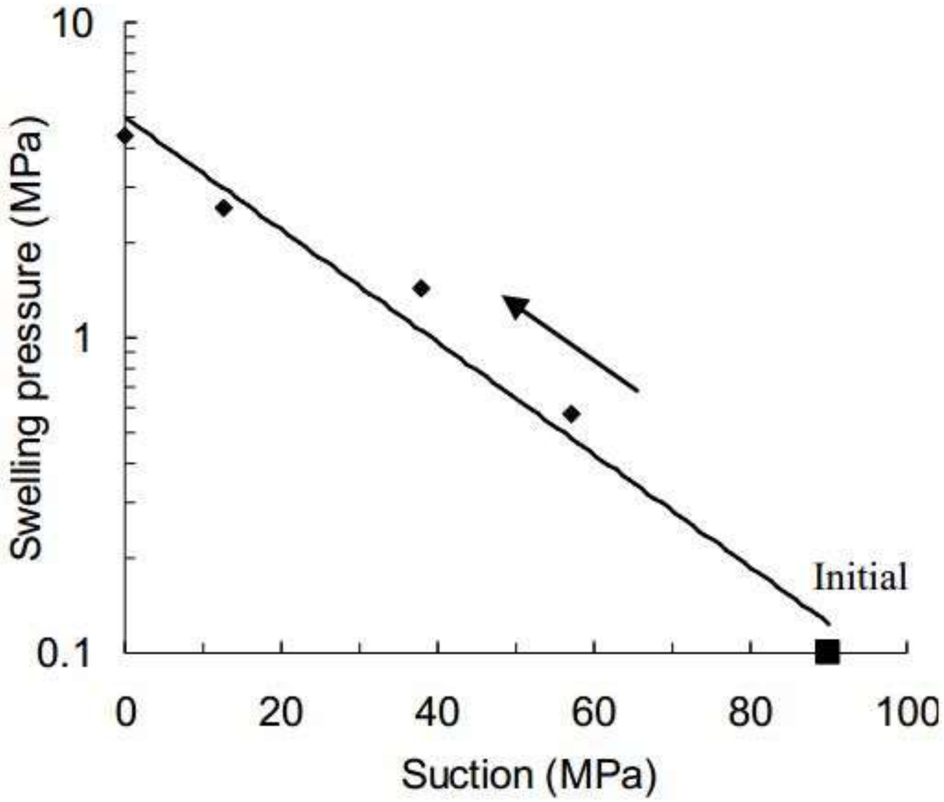
Bentonite	A	β	Montmorillonite Content (%)	Type
MX 80	1.78×10^{-4}	6.75	75–90	Na
FEBEX	9.80×10^{-5}	6.85	92	Ca
FoCa	7.83×10^{-7}	9.24	50 Beidellite 50 Kaollite	Ca
Kunigel V1	3.67×10^{-3}	3.32	48	Na

Relationship between swelling pressure and bentonite final dry density (Wang, 2012)

III – Swelling pressure of bentonite

Heterogeneities:

Constant volume conditions: Swelling pressure develops upon suction decrease



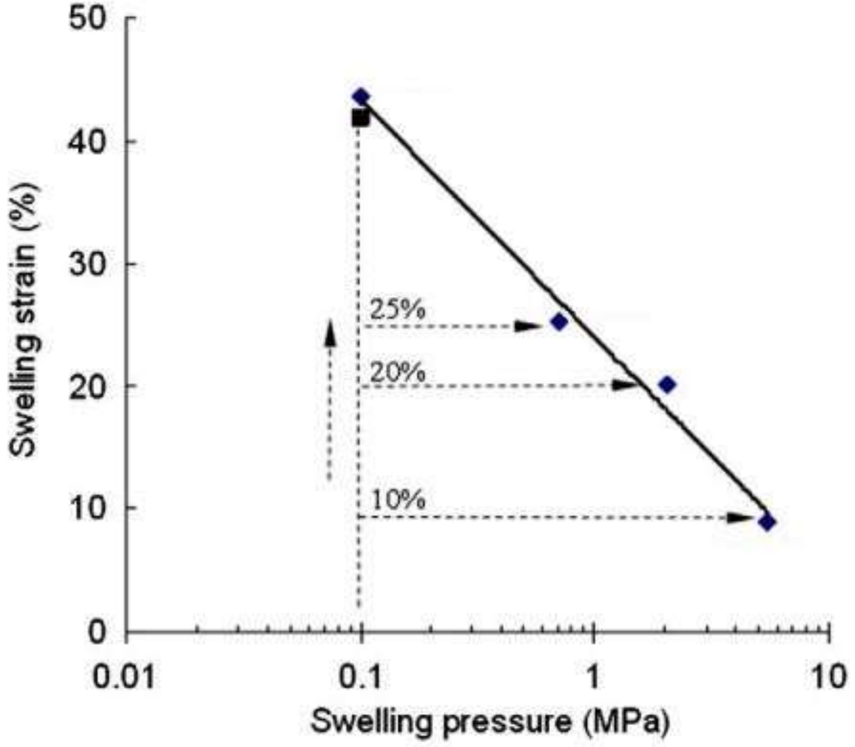
Swelling pressure test (Wang, 2012)

III – Swelling pressure of bentonite

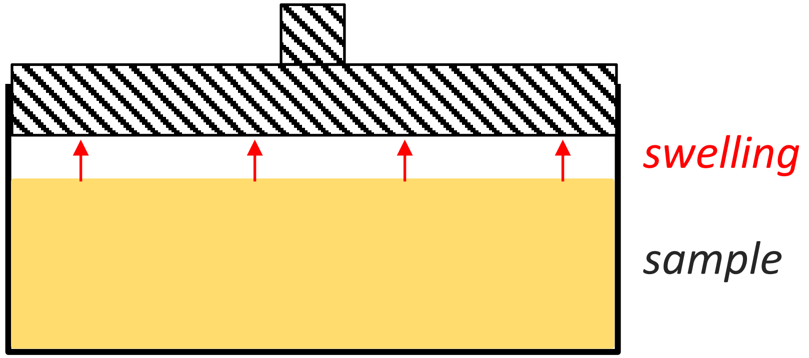
Heterogeneities :

Technological voids : Swelling does not occur in true constant-volume conditions

Dry density reduction: Influences the swelling pressure



Laboratory study:
Sample first allowed to swell freely, then constant volume conditions are applied and the swelling pressure is measured



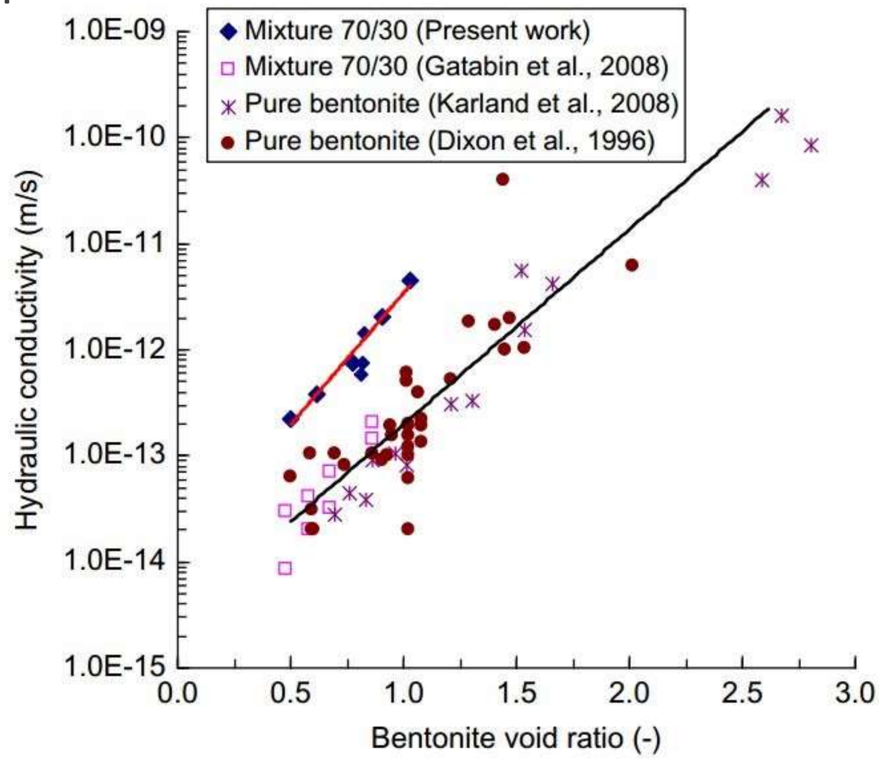
Relationship between swelling pressure and swelling strain allowed before constant-volume conditions. Initial dry density is 1.90 Mg/m^3 (Wang, 2012)

III – Swelling pressure of bentonite

Heterogeneities :

Technological voids : Heterogeneous density

Preferential flow pathways suspected



Relationship between hydraulic conductivity and final void ratio (Wang, 2012)

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IV – Pellets-powder mixtures

Candidate material for engineered barriers:

Reduction of technological voids

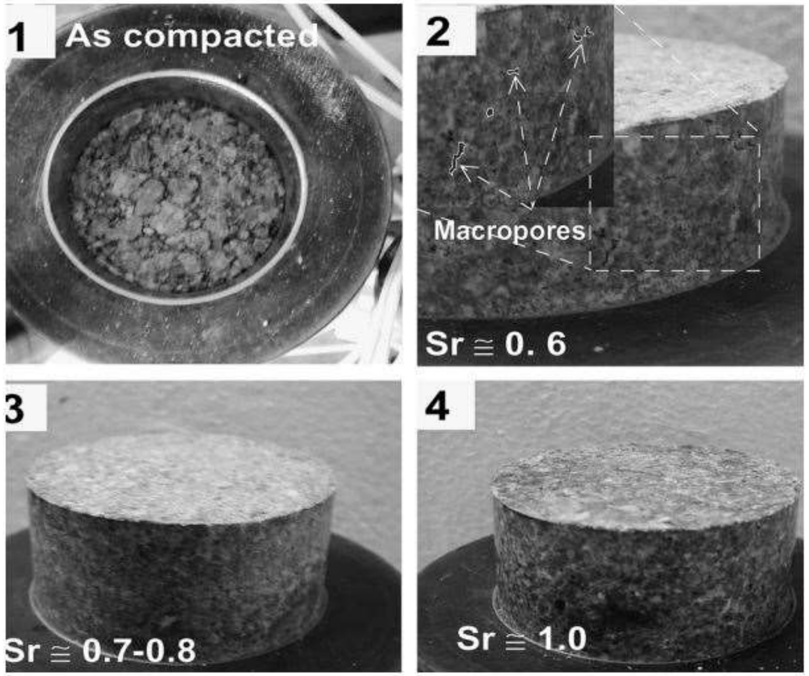
Compaction easier

Operational convenience

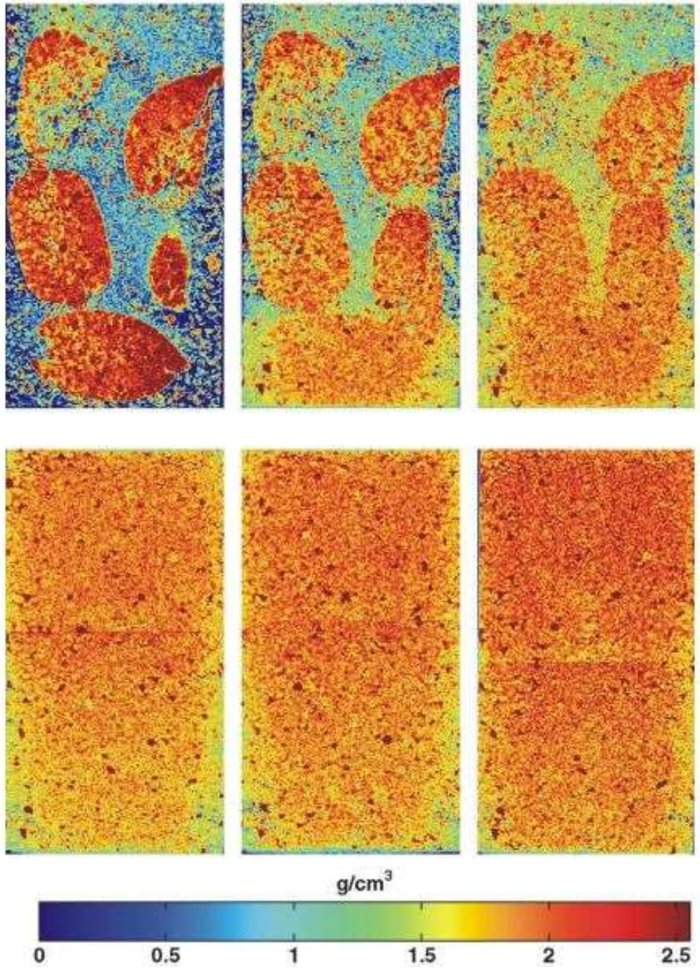
Upon hydration:

Homogenisation of the mixture

MX80-bentonite pellets-powder mixture



Evolution of a granular bentonite sample during hydration (Hoffmann et al. 2007)



Density variation upon hydration of a bentonite pellets-powder mixture. (van Geet et al. 2005)

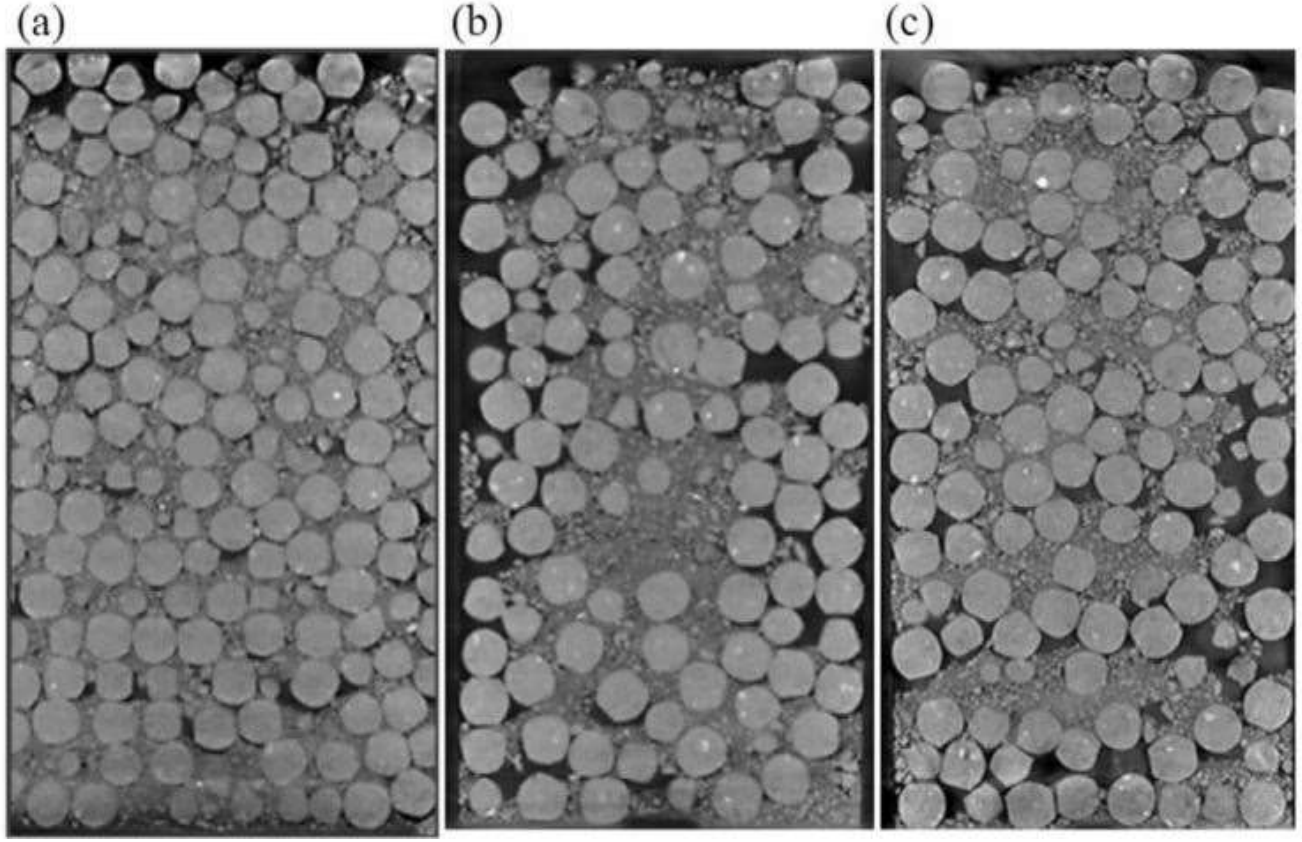
IV – Pellets-powder mixtures

Heterogeneities:

Heterogeneous distribution of pellets and powder in the samples (initial state)

Local rearrangements of the granular assembly during swelling

Hydro-mechanical behaviour of the mixture?



X-ray computed microtomography images of a mixture of bentonite pellets-powder mixture.
(a) One layer of pellets; powder
(b) Two layers of pellets; powder
(c) Pellets and powder previously mixed
(Molinero-Guerra et al. 2017)

Contents

V – Current works

Hydro-mechanical behaviour of bentonite pellets-powder mixture:

Swelling pressure tests:

- *Constant volume cells, suction controlled by vapour equilibrium technique,*
- *Influence of powder content,*
- *Test duration: >1 year*

DEM simulations:

- *Model hydration at high suction values (granular assembly) in the constant volume cell,*
- *Influence of local heterogeneities on swelling pressure at high suction values,*
- *Comparison with experimental results*

V – Current works

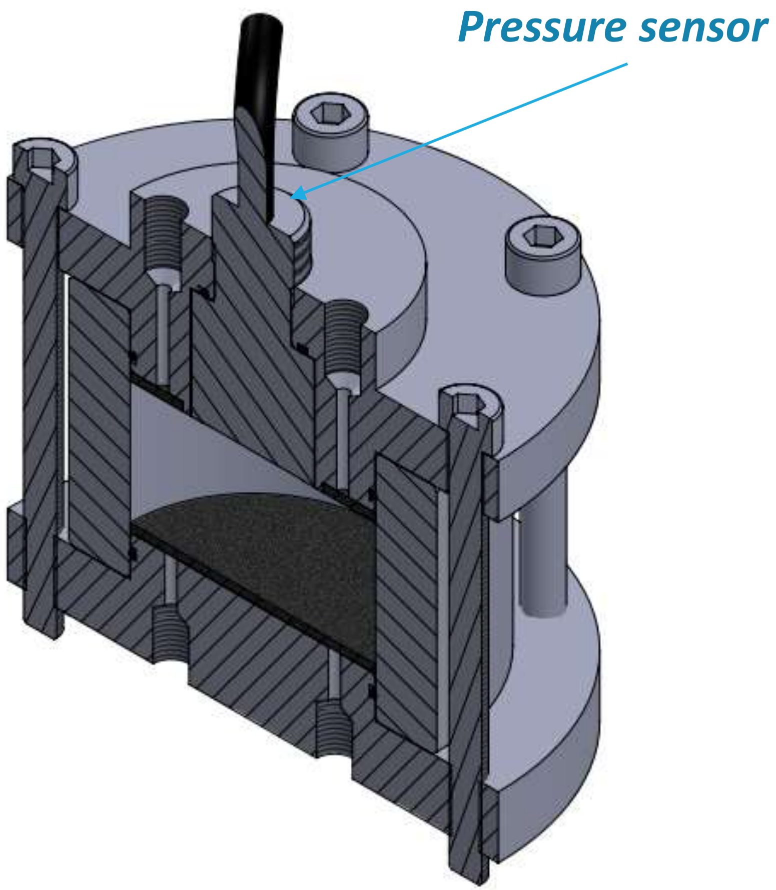
Experimental device:

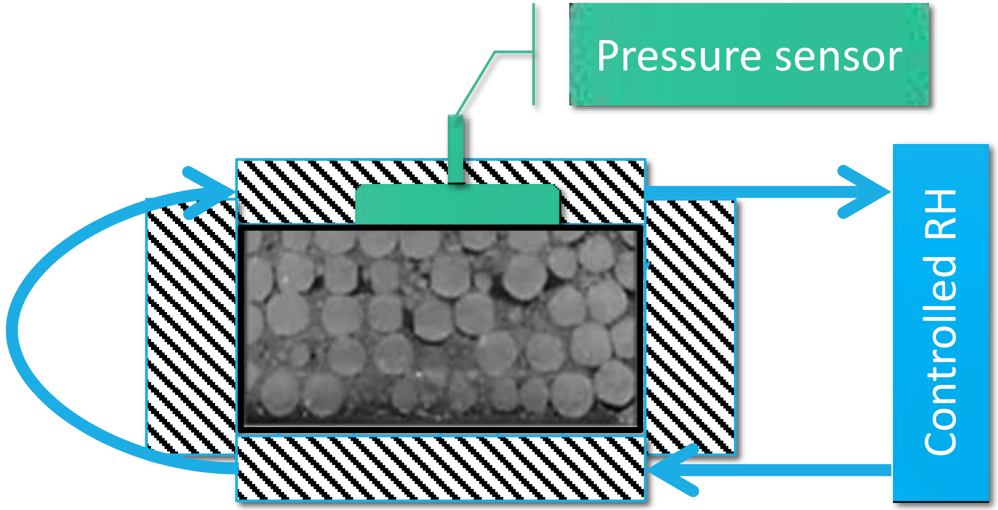
Pellets: sub-spherical, diameter 7 mm

Cell height: 30 mm; ~4 pellets layers
Cell diameter: 60 mm

Test duration: >1 year

Pressure sensor: measure swelling pressure upon suction decrease





V – Current works

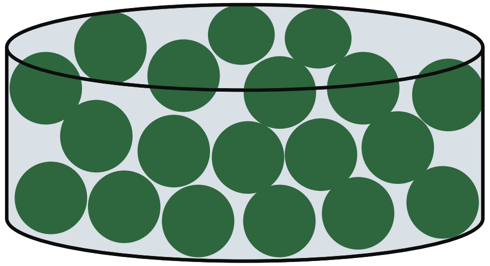
Discrete Element Method:

Pellets: beads in the simulations

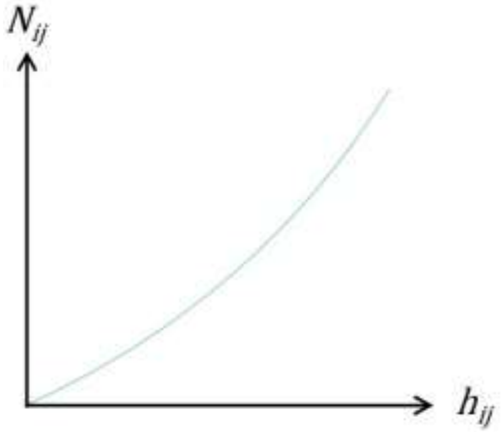
Swelling: impose a radius increase in the simulations

Hydration: reduce modulus in the simulations

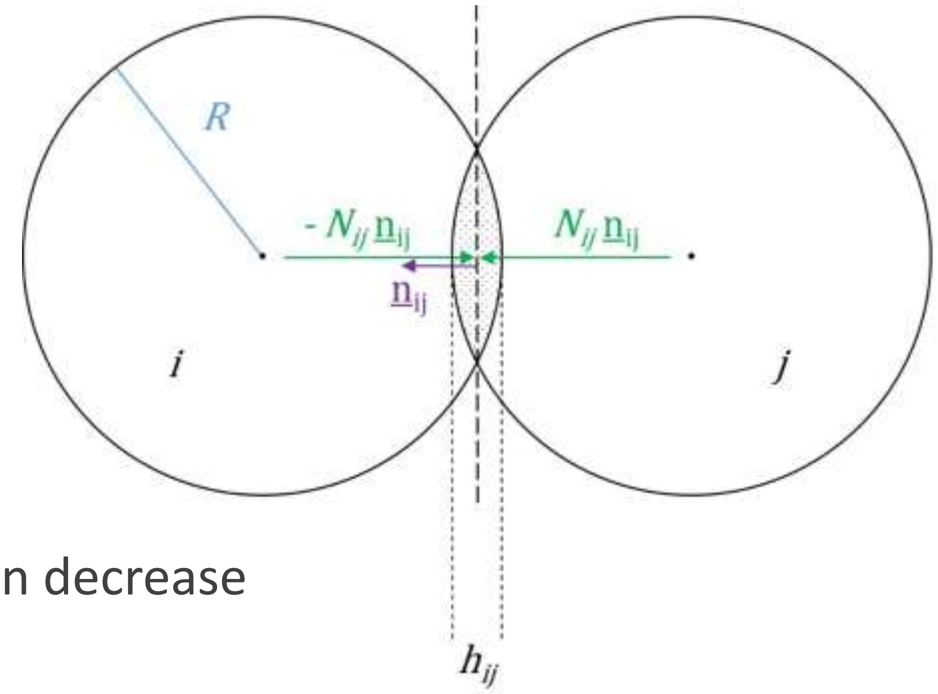
Hertz's law: relates normal force to deflection at contact area



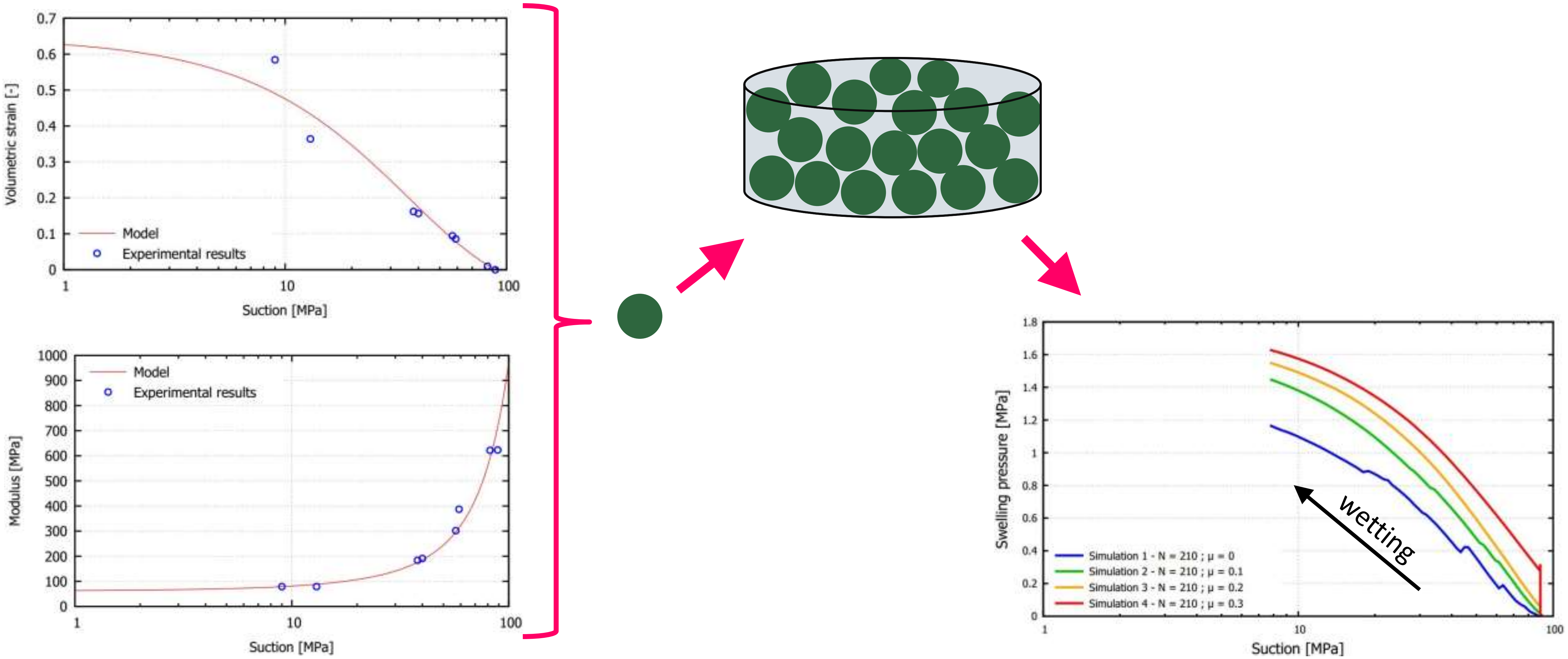
➔ Determine swelling behaviour and modulus decrease upon suction decrease



$$N_{ij} = \frac{E}{3\,(1-\nu^2)}\,(2R)^{1/2}\,h_{ij}^{\;3/2}$$



V – Current works



Thank you for your attention

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Strain model

<u>From BExM model</u> *(Alonso et al. 1999)*

Microstructural volumetric strain :

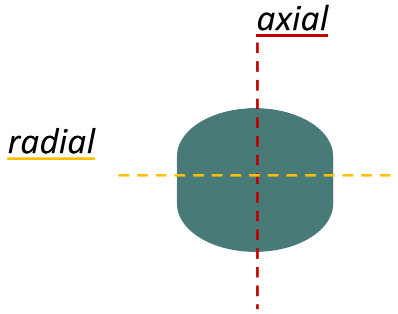
$$d\varepsilon_{v\,m}^{e} = \frac{dp'}{K_m}$$

$$K_m = \frac{\exp(\alpha_m\,p')}{\beta_m}$$

Alonso E. E. et al. – Engineering Geology (1999) ***54,*** *173-183*

➔ E (s)

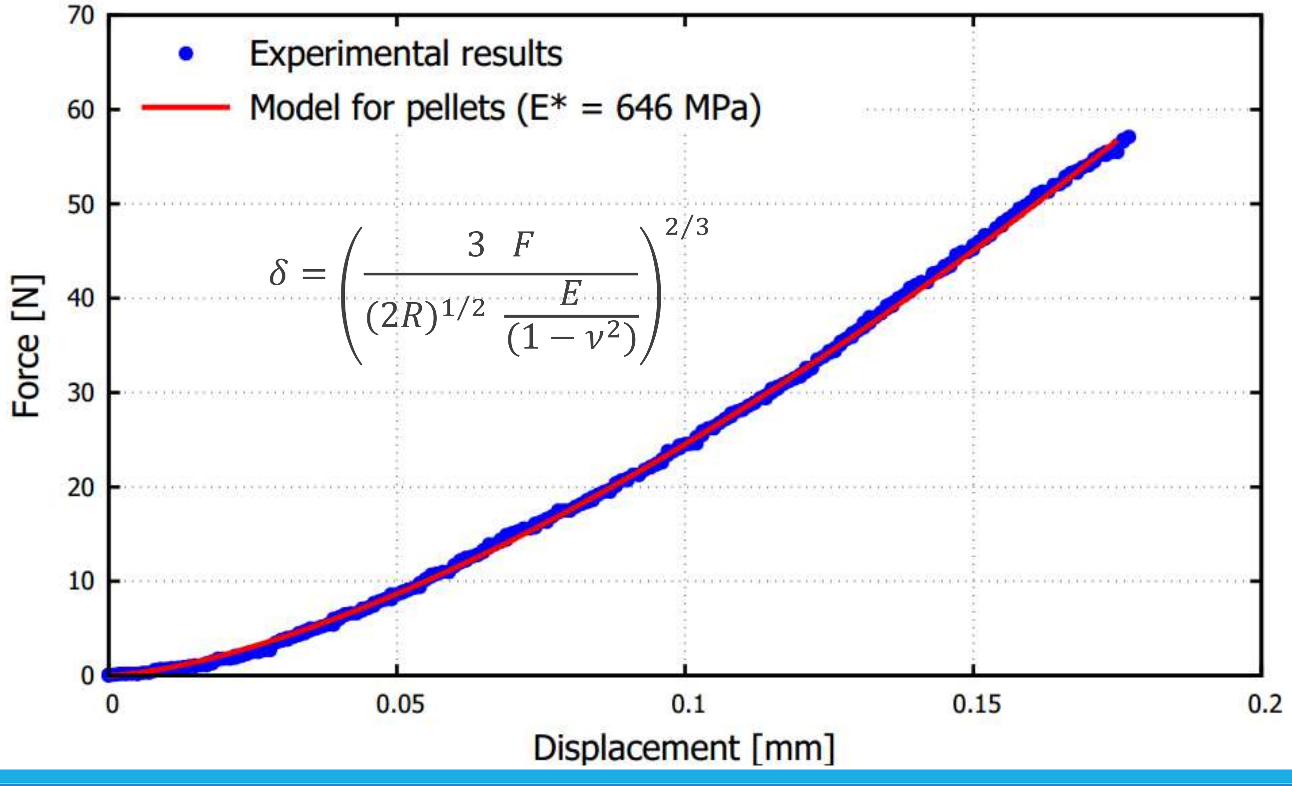
➔ $\varepsilon_{v\,m}^{e} = -\frac{\beta_m}{\alpha_m}\left[\exp(-\alpha_m\,p_0') - \exp(-\alpha_m\,p')\right]$



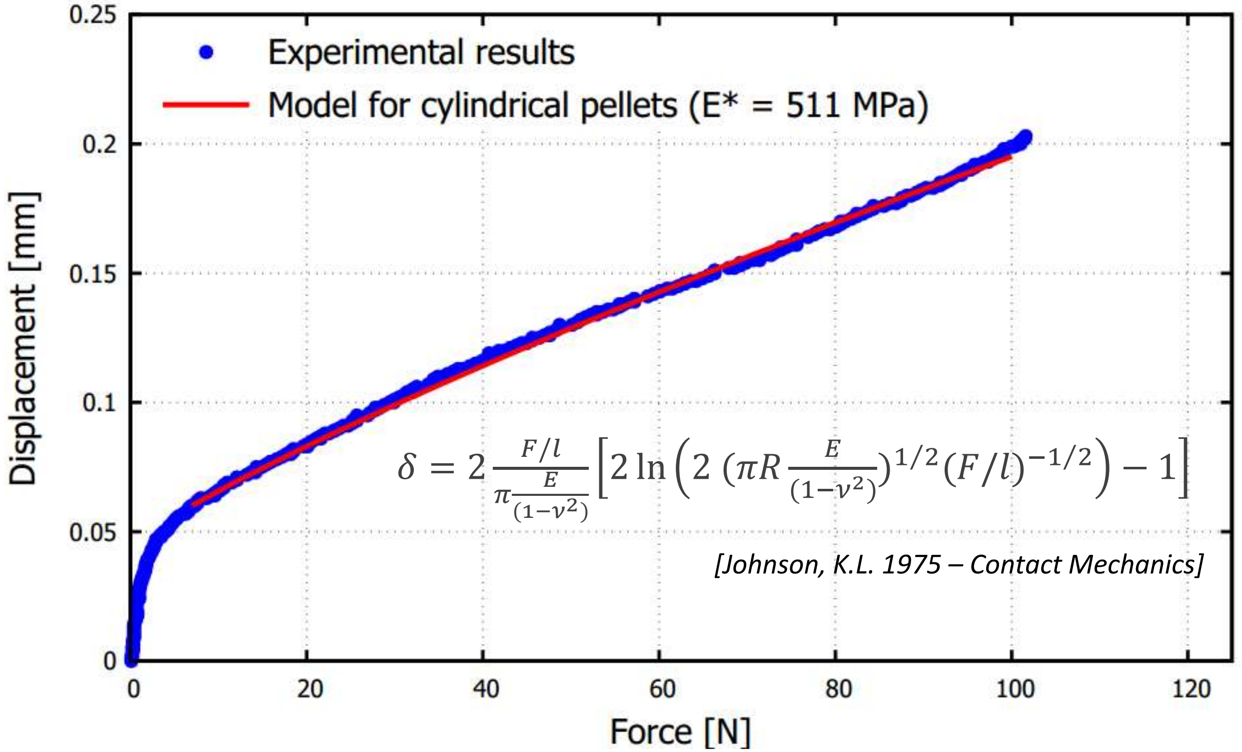
Modulus model

Crushing tests *results :*

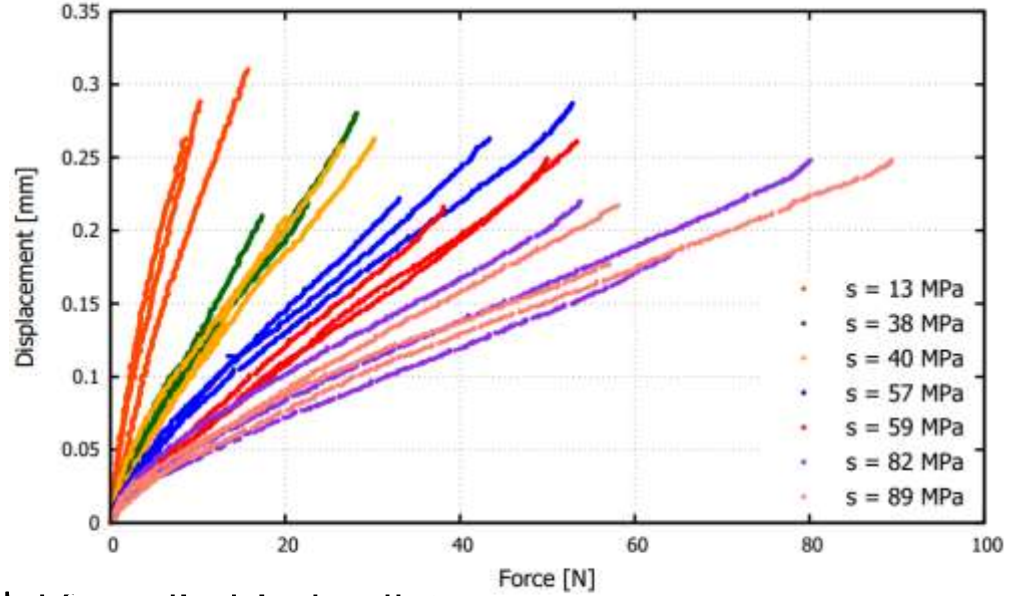
- Axial direction : model for spherical pellets

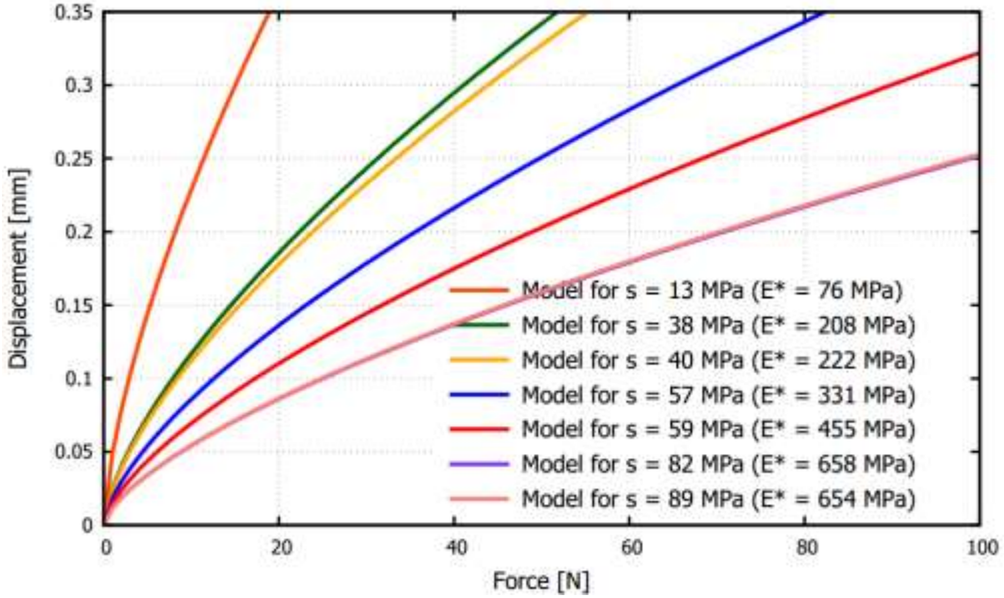


- Radial direction: model for cylindrical pellets



Model for spherical pellets :





Model for cylindrical pellets