BEACON
Bentonite Mechanical Evolution

On the Mechanical Behaviour of Bentonite
Why Beacon

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Workshop on Mechanical Properties of Bentonite Barriers

Lithuanian Energy Institute

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Outline

- Introduction: sources of heterogeneity
- A Soil Mechanics perspective
- Laboratory experiments: isothermal
  - RESEAL tests
  - Homogenization tests
- Laboratory experiments: non-isothermal
  - UPC thermal test
  - CIEMAT hydro-thermal test
- Large-scale field tests: isothermal
  - EB test
- Large-scale field tests: non-isothermal
  - Prototype test
  - Canister Retrieval Test
  - FEBEX test
- Summary and concluding remarks

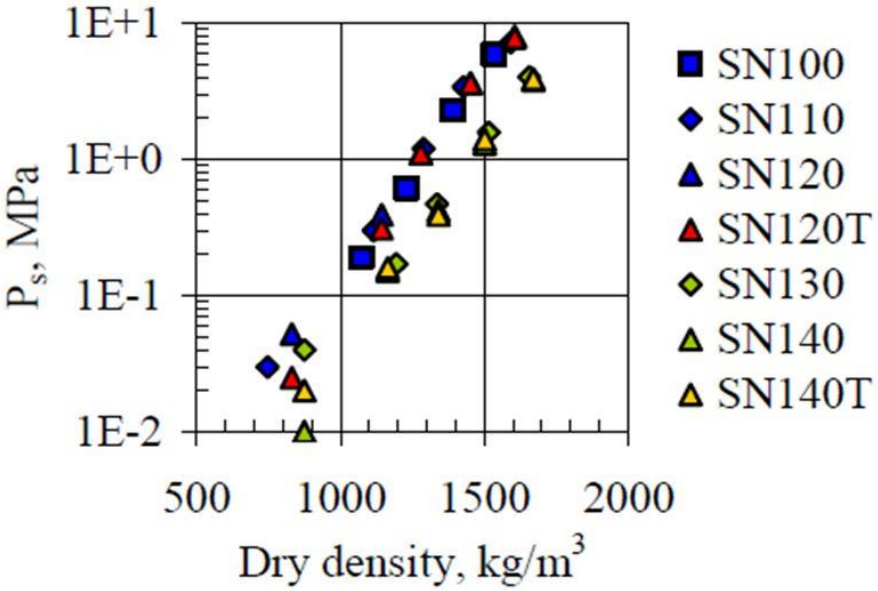
Introduction

- Safety functions of the bentonite engineered barrier (some are applicable to seals)
  - Low hydraulic conductivity and low diffusivity ($k < 10^{-11}$ - 10^{-12} m/s)
    - Minimization of advective flow
    - Low diffusion
  - Significant swelling pressure (0.5 - 2MPa)
    - Adequate sealing capacity
    - Minimization of microbial activity
  - Resistance to mineral transformation
  - High radionuclide sorption
- Hydraulic conductivity and swelling pressure are basically controlled by dry density (porosity)
  - Dry density values of 1.25 – 1.5 g/cm^3 are often specified (requiring a higher emplacement dry density)

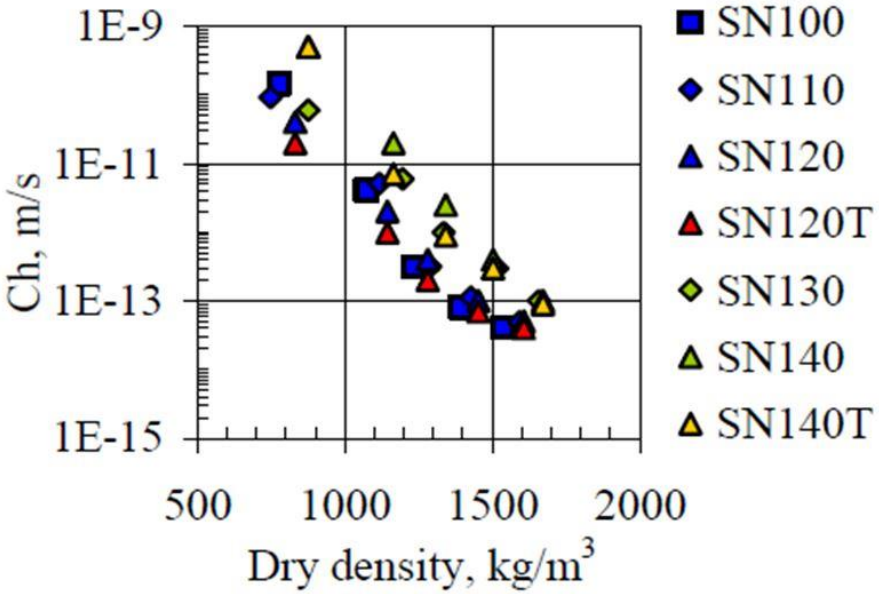
Introduction

- For a given bentonite…
  - Swelling pressure and hydraulic conductivity depend mainly on dry density (or porosity)

MX-80 bentonite (Na)



Swelling pressure



Hydraulic conductivity

(NAGRA, NAB 07-23)

Introduction

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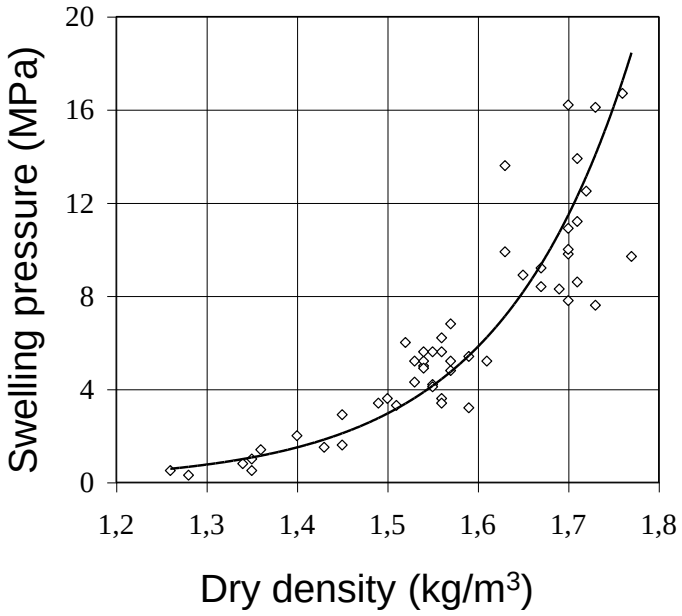
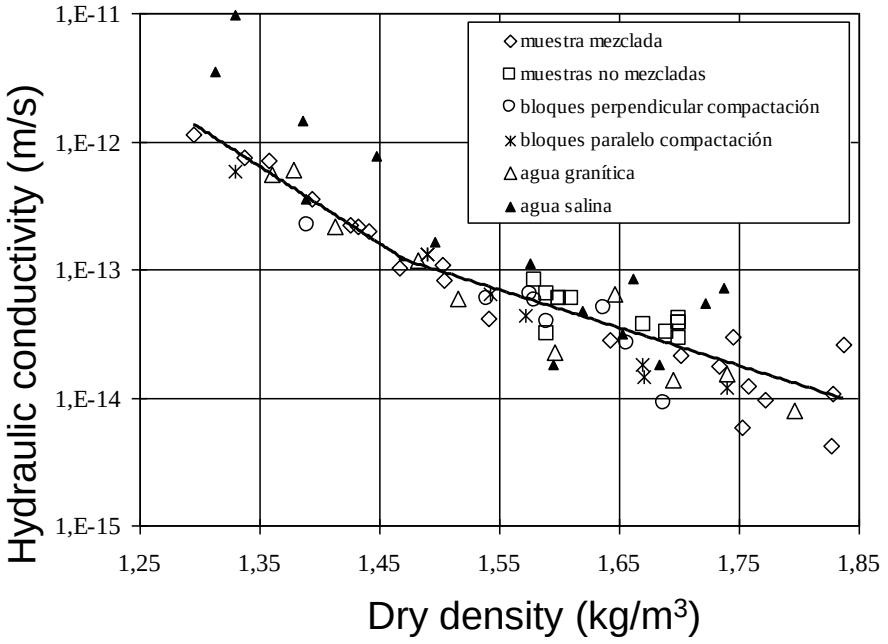
  - Swelling pressure and hydraulic conductivity depend mainly on dry density (or porosity)

Febex bentonite (Na-Ca-Mg)





Swelling pressure

Hydraulic conductivity

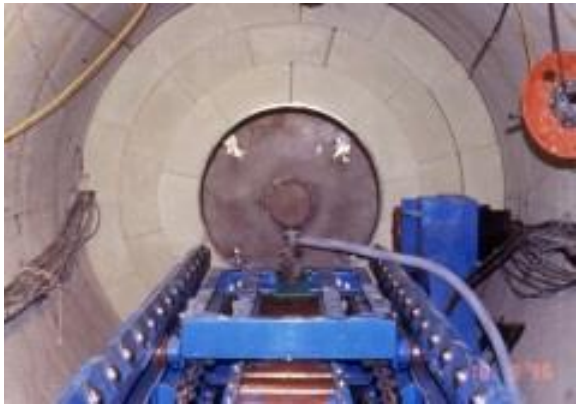
(Lloret et al., 2002)

Introduction

- If heterogeneity is present , average dry density is not sufficient to characterize the state of the barrier or a seal
  - The maximum hydraulic conductivity will be controlled by the connected zone of lowest dry density
    - Potential for preferential paths
  - Gas migration is often a local phenomena controlled by the weakest, more permeable zones
    - Heterogeneity of the saturated barrier will dominate the pattern of gas migration
  - Swelling pressure shows a stronger trendency towards homogenization
    - But it may also be non-uniform
- Bentonite heterogeneity has been observed at the final state of a range of laboratory and field tests although the evidence is not uniform
    - A degree of heterogeneity has been observed even with the bentonite at or close to saturation

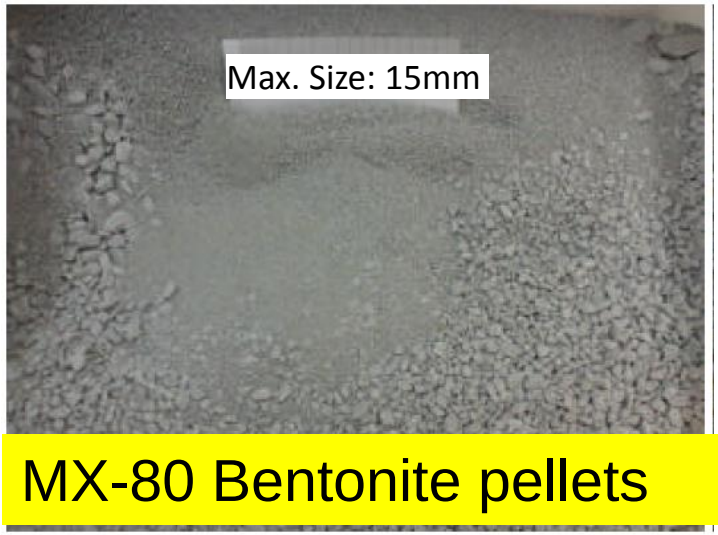
Introduction

- Sources of heterogeneity (1/4)
  - Design / Emplacement
    - Combination of pellets and blocks in the same section
    - Geometrical irregularity of the opening
    - Presence of technological gaps and voids
    - Segregation of granular material



Introduction

- Sources of heterogeneity (2/4)
  - Material
    - Pellets
    - Mixture pellets/powder
    - Sand/bentonite mixture

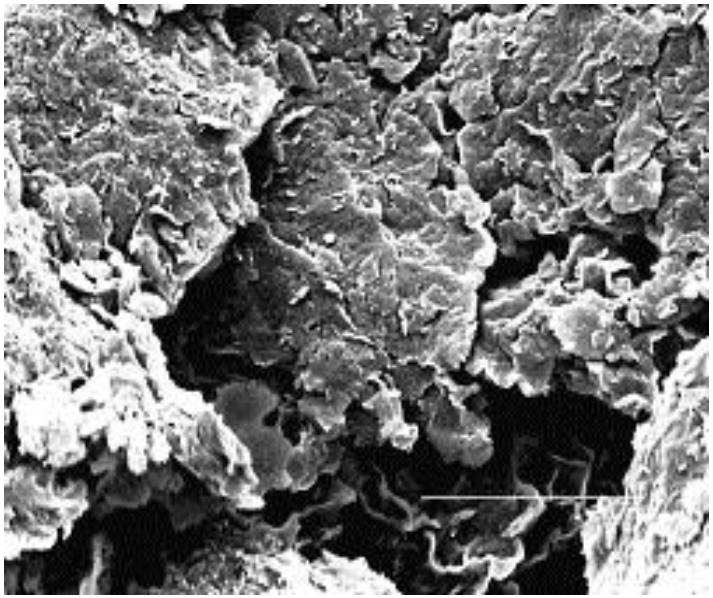


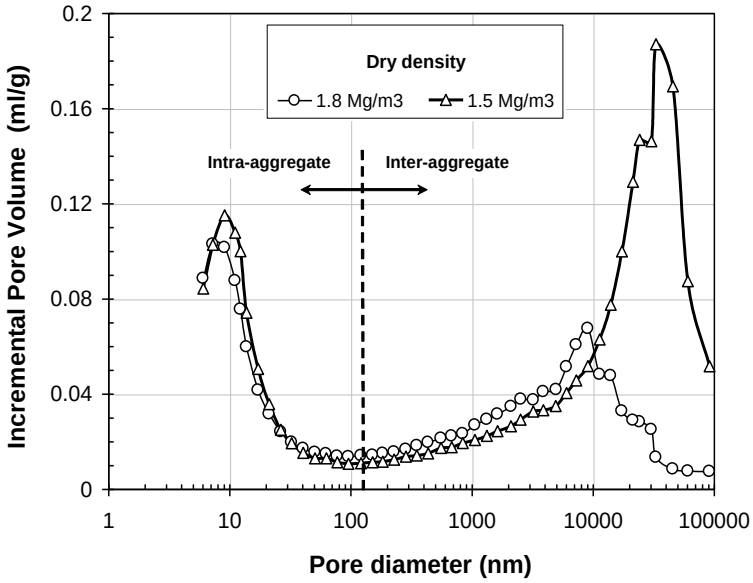
MX-80 Bentonite pellets

Sand-bentonite mixture

Introduction

- Sources of heterogeneity (2/4)
  - Material
    - Pellets
    - Mixture pellets/powder
    - Sand/bentonite mixture
    - Compacted bentonite

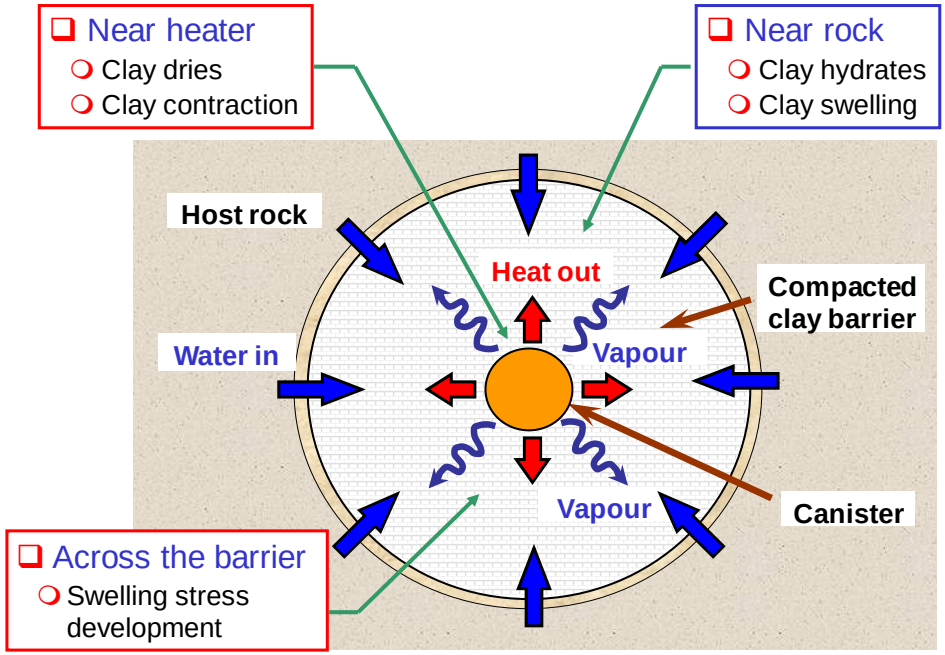




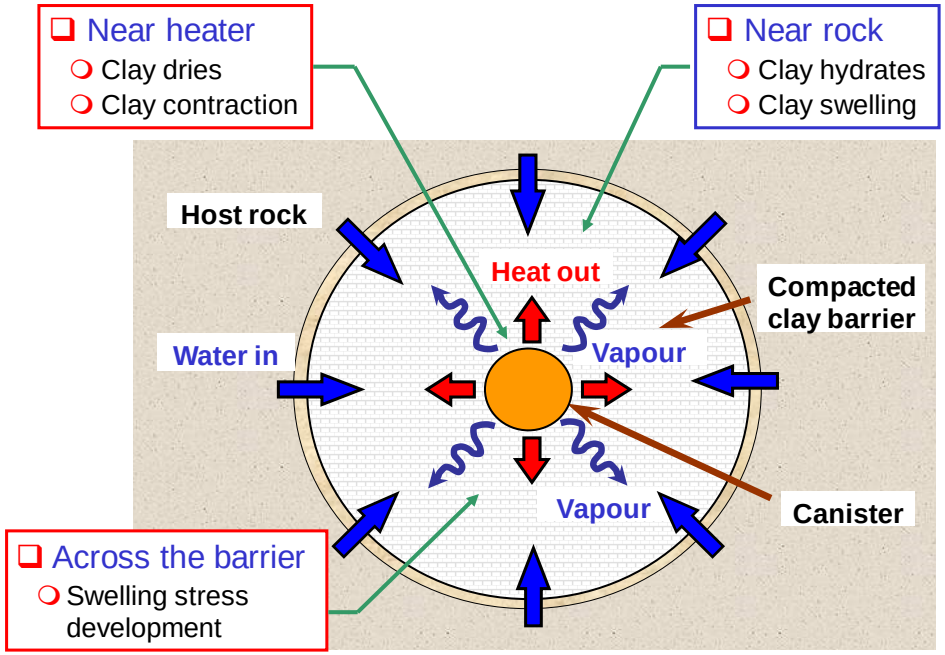
Introduction

Sources of heterogeneity (3/4)

Behaviour during the transient stage



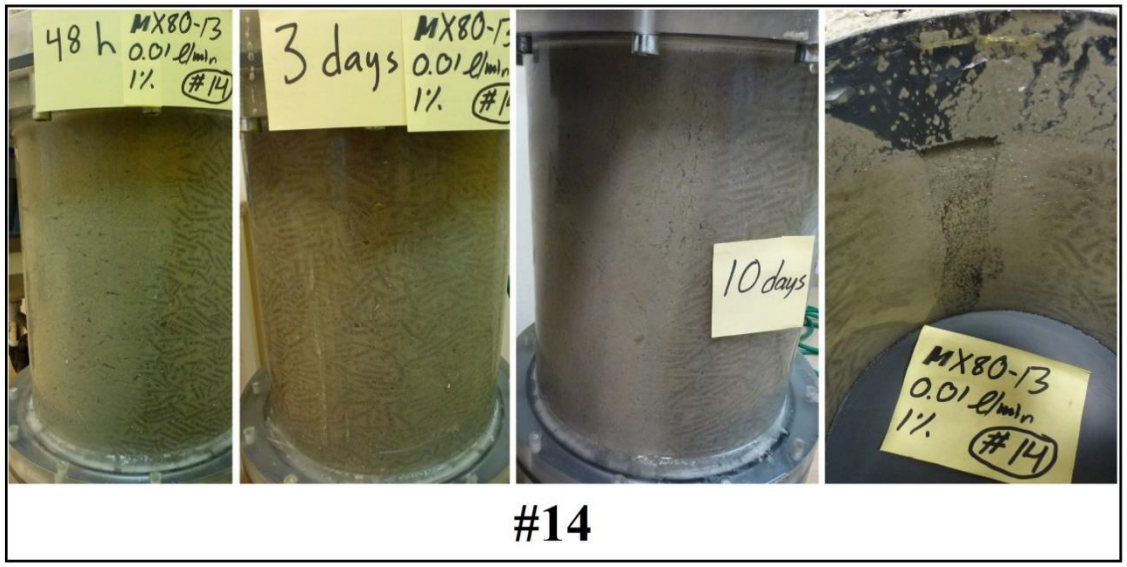
Isothermal



Non-isothermal

Introduction

- Sources of heterogeneity (4/4)
  - Events in the saturated phase (after transient phase)
    - Erosion, piping, dissolution, colloid formation



Börgesson L. et al. (2014) Consequences of water inflow and early water uptake in deposition holes. EVA-PROJECT

Introduction

- The degree and distribution of heterogeneities will vary during the transient phase involving only hydration (backfills, seals and plugs) or hydration and heating (buffers)
  - It is necessary to predict the evolution and final state of the heterogeneities
  - The degree of homogenization achieved may be affected by thermal effects
  - Potentially, heterogeneity may evolve beyond the end of the transient phase
- The final state of the barrier will depend on features of bentonite mechanical behaviour such as:
  - Interaction with hydraulic processes
  - Interaction with thermal processes
  - Irreversibility and stress path-dependency

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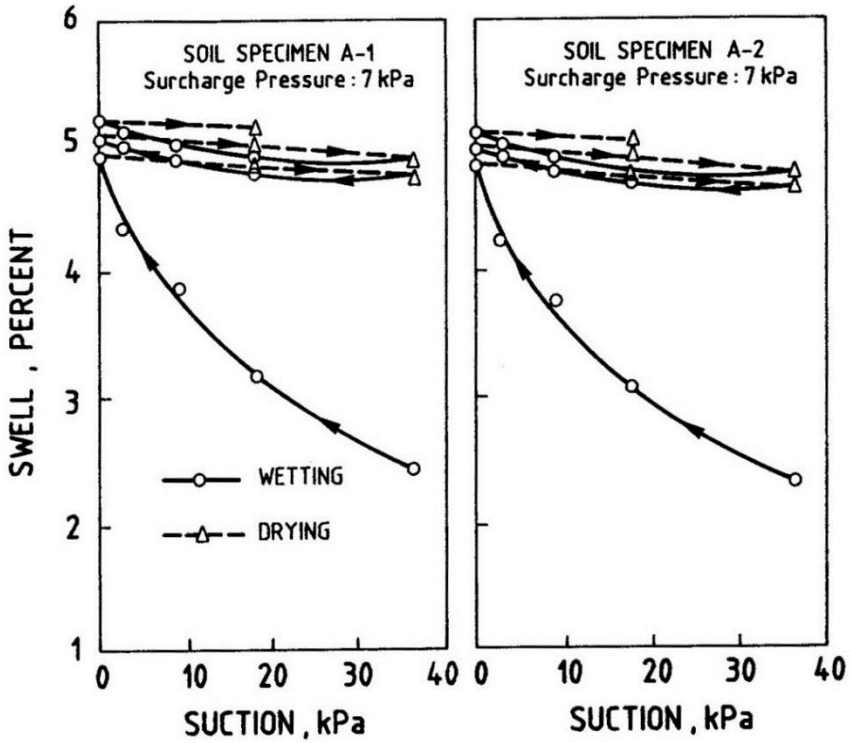
A Soil Mechanics perspective

Expansive clays

- Because the physico-chemical phenomena occurring at particle level are basically reversible, one would expect expansive clay behaviour to be reversible and (possibly) stress path independent.
- In fact, it is not! It has been long known that highly expansive clays exhibit behaviour features such as irreversibility and street path dependency *(Gens & Alonso, 1992 Canadian Geotechnical Journal)*



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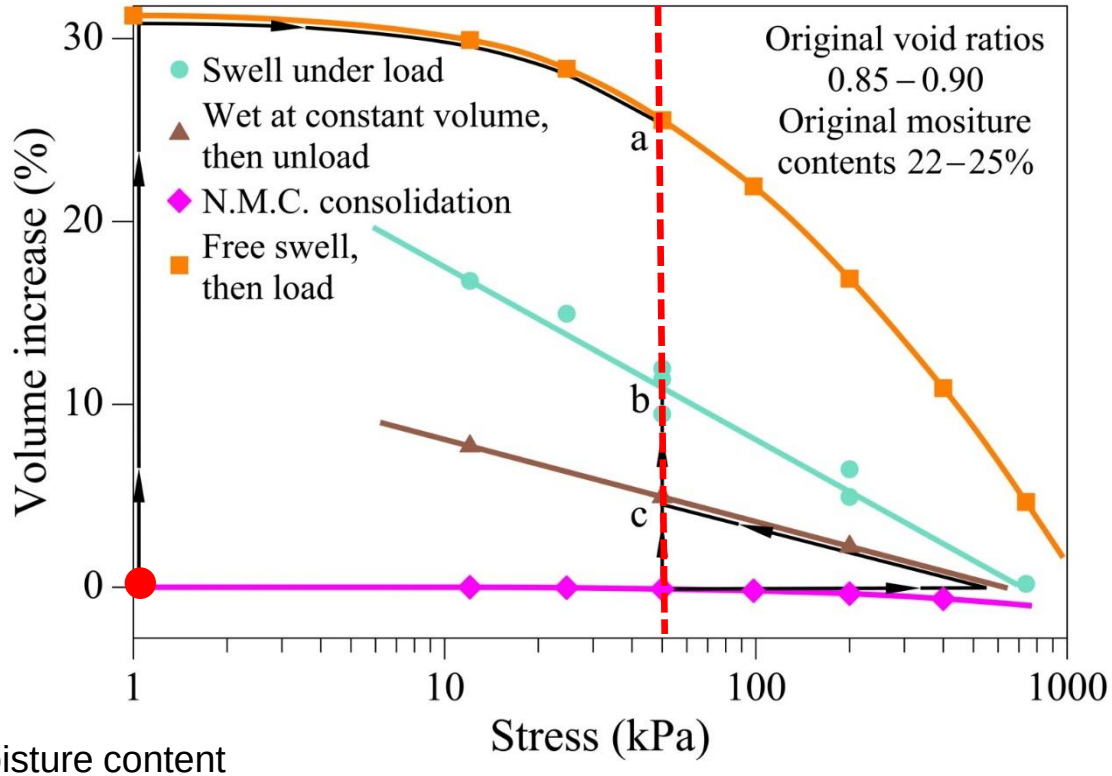

(Brackley, 1975)

NMC: natural moisture content

A Soil Mechanics perspective

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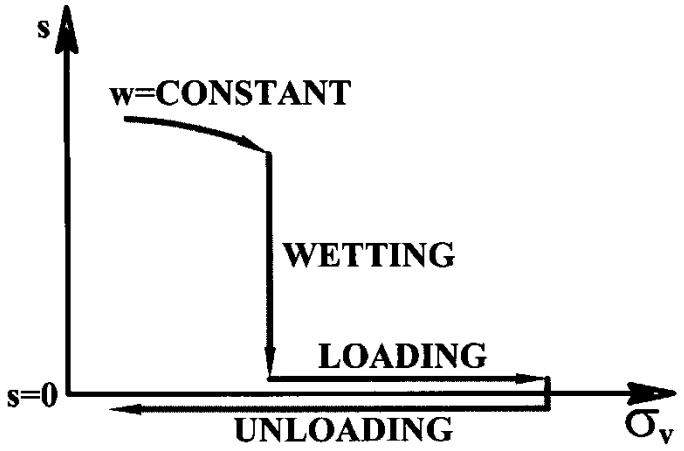
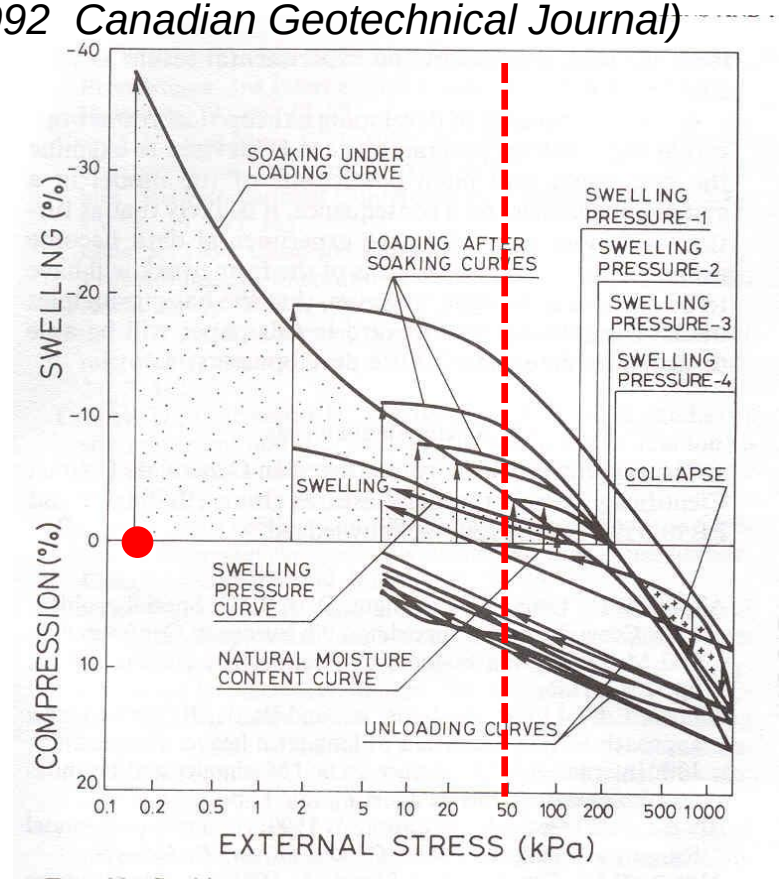
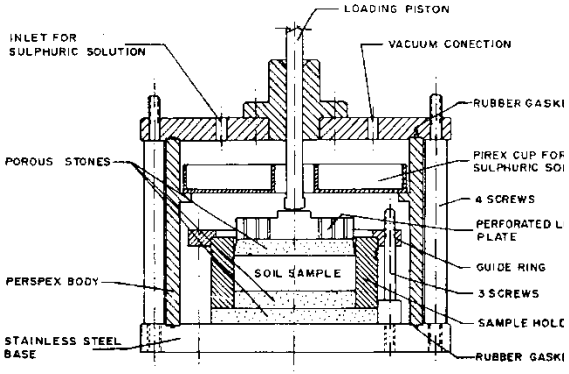


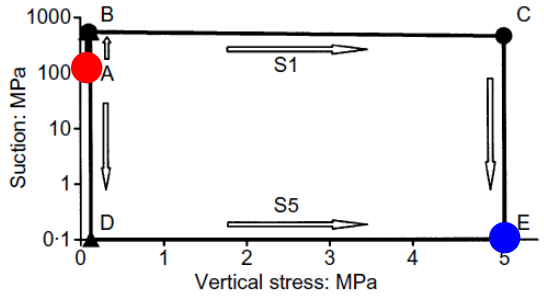
Wetting under load tests of specimens of compacted Arahal high plasticity clay from Sevilla (Justo et al, 1984)

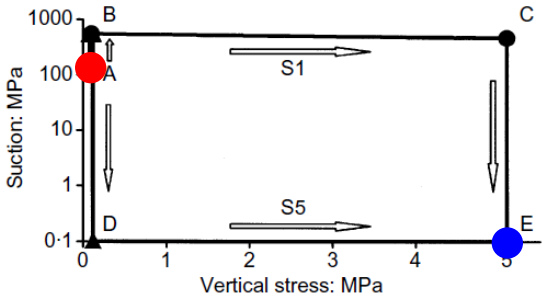


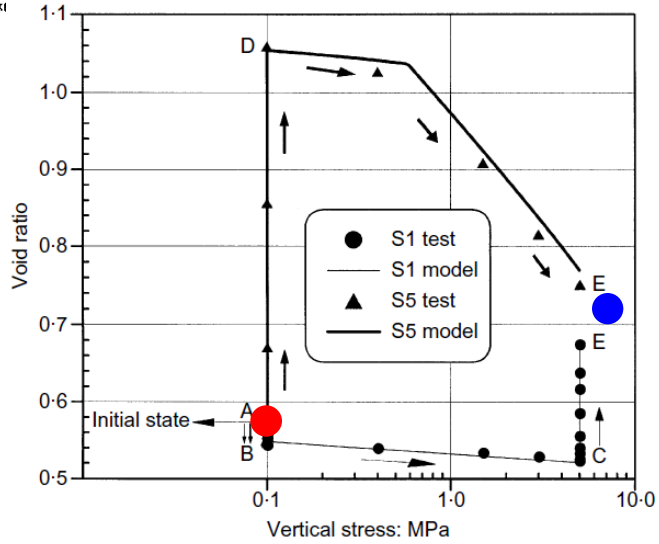
A Soil Mechanics perspective

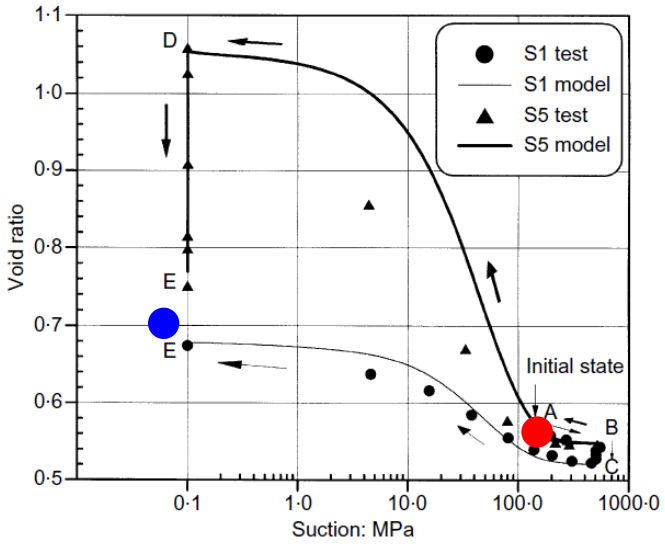
- CIEMAT suction-controlled oedometer tests on FEBEX bentonite
  - Dry density: 1.70 g/cm^3, w/c: 13.7%









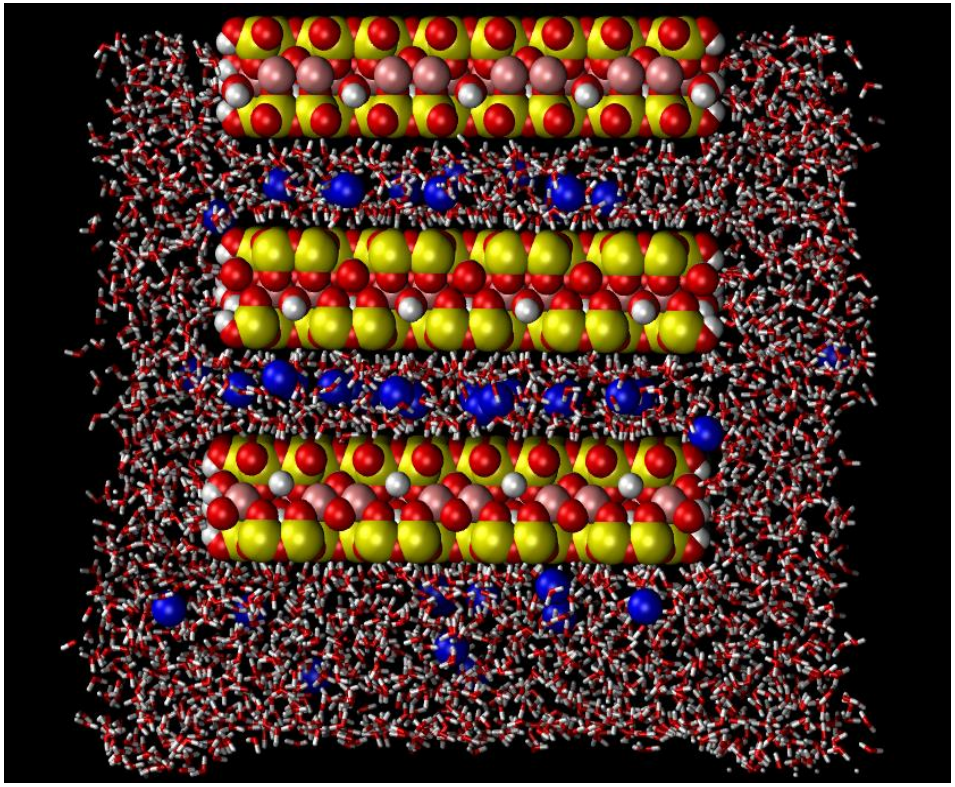


(Lloret et al. 2003)

A Soil Mechanics perspective

Expansive clays: basis of behaviour

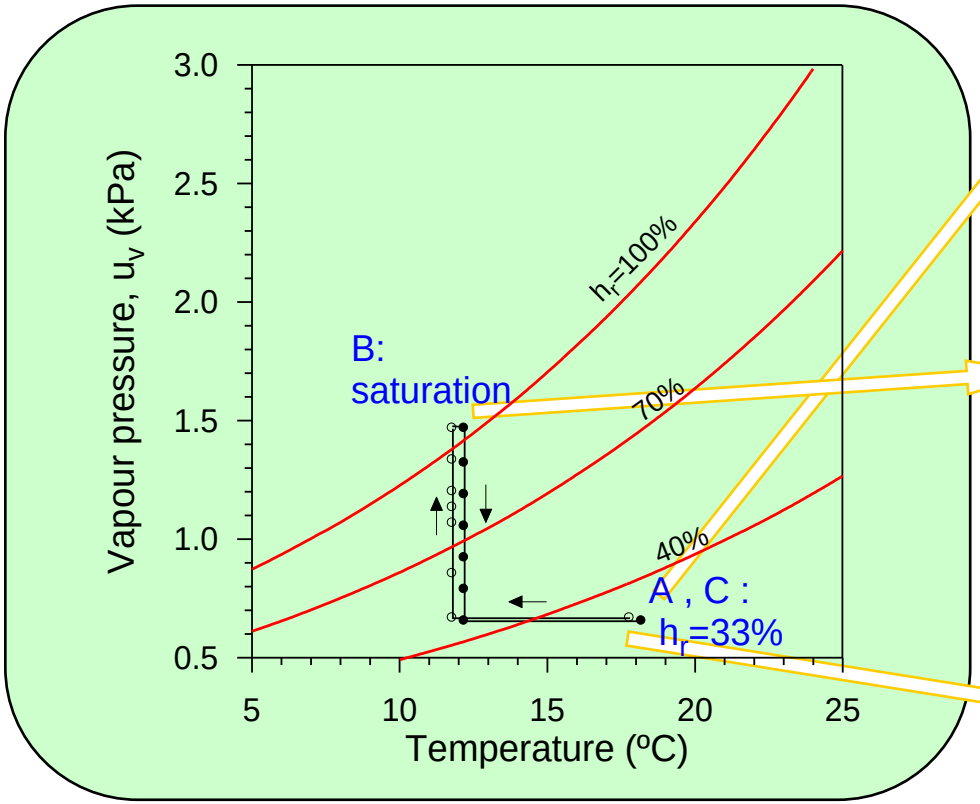
- Physico-chemical effects close to the clay mineral are basically reversible
- Strain irreversibility and stress path dependency are attributed to the effects of microstructural (particle level) deformation on the macrostructure (Gens & Alonso, 1992)

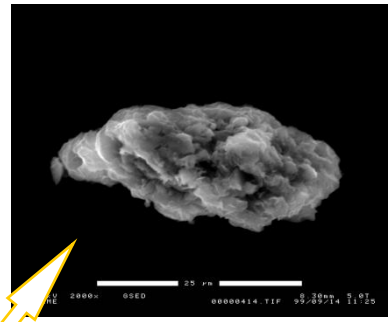


(Hedstrom, pers. comm.)

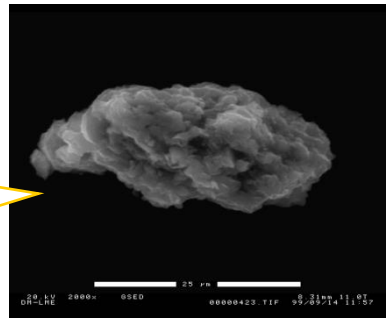
A Soil Mechanics perspective

- Direct observation of an aggregate in the ESEM

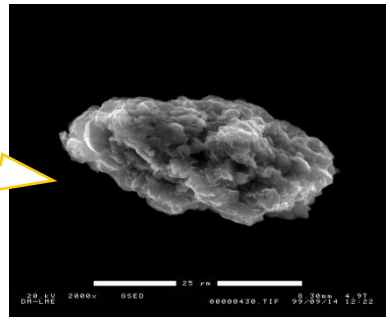




A



B



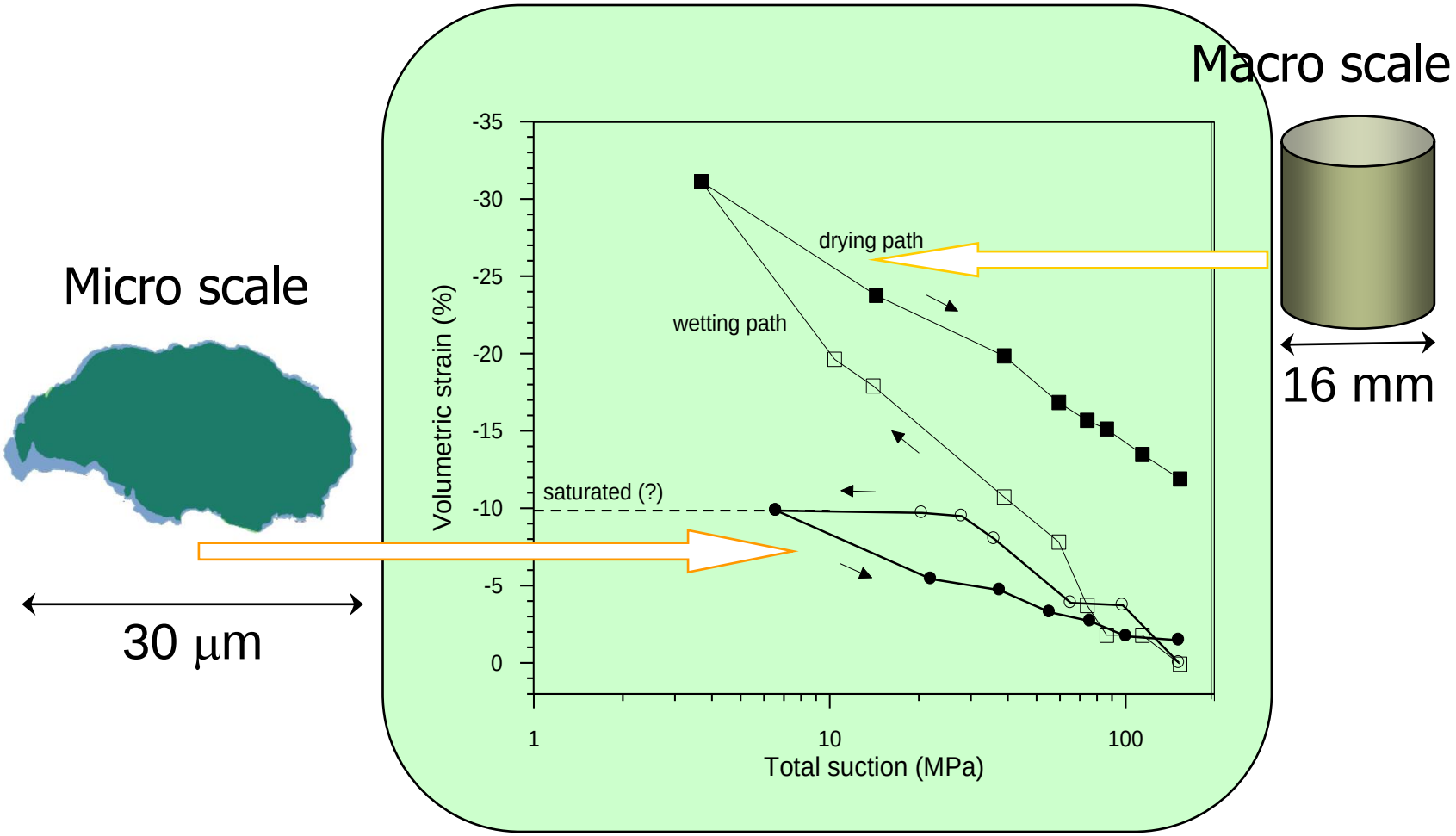
C

30 μm

(Romero, pers. comm.)

A Soil Mechanics perspective

- Microstructural ESEM observations – Macrostructural swelling measurements

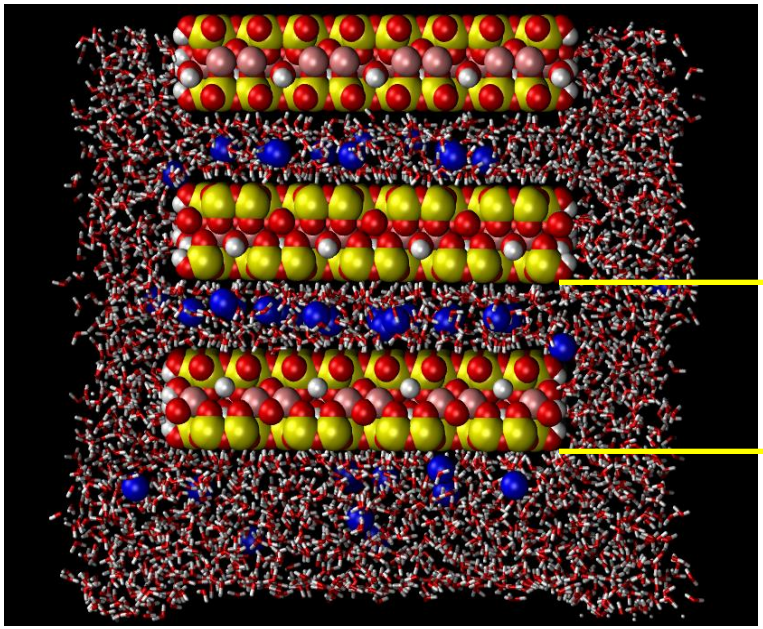


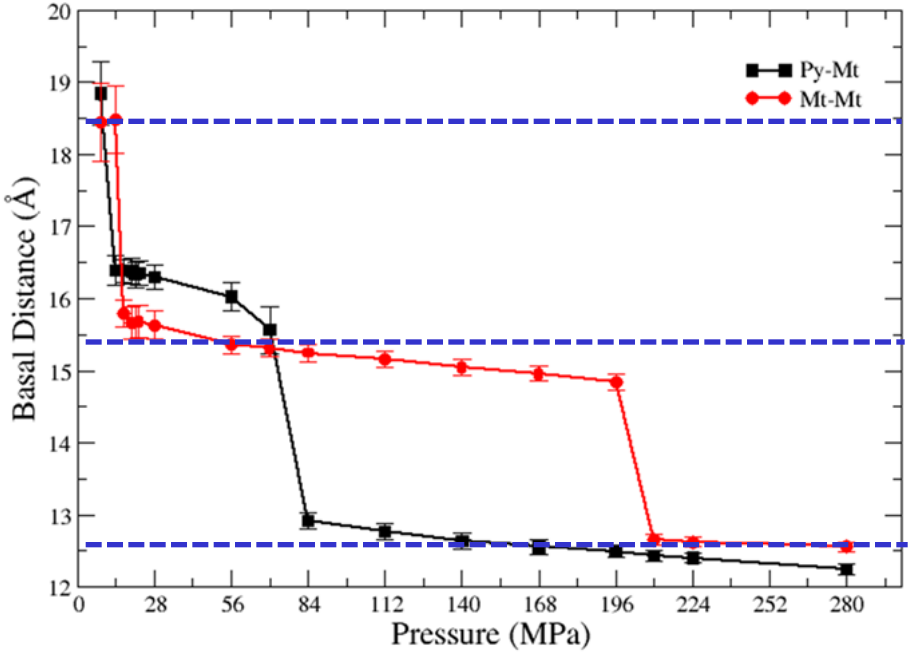
(Romero, pers. comm.)

On the sources of irreversibility

Microstructural behaviour

- Microstructural deformation is connected with the number of layers of interlayer water
- The number of water layers define the basal spacing
- In high density bentonite, a very large proportion of water is interlayer water (Pusch et al. 1990)





Molecular dynamics

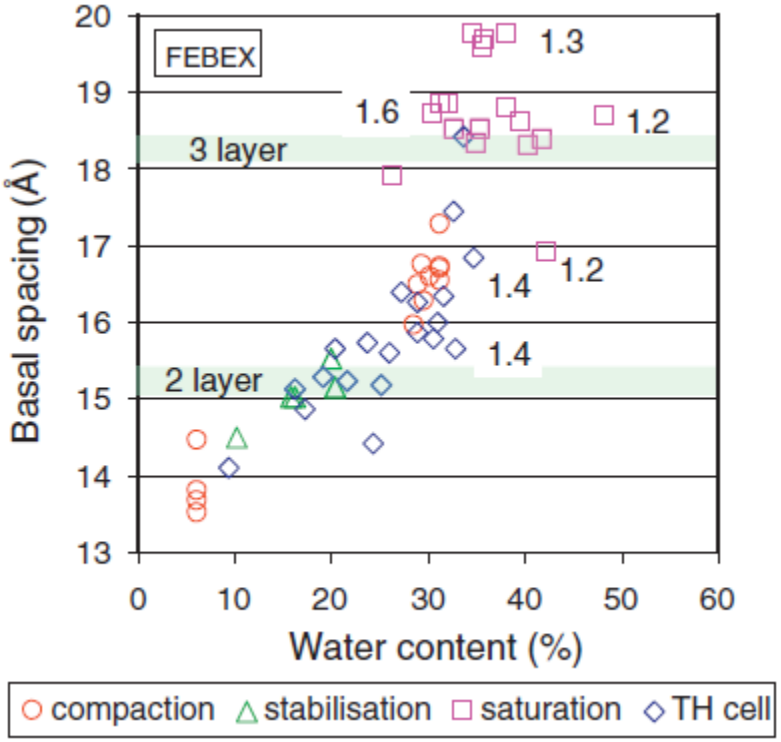
(Hedstrom, pers. comm.)

A Soil Mechanics perspective

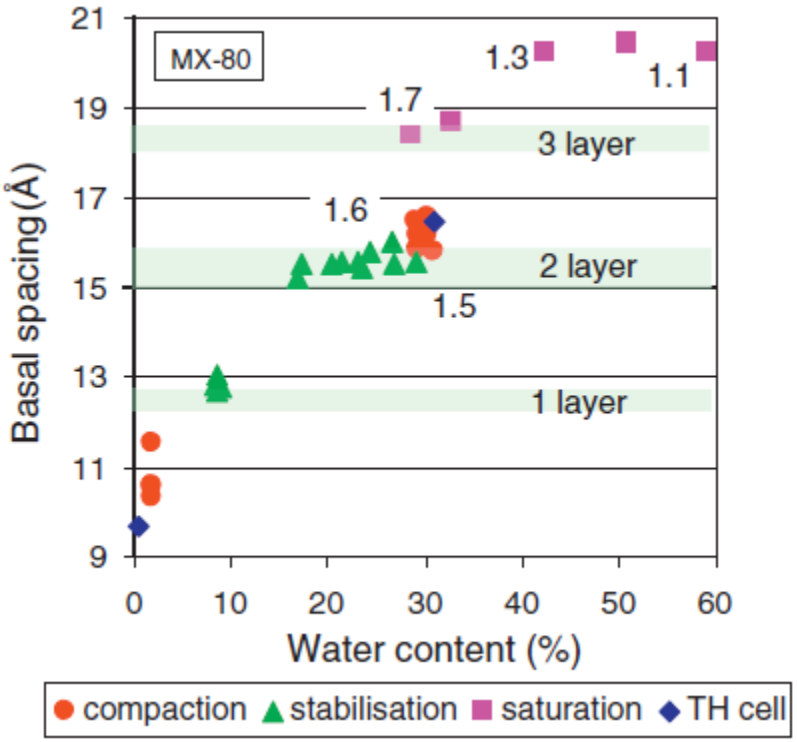
Microstructural behaviour

(Villar et al. 2012)

- Basal spacing correlated with water content
- The hydration state of the interlayer is a function of the layer charge, water activity, temperature, external pressure and salinity
- A degree of dependence on dry density and hydration time



FEBEX bentonite

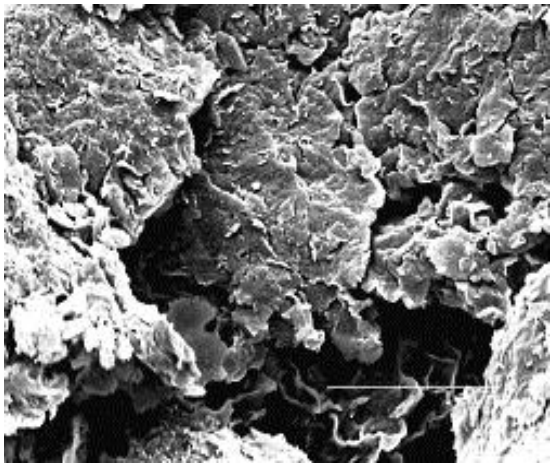


MX-80 bentonite

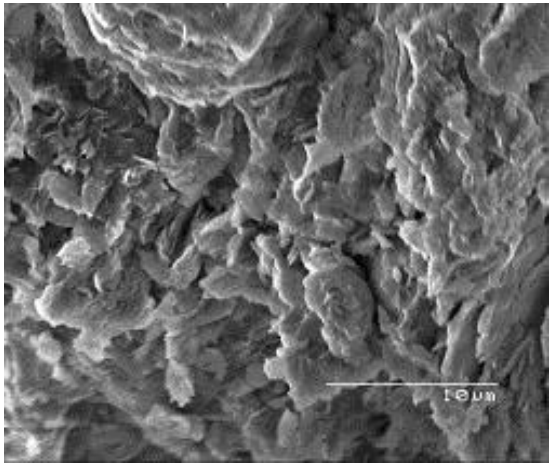
A Soil Mechanics perspective

Expansive clays

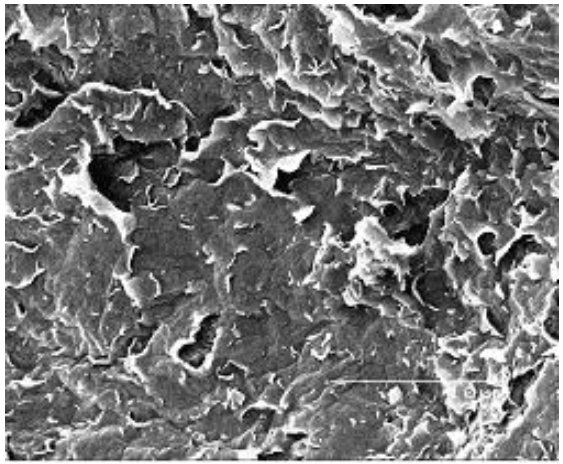
- Macrostructural and microstructural state variables may change significantly due to the application of stress and suction changes



Compacted (suction ≈ 110 MPa)



Suction = 10 MPa



Saturated

FEBEX bentonite

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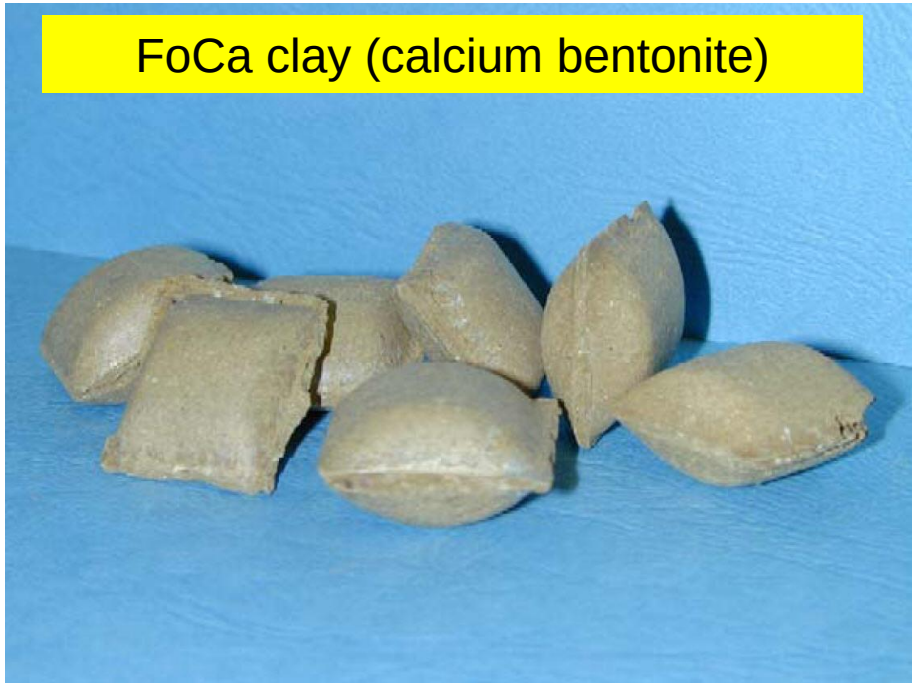
Laboratory experiments: isothermal

- RESEAL project tests
  - A mixture of bentonite powder and highly compacted pellets
  - Adequate average density even if poorly (or non) compacted

FoCa clay (calcium bentonite)



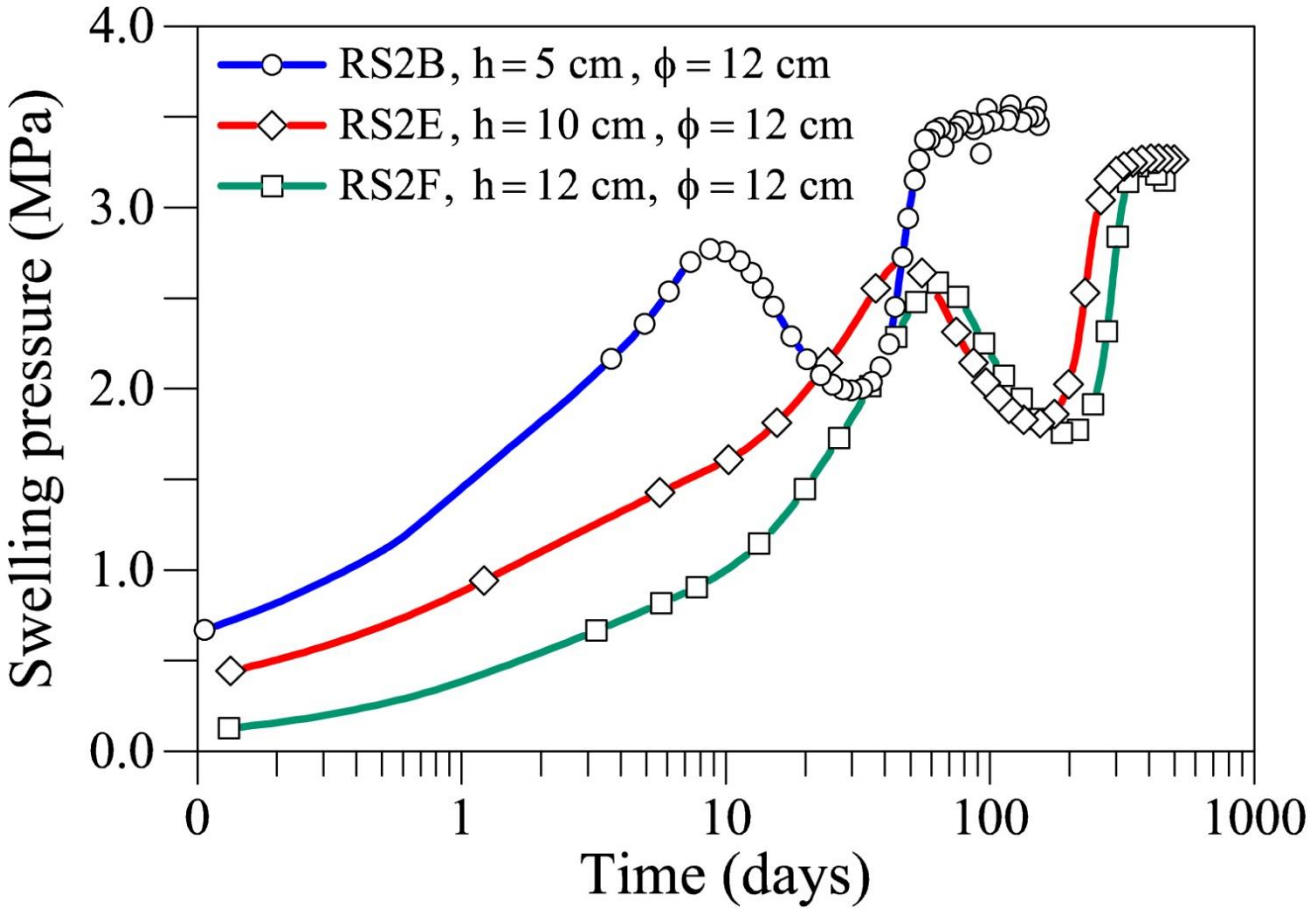
Pellet size: 25 x 25 x 15mm
Dry density: 1.89 g/cm^3, w/c: 4%-5%

50% powder – 50 % mixture

- How does it behave on hydration?

Laboratory experiments: isothermal

- How does it behave on hydration?
  - A mixture of 50% powder and 50% pellets by dry weight (FoCa clay)
  - Swelling pressure tests performed at CEA laboratory (dry density 1.60 g/cm^3). Oedometric conditions, hydration from one end
  - Complex swelling pressure development, scale-dependent



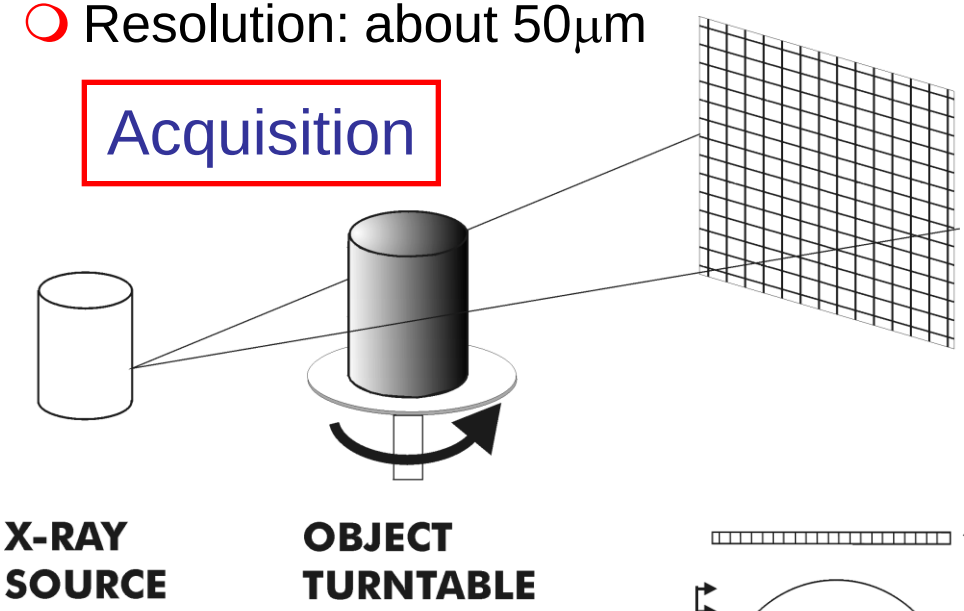
Laboratory experiments: isothermal

❑ Microfocus X-ray computer tomography (µCT)

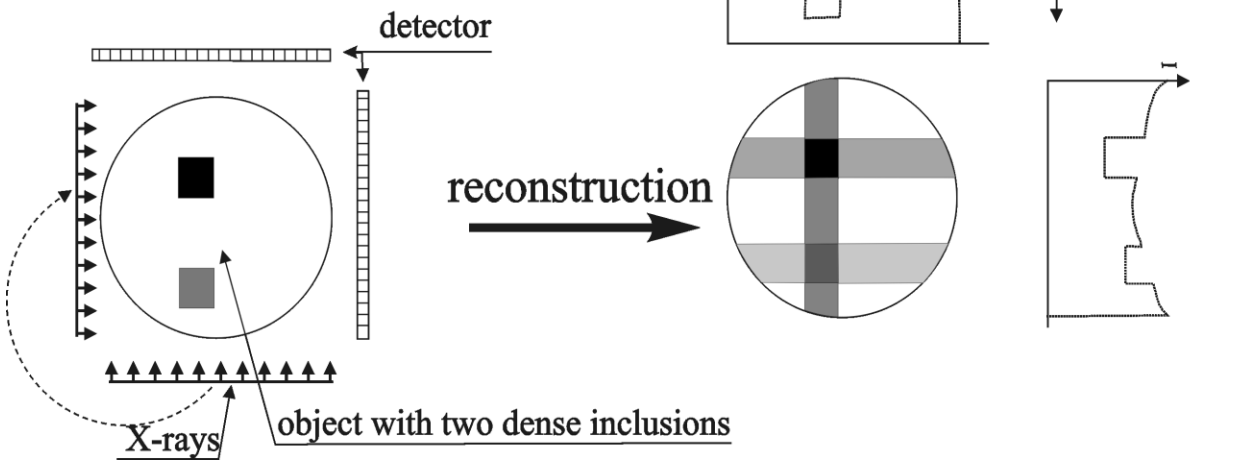
- Material: 50 % bentonite powder, 50 % high-density bentonite pellets
- Density obtained from attenuation coefficient
- Resolution: about 50µm

Principles of µCT

Acquisition

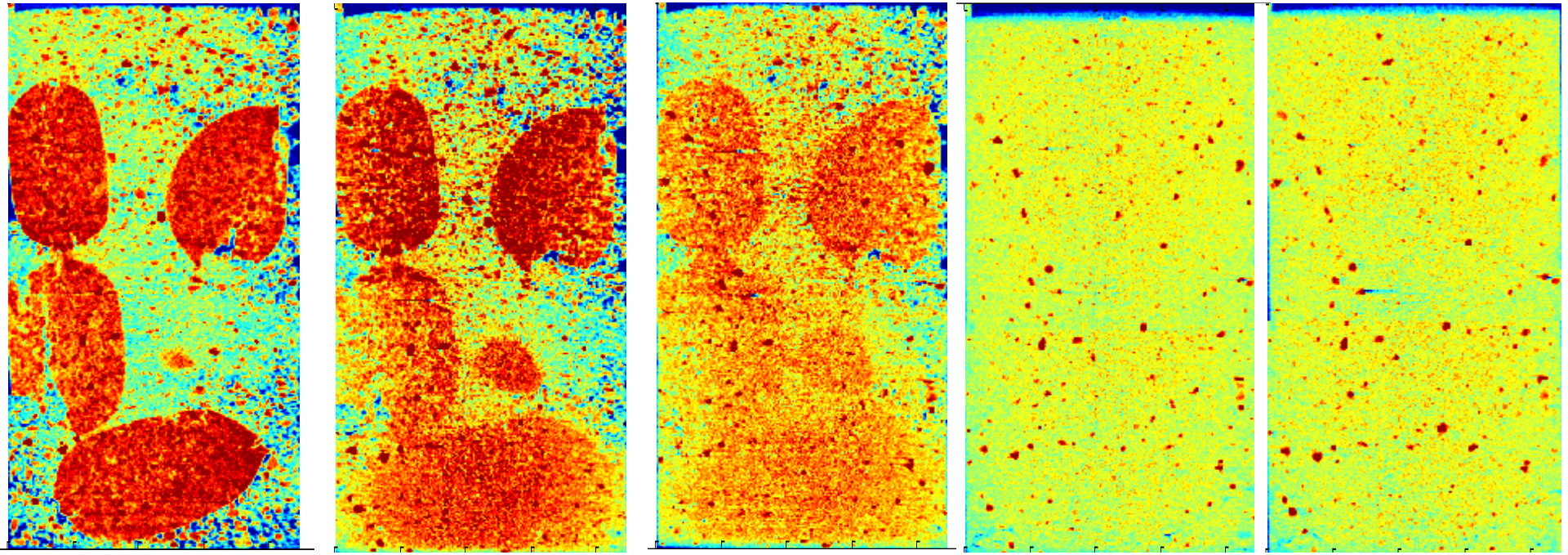


Reconstruction



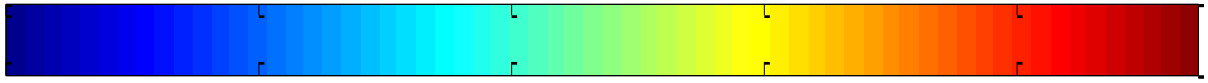
(Van Geet et al., 2005)

Time evolution

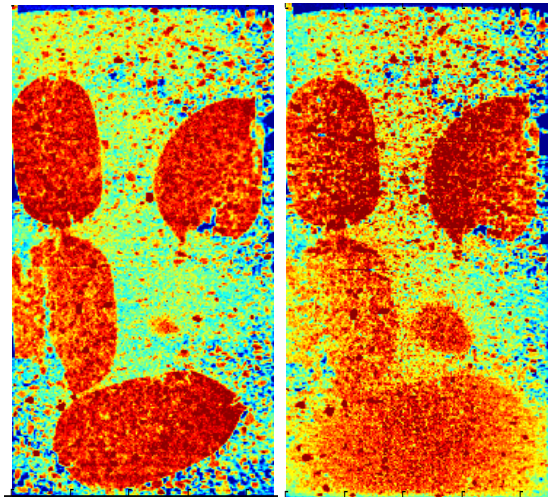


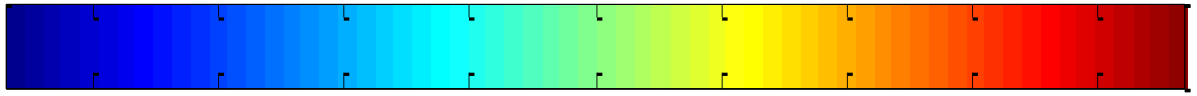
Initial ½ months 1 ½ months 2 ½ months 5 ½ months

Density (g/cm^3)

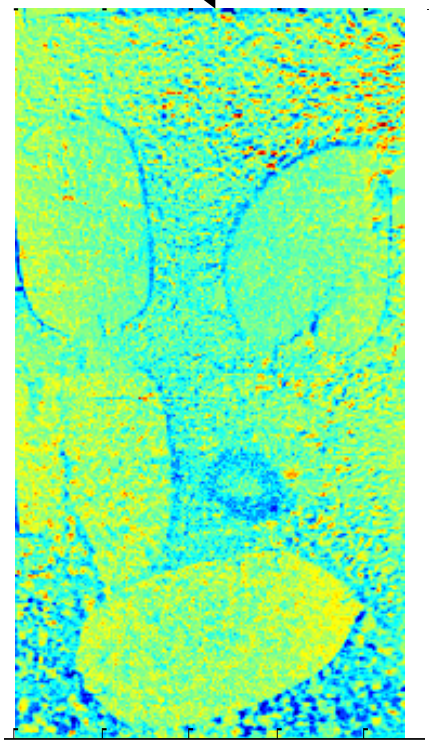


Difference images in time

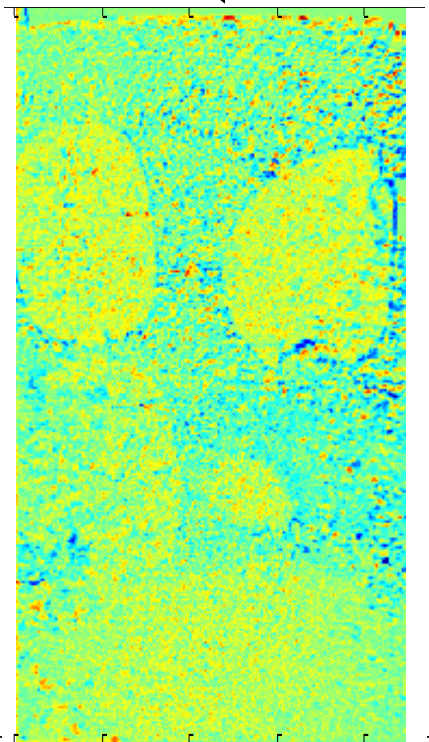




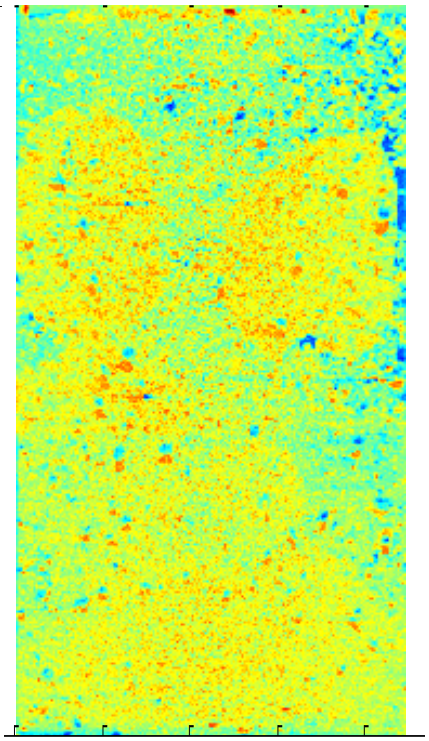
Initial - ½ months



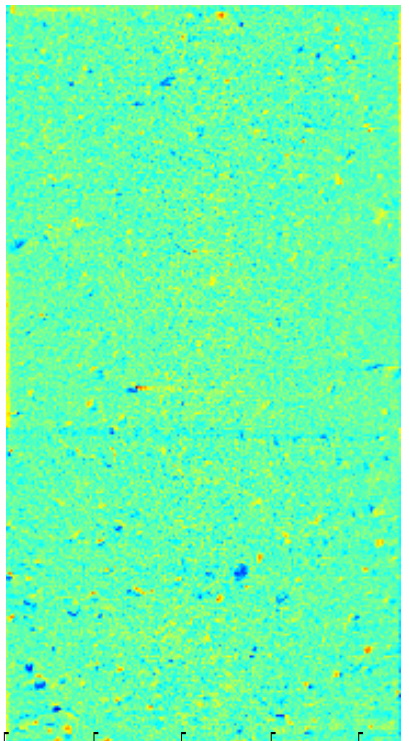
½ months – 1 ½ months



1½ months – 2½ months



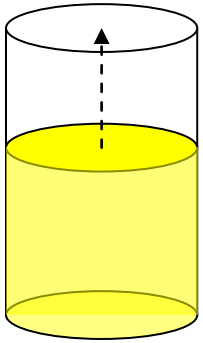
2½ months – 5½ months

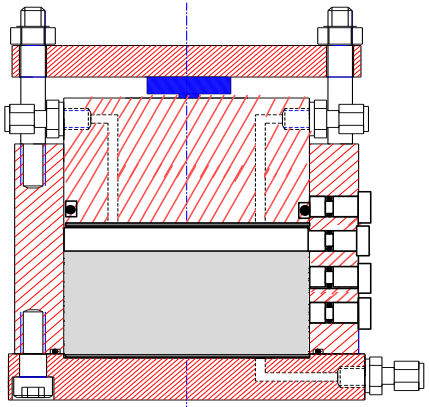


Laboratory experiments: isothermal

- Homogenization tests by Clay Technology (Dueck et al, 2011, 2014, 2016)
  - Saturated samples of bentonite

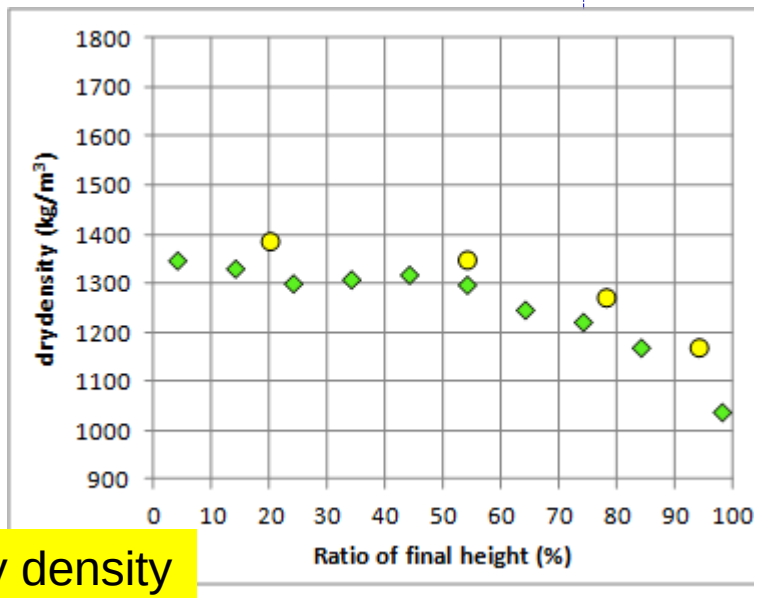
Axial swelling



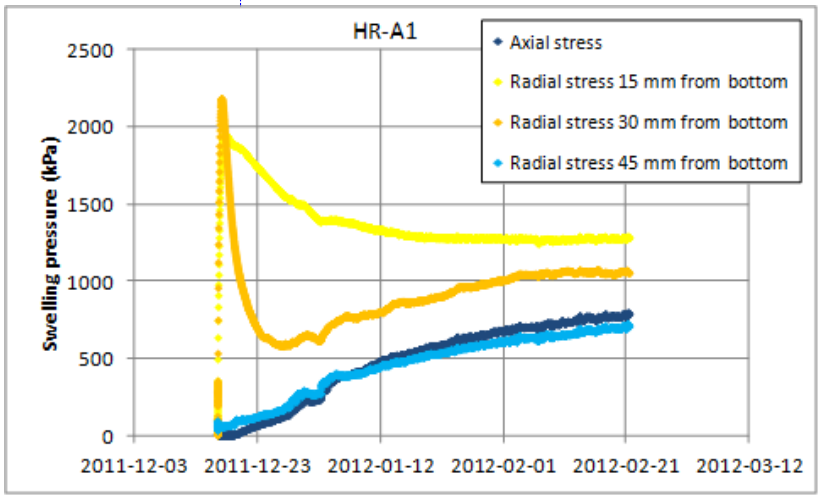


Axial force transducer

Radial stress transducers at four levels



dry density

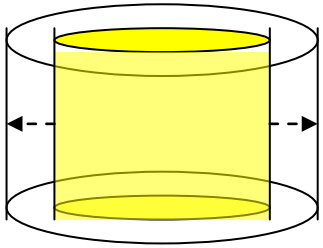


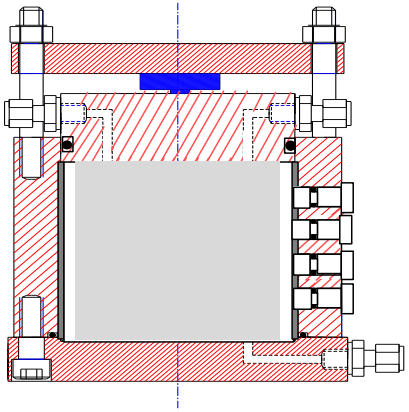
stresses

Laboratory experiments: isothermal

- Homogenization tests by Clay Technology (Dueck et al, 2011, 2014, 2016)
  - Saturated samples of bentonite

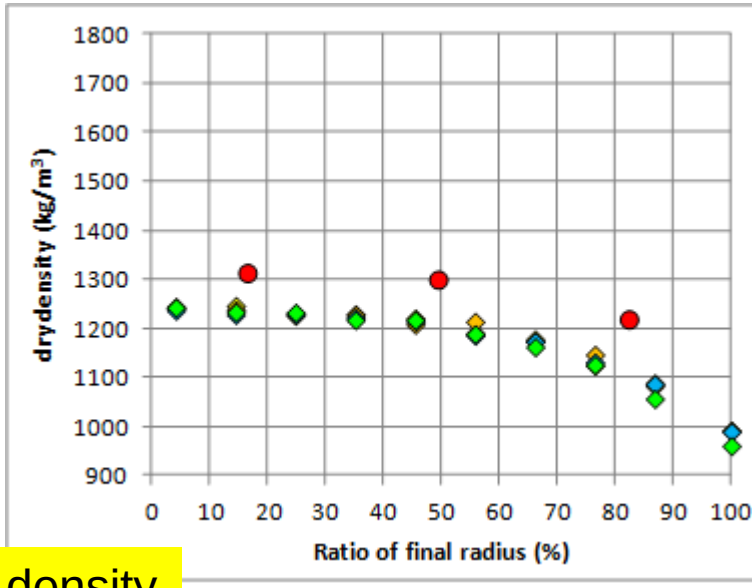
Radial outwards swelling



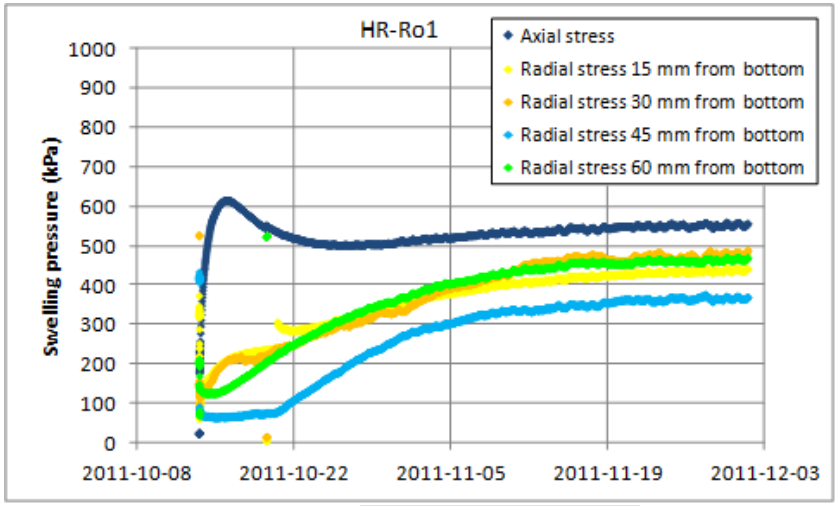


Axial force transducer

Radial stress transducers at four levels



dry density

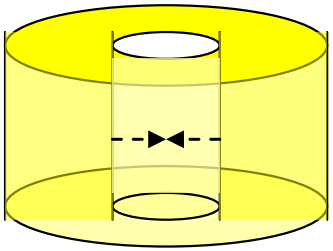


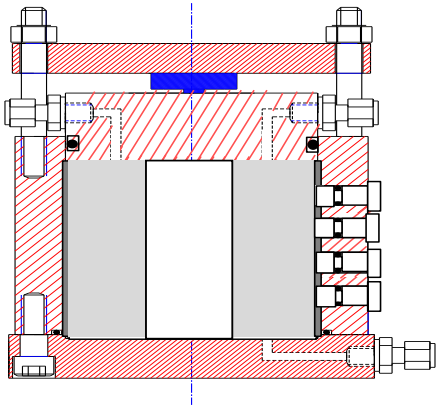
stresses

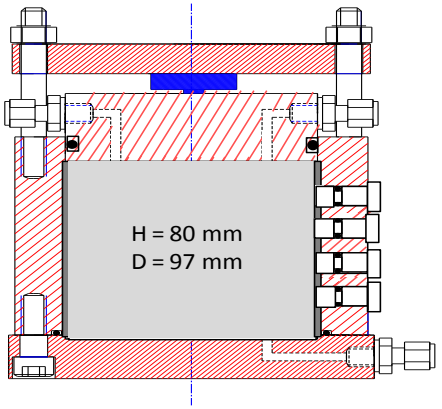
Laboratory experiments: isothermal

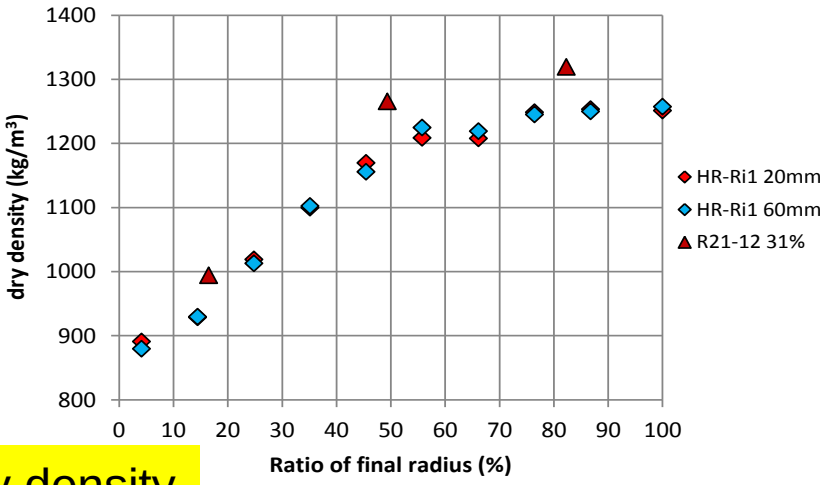
- Homogenization tests by Clay Technology (Dueck et al, 2011, 2014, 2016)
  - Saturated samples of bentonite

Radial inwards swelling

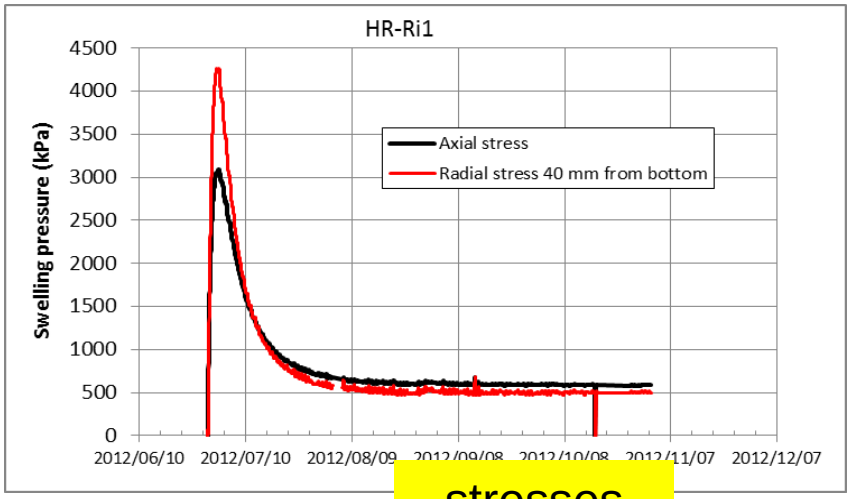








dry density



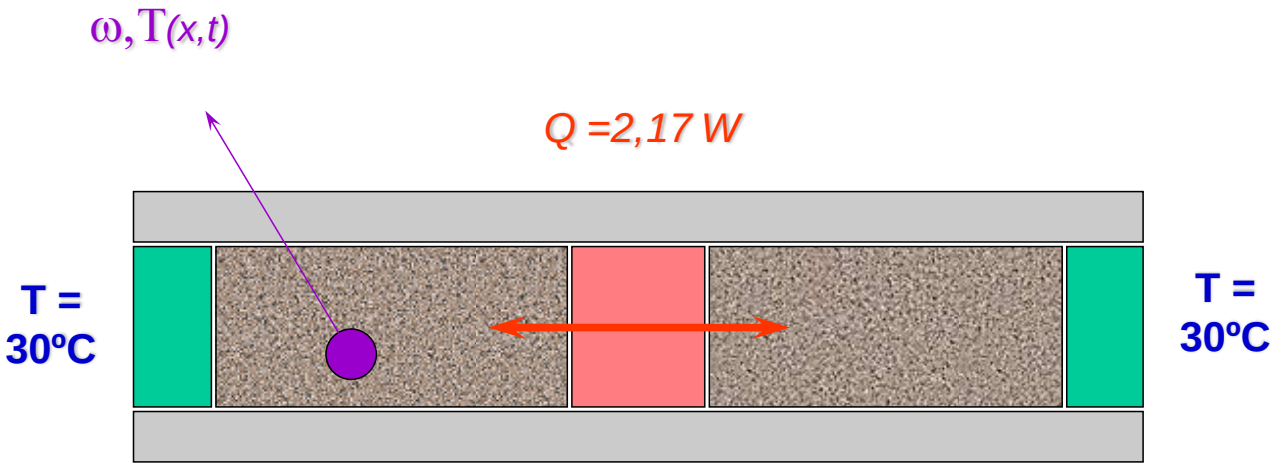
stresses

Outline

- Introduction: sources of heterogeneity
- A Soil Mechanics perspective
- Laboratory experiments: isothermal
  - RESEAL tests
  - Homogenization tests
- Laboratory experiments: non-isothermal
  - UPC thermal test
  - CIEMAT hydro-thermal test
- Large-scale field tests: isothermal
  - EB test
- Large-scale field tests: non-isothermal
  - Prototype test
  - Canister Retrieval Test
  - FEBEX test
- Summary and concluding remarks

Laboratory experiments: non-isothermal

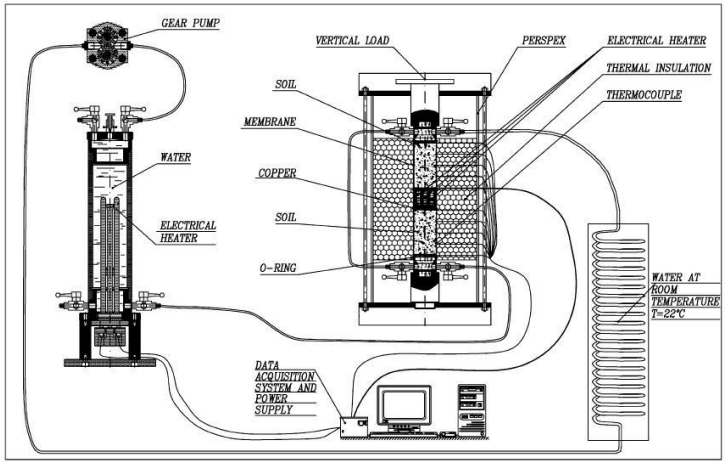
- UPC Thermal test (Pintado et al. 2002)
  - Compacted samples of bentonite



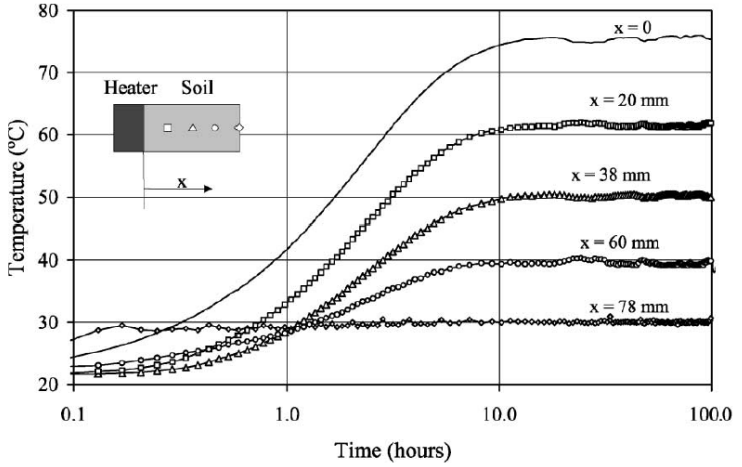
- Specimen: 38mm diameter, 76mm high
- FEBEX bentonite, dry density: 1.63g/cm^3, w/c = 15.33%, S_w = 0.63
- Initial temperature: 22ºC
- Test duration 7 days
- Measurements during the test: temperatures
- Measurements after the test: water content and sample diameter

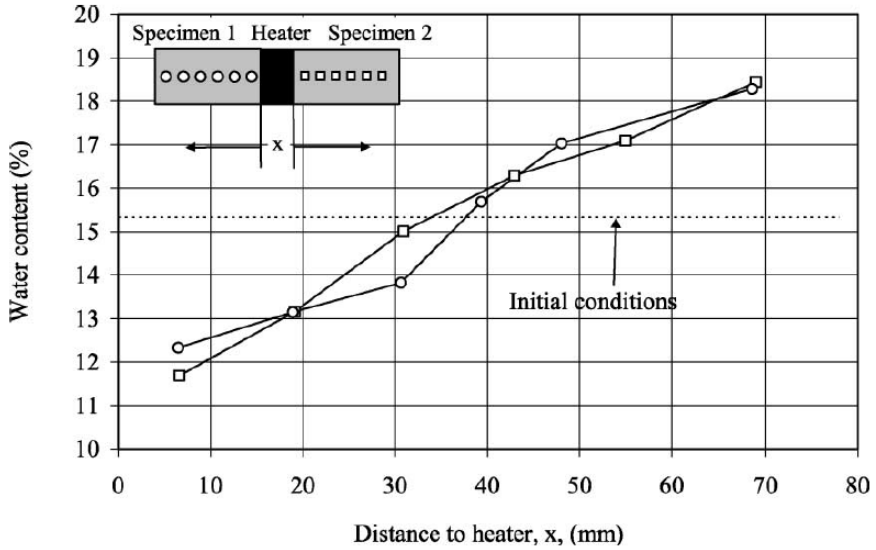
Laboratory experiments: non-isothermal

- UPC Thermal test (Pintado et al. 2002)
  - Compacted samples of bentonite

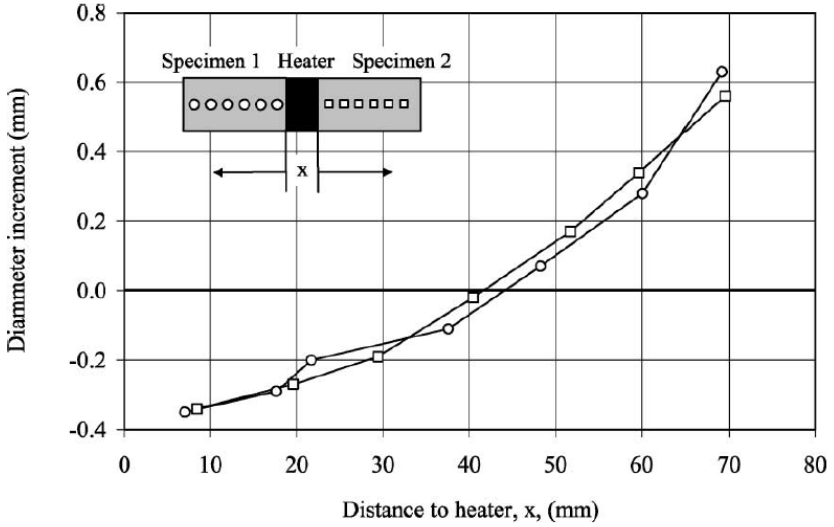


temperatures





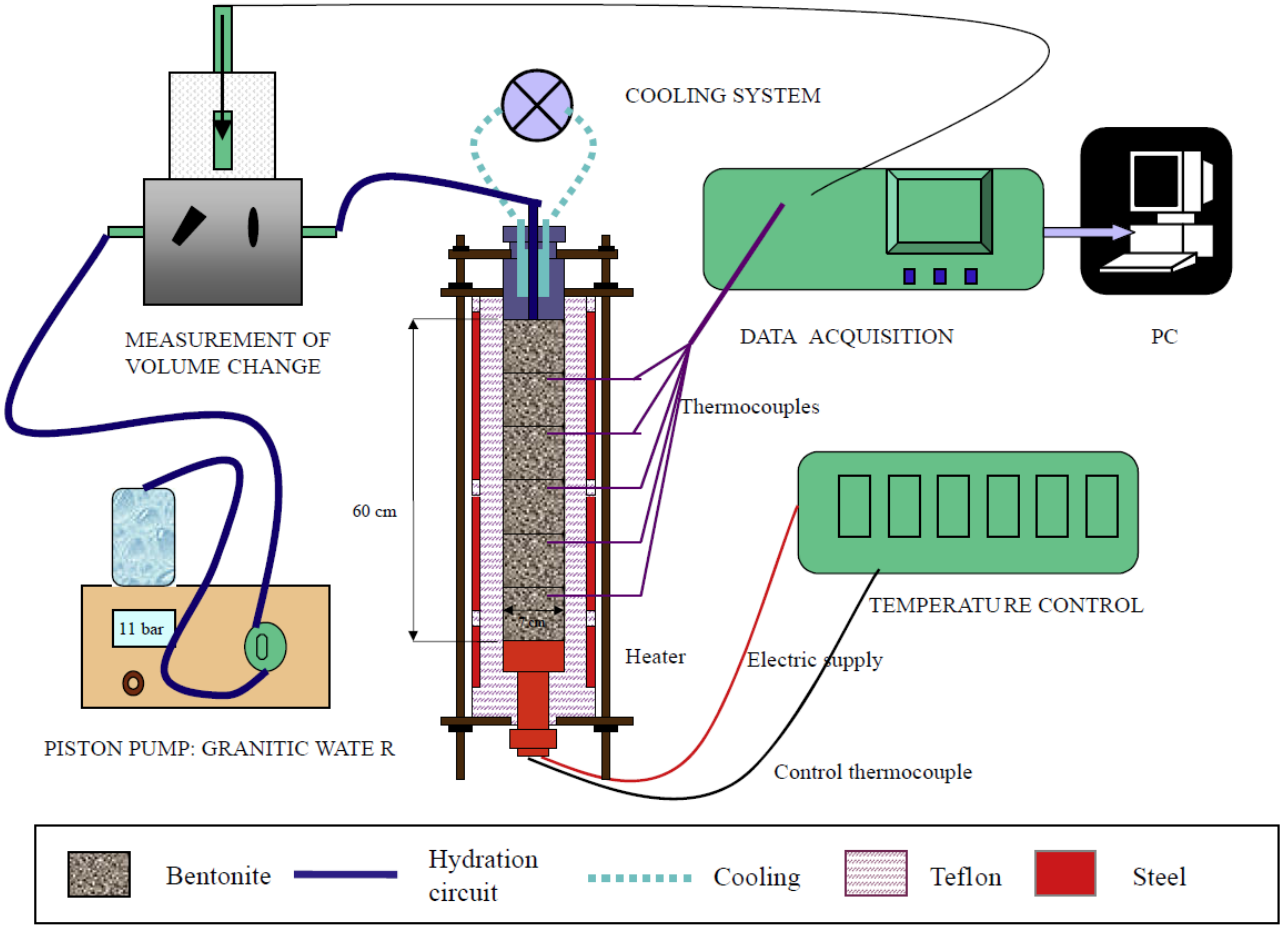
water content



diameter change

Laboratory experiments: non-isothermal

- CIEMAT thermo-hydraulic tests (Villar et al. 2008, 2012)
  - Compacted samples of FEBEX bentonite.
  - Dry density: 1.66 g/cm^3, w/c: 13.6%
  - Length; 60 cm, temperature 100ºC
  - Tests dismantled at 6 months (2), 12 months (2), 24 months (2) and 7.6 years (1)



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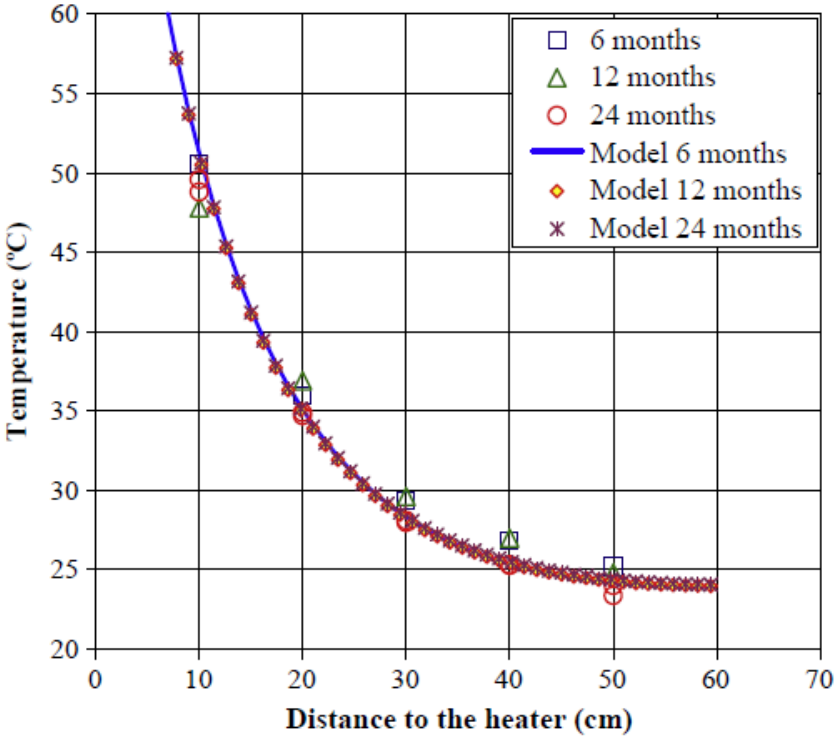
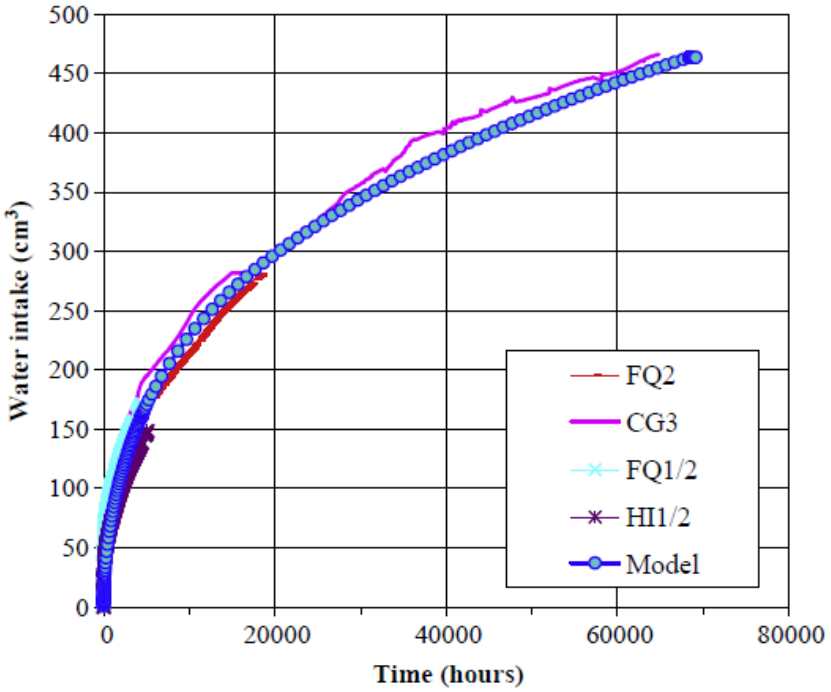


temperatures



water intake

Laboratory experiments: non-isothermal

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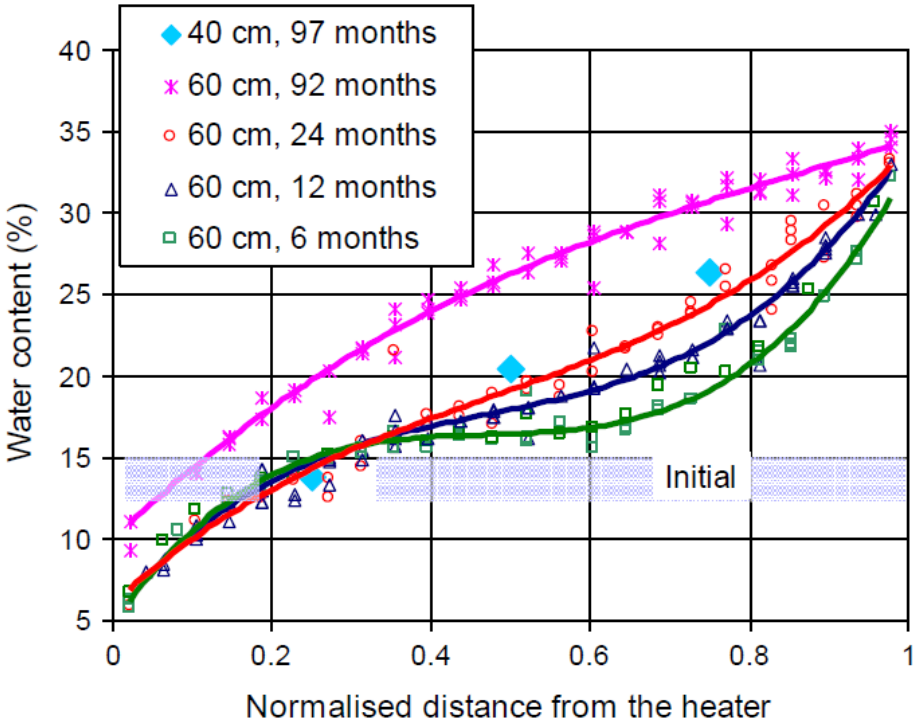
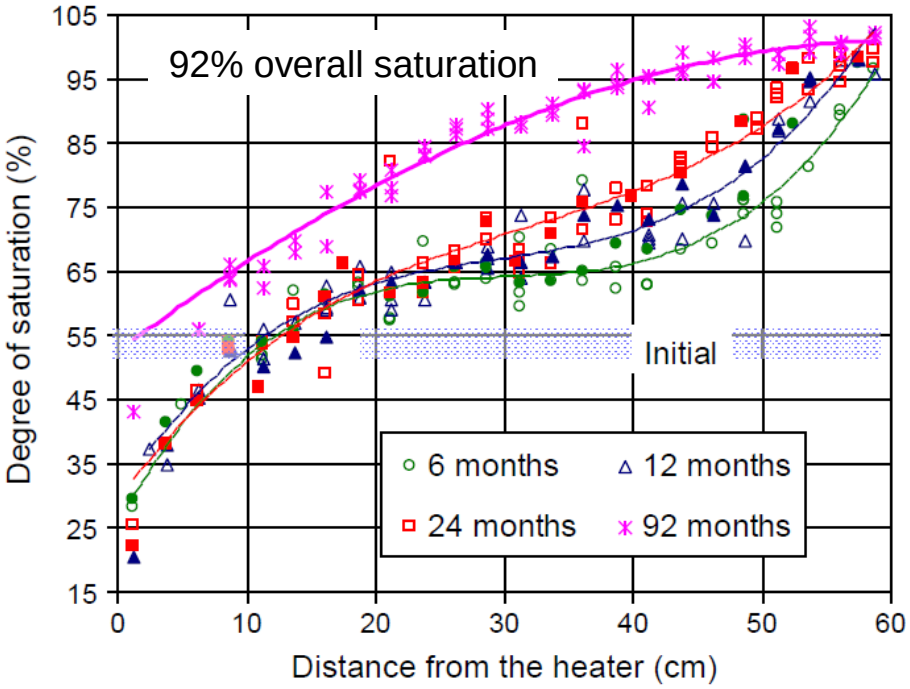
  - Compacted samples of FEBEX bentonite.
  - Dry density: 1.66 g/cm^3, w/c: 13.6%
  - Length; 60 cm, temperature 100ºC
  - Tests dismantled at 6 months (2), 12 months (2), 24 months (2) and 7.6 years (1)



water content



degree of saturation

Laboratory experiments: non-isothermal

- CIEMAT thermo-hydraulic tests (Villar et al. 2008, 2012)
  - Compacted samples of FEBEX bentonite.
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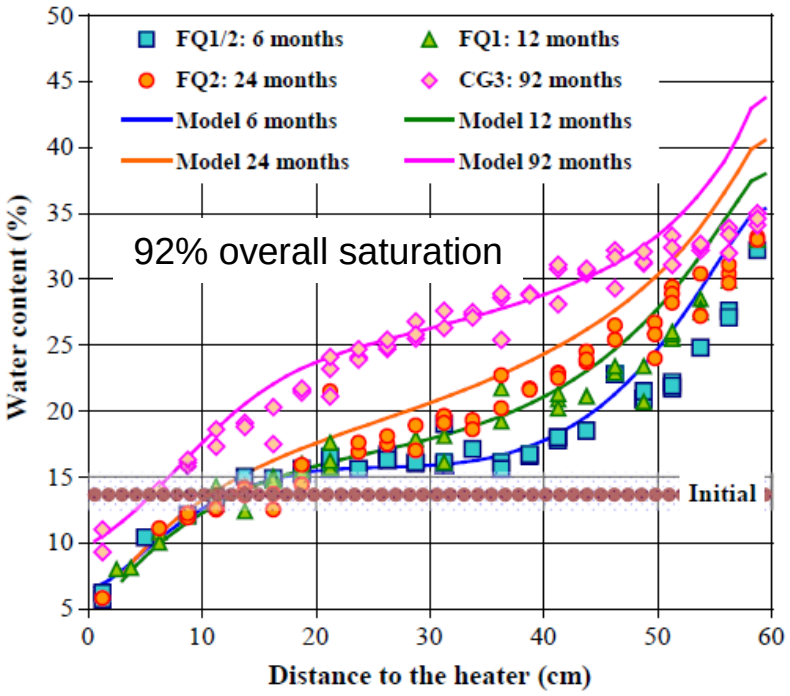
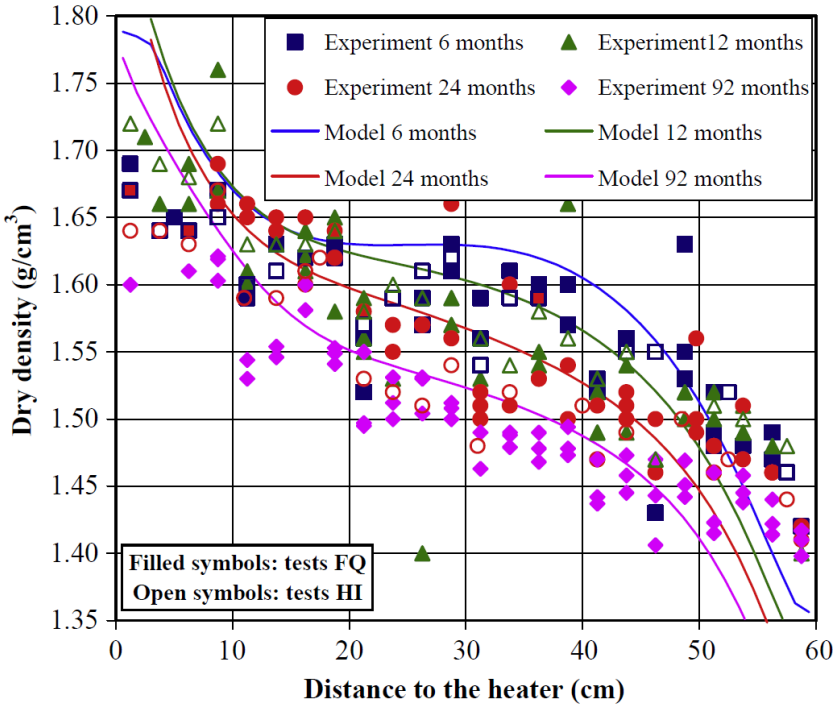


water content



dry density

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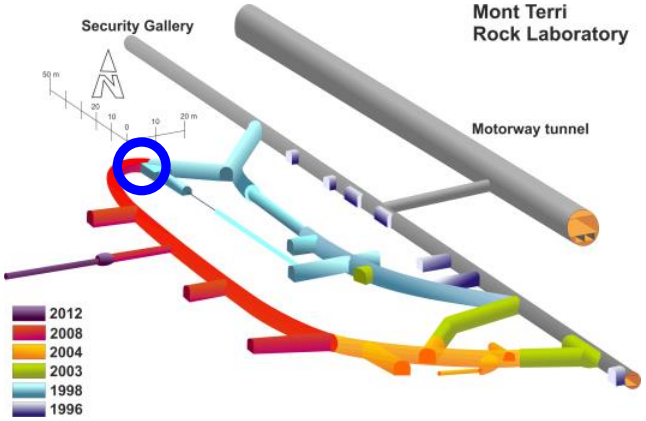
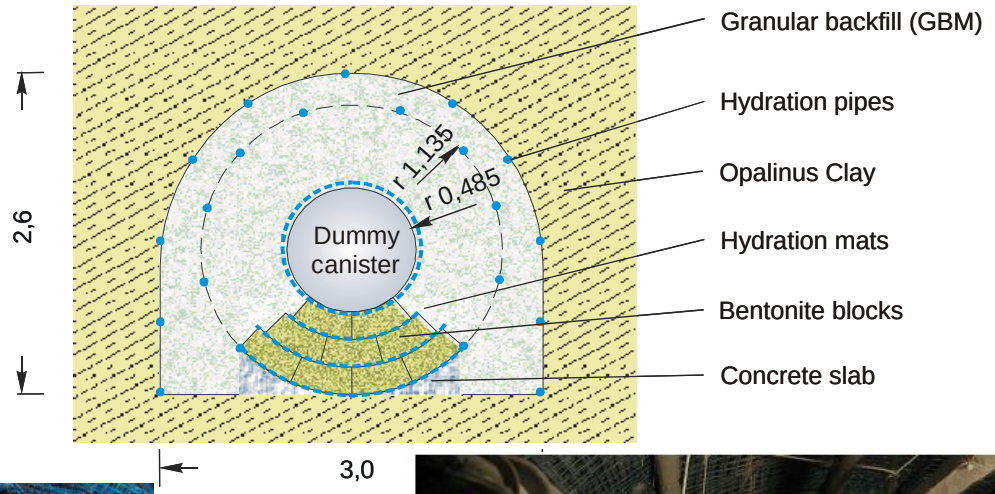
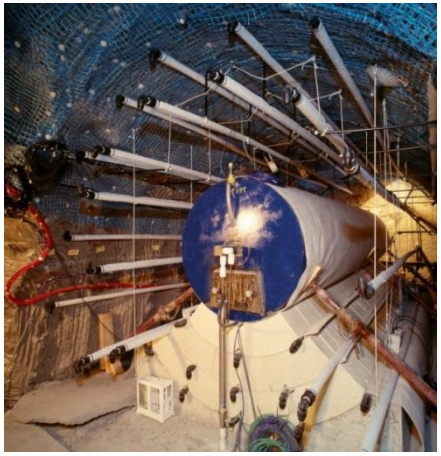
Large-scale field experiments: non-isothermal

EB experiment: main features

- Performed at the Mont Terri laboratory (Opalinus clay)
- Engineered barrier made up of a lower bed made of compacted bentonite blocks and an upper backfill made with a bentonite pellets based granular material
- Isothermal test, artificial hydration

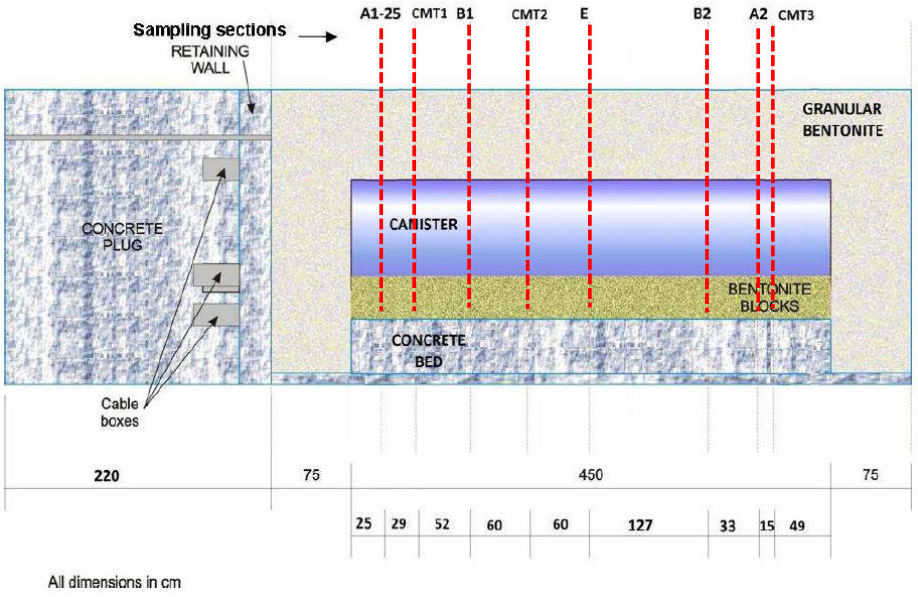






Large-scale field experiments: non-isothermal

- EB experiment: main features
  - Instrumentation to measure canister displacements, relative humidity in the buffer, pore pressures in the rock and total stress in the interfaces canister/buffer and rock/buffer.
  - Dismantled after 10.5 years of years of testing (water content and dry density distributions available). During dismantling, it has been confirmed that the barrier was saturated at the end of the experiment

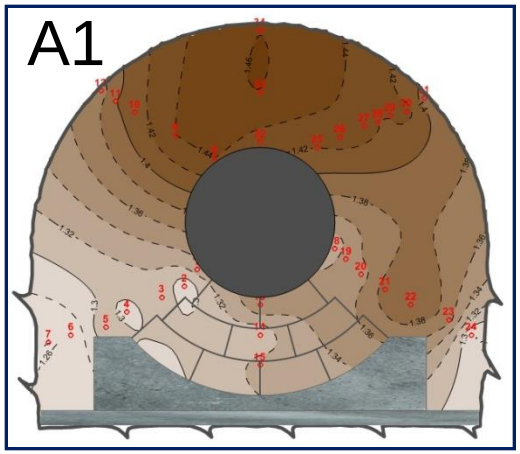


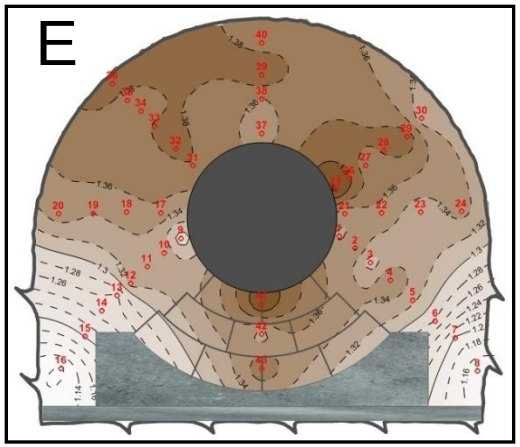
(Mayor & Velasco., 2014)

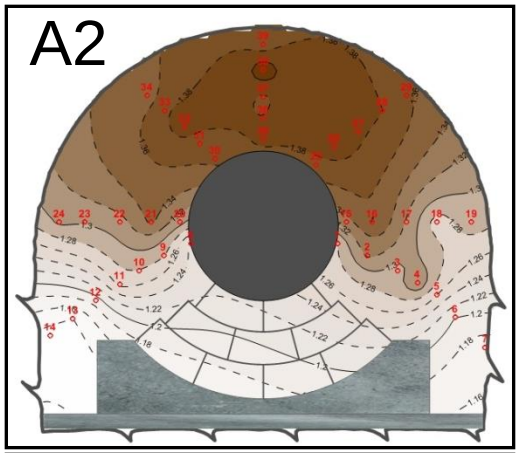
Large-scale field experiments: non-isothermal

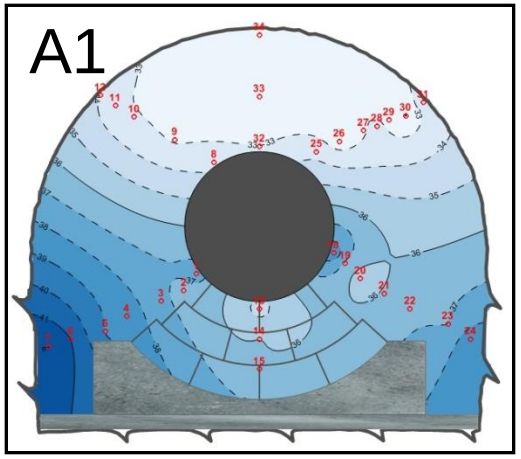
dry density

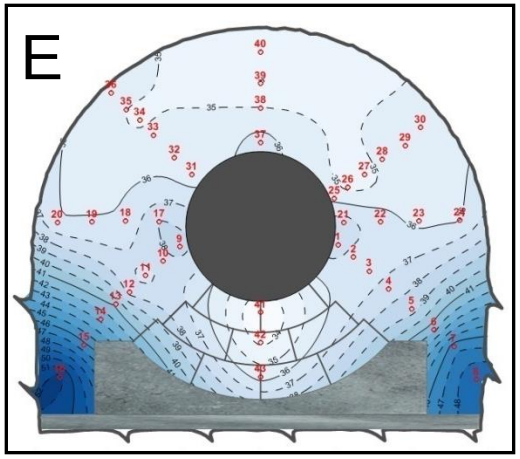
water content

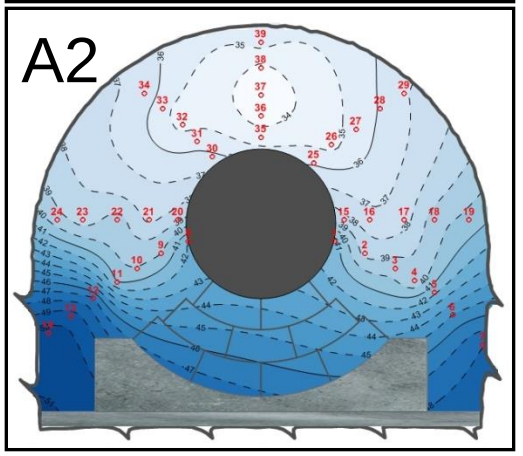


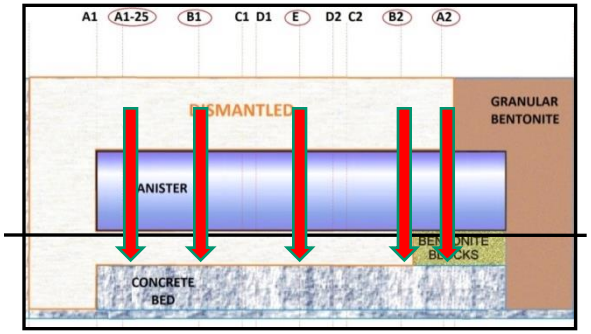












(Mayor & Velasco., 2014)

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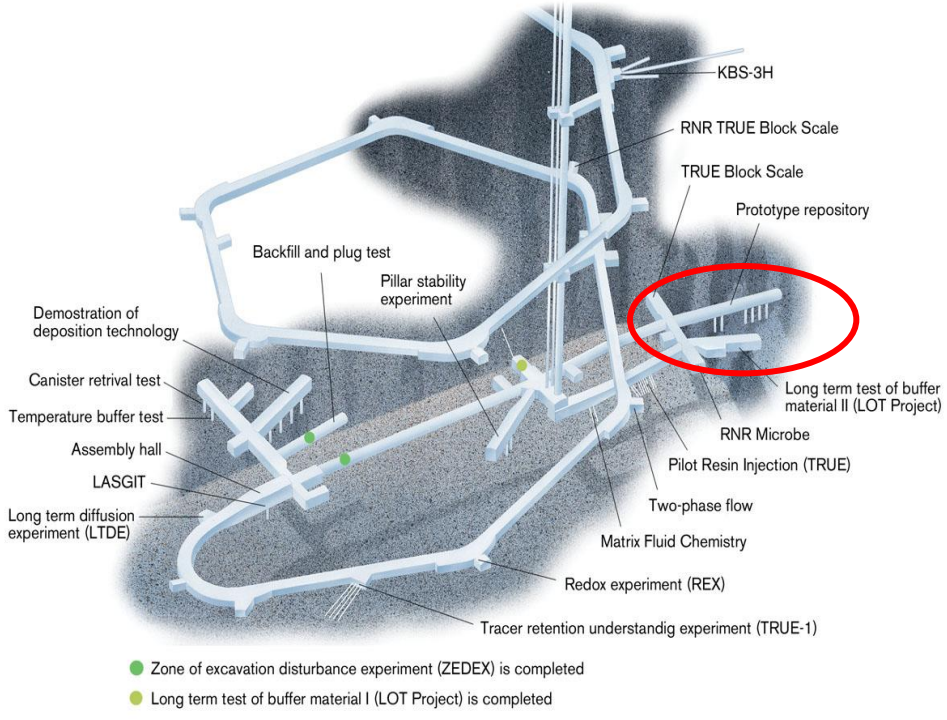
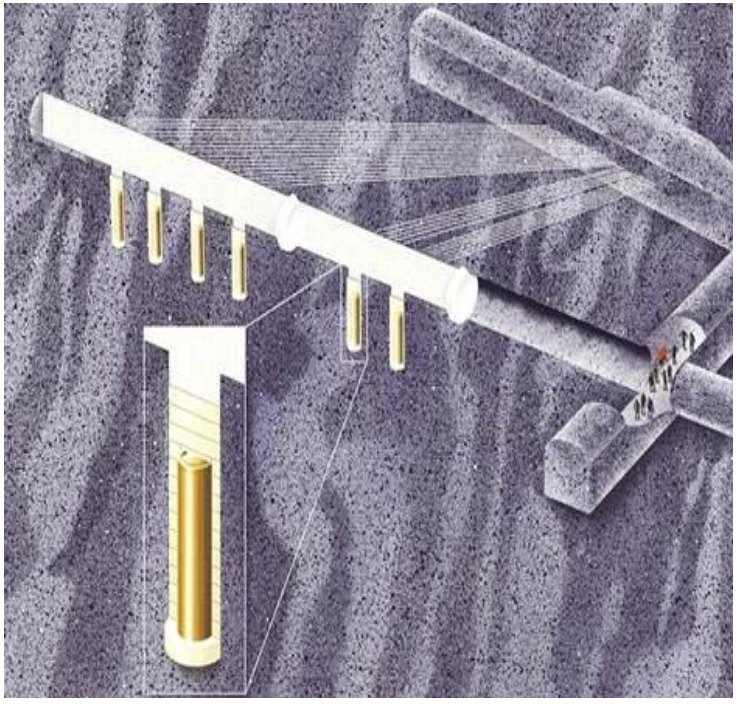
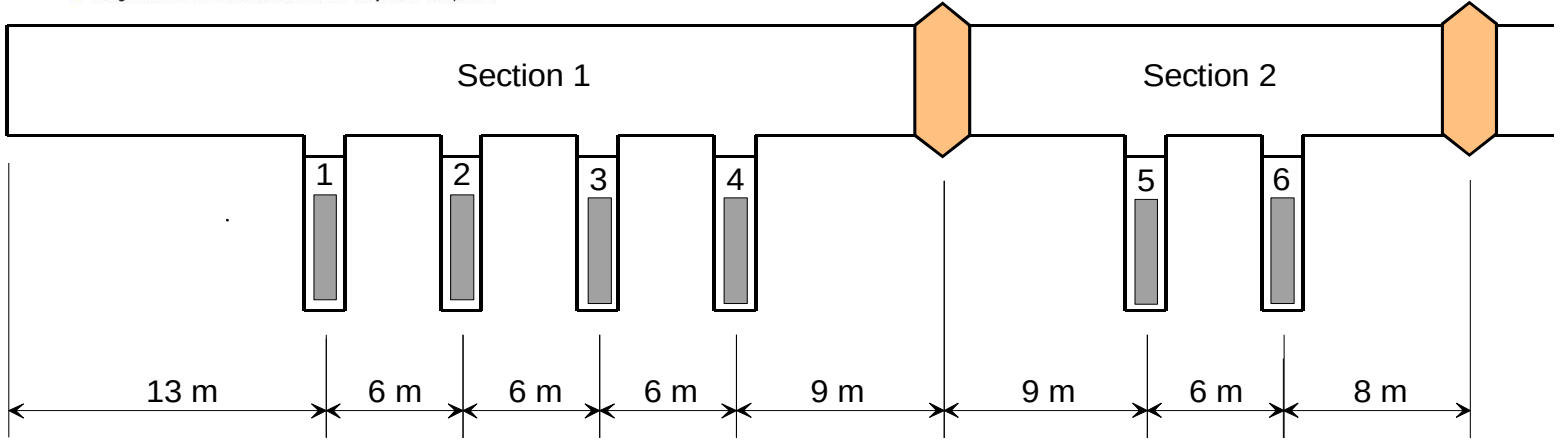
Large-scale field experiments: non-isothermal

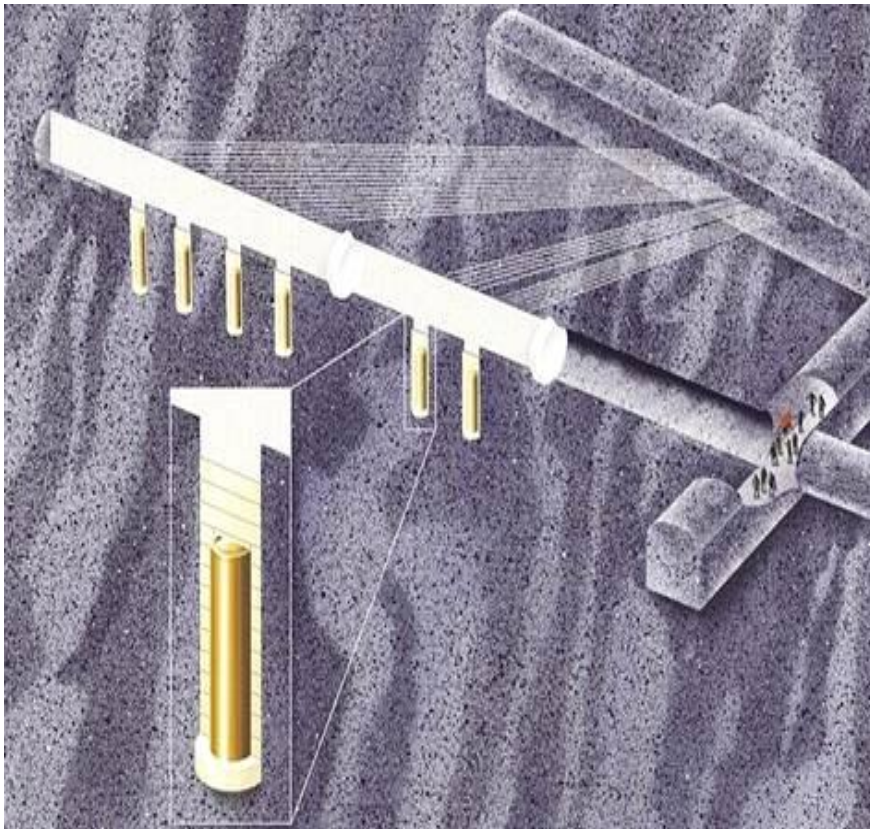
- Prototype experiment
  - Performed at Aspö HRL (level -450 m)







Large-scale field experiments: non-isothermal

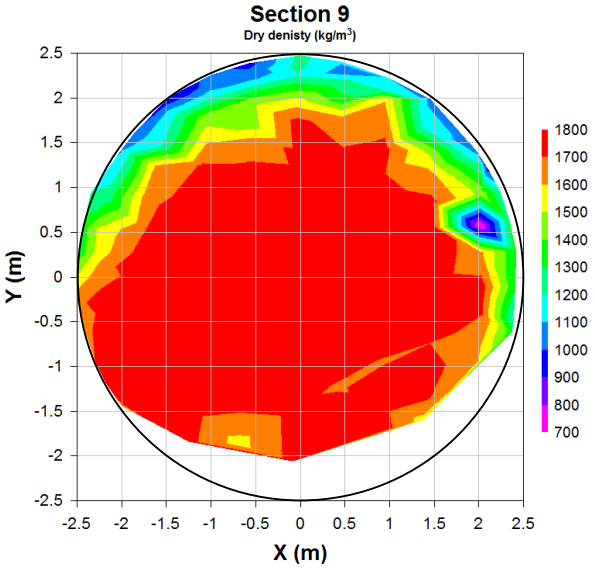


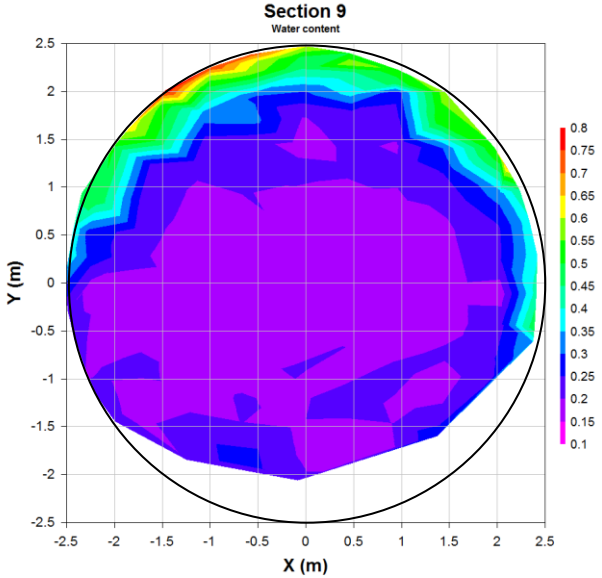
- Tunnel: 65 m long and 5 m in diameter
- Deposition holes: 8.37 m deep and 1.75 m in diameter
- There are two sections, both ending with a concrete plug.
- The deposition holes were installed with canisters/heaters and buffer.
- The first 11 m tunnel is backfilled with crushed rock and the remaining tunnel with 30% bentonite and 70% crushed rock.

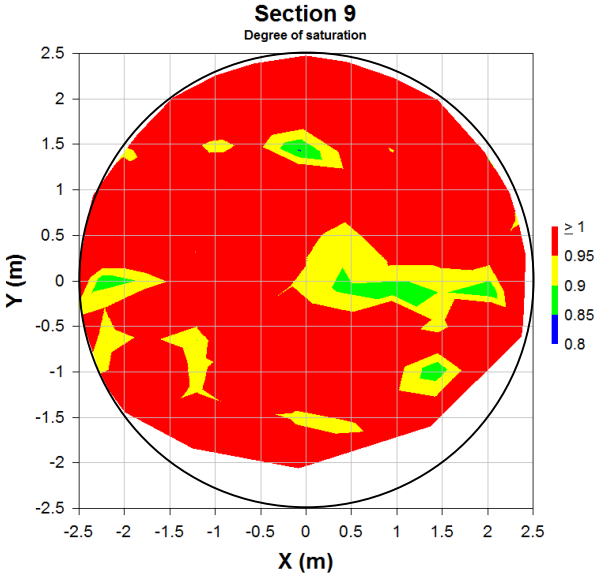
- 2001 inner part installed
- 2003 outer part installed
- 2004 outer plug installed
- 2004 heater problems began
- 2010 excavation of outer part began
- 2011 excavation carried out and finished
- 2014 reporting finished of excavation phase
- Approx. 2021 inner section to be excavated

Large-scale field experiments: non-isothermal

- Prototype experiment
  - Dismantling the backfill







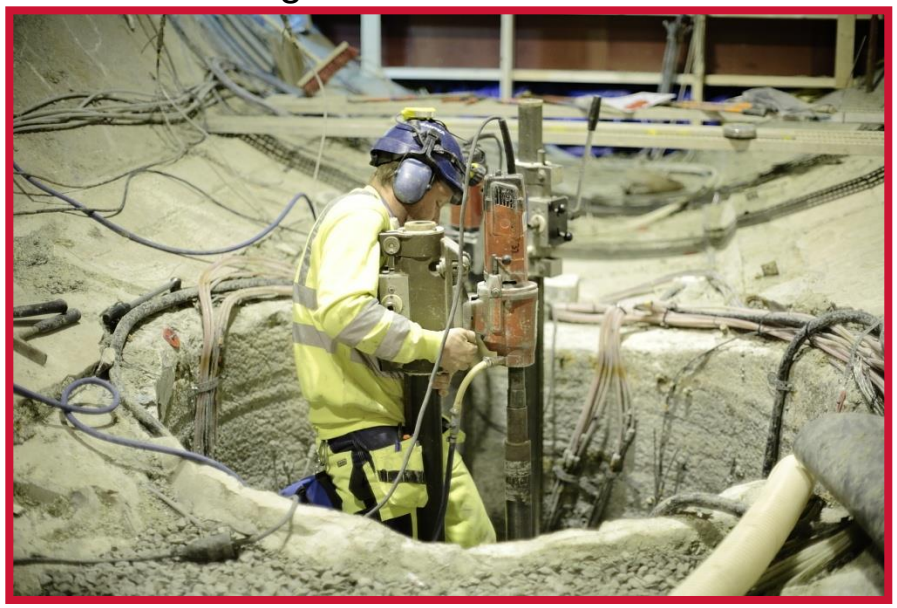
dry density

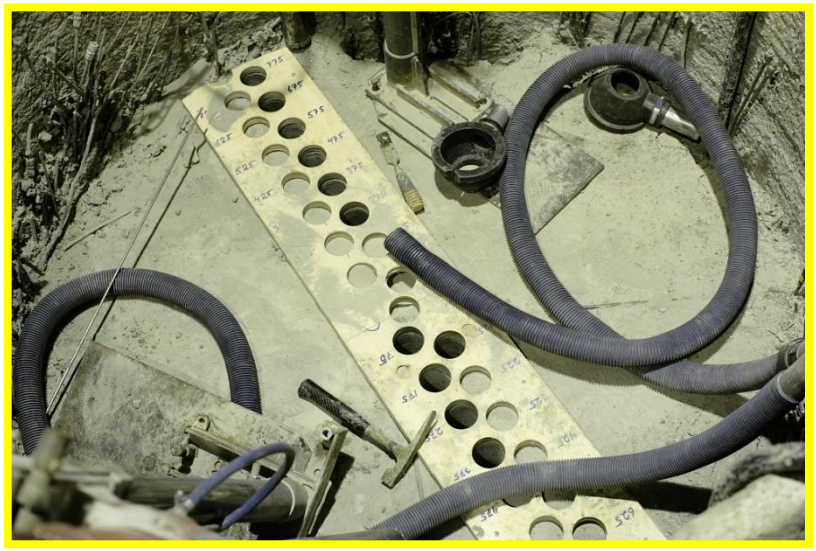
water content

degree of saturation

Large-scale field experiments: non-isothermal

- Prototype experiment
  - Dismantling the Buffer

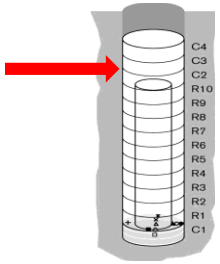




(Kristensson & Malmberg 2013)

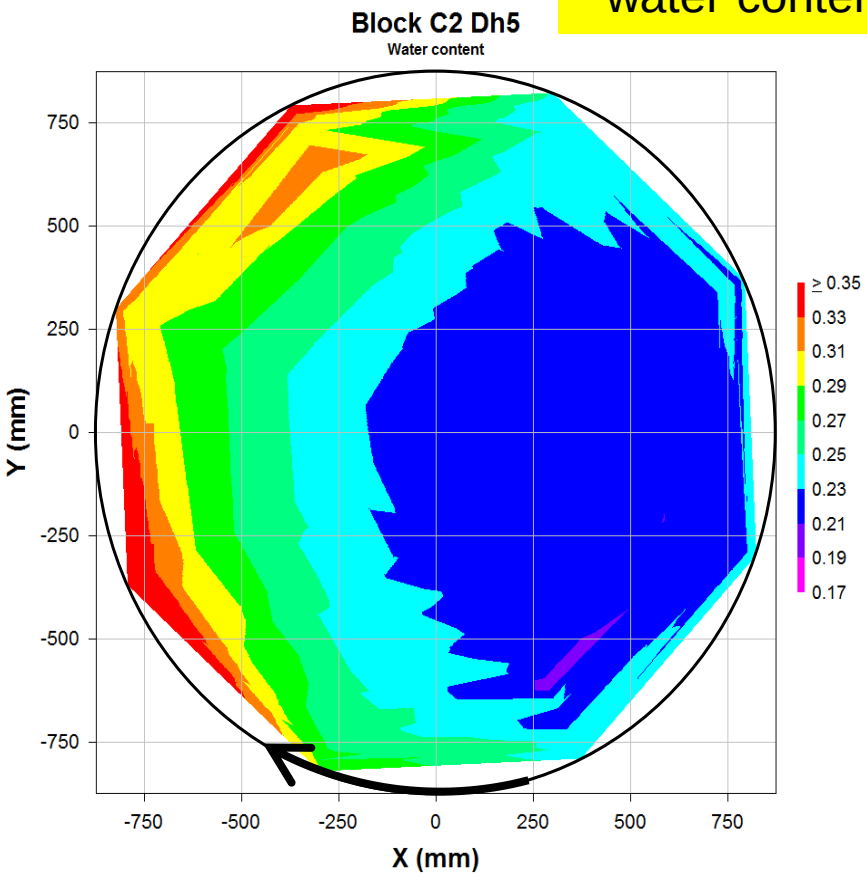
Large-scale field experiments: non-isothermal

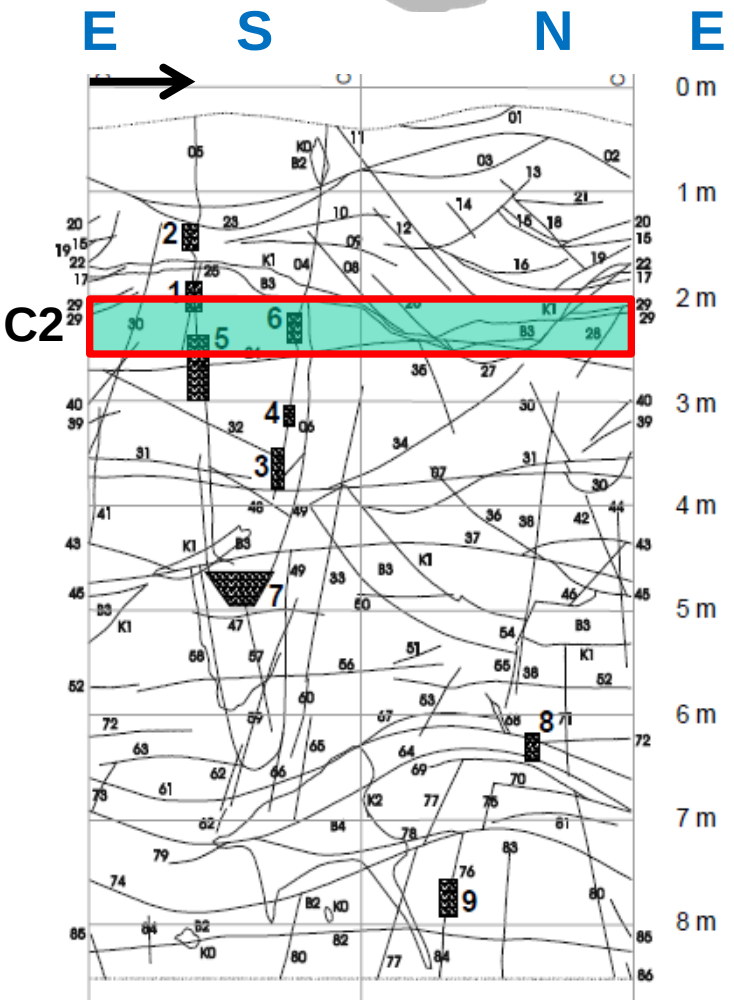
- Prototype experiment
  - Dismantling the Buffer



DH5:C2

water content



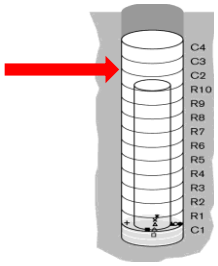


N

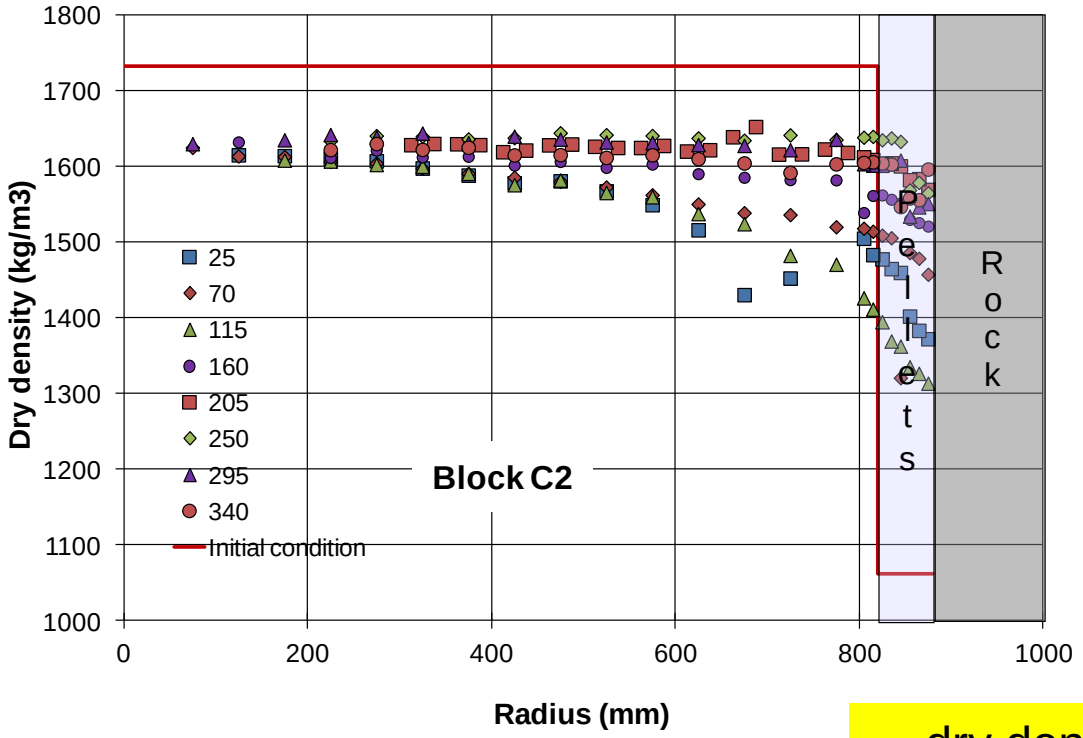
(Kristensson & Malmberg 2013)

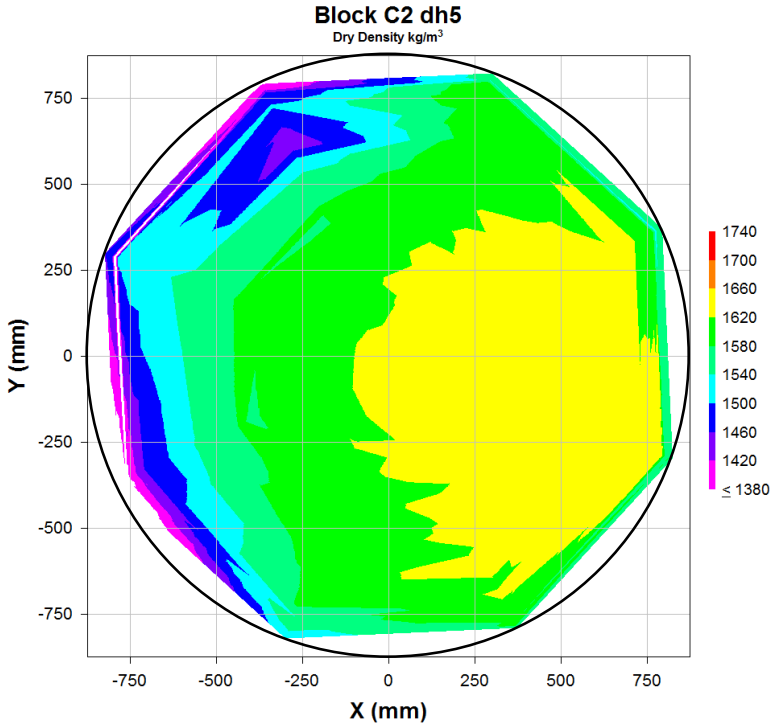
Large-scale field experiments: non-isothermal

- Prototype experiment
  - Dismantling the Buffer
    - Swelling of the outer part of the blocks
    - Compression of the pellet filled slot
    - The initial inner gap has closed
    - Processes have been non-symmetric



DH5:C2





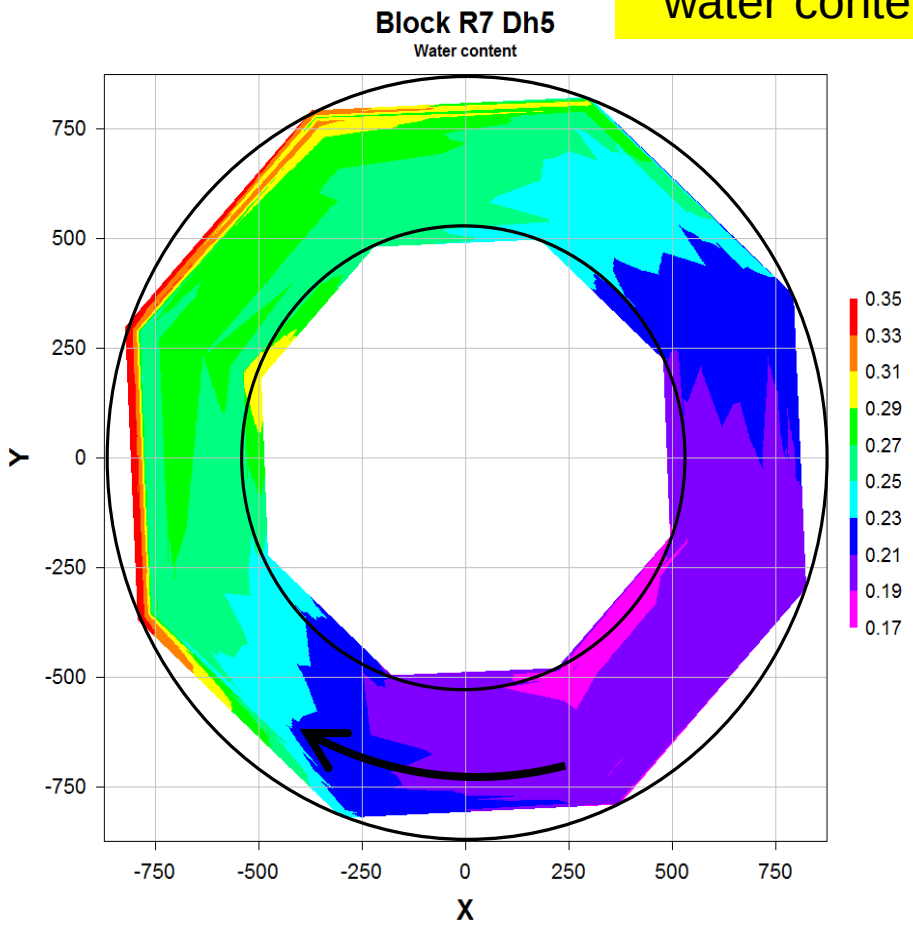
dry density

(Kristensson & Malmberg 2013)

Large-scale field experiments: non-isothermal

- Prototype experiment
  - Dismantling the Buffer

water content



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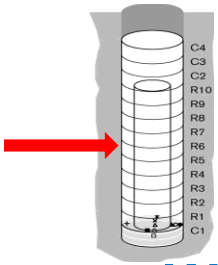
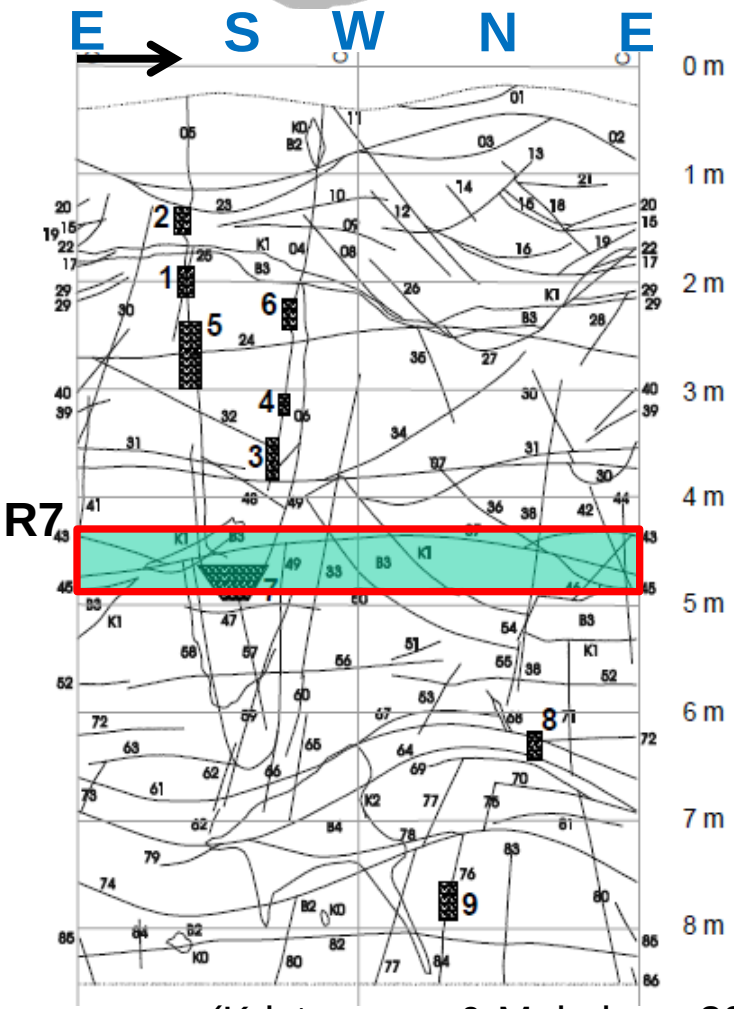


DH5:R6



(Kristensson & Malmberg 2013)

Large-scale field experiments: non-isothermal

- Prototype experiment
  - Dismantling the Buffer
    - Swelling of the outer part of the blocks
    - Compression of the pellet filled slot
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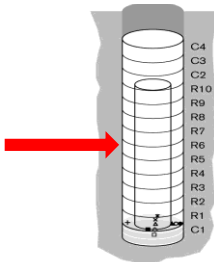
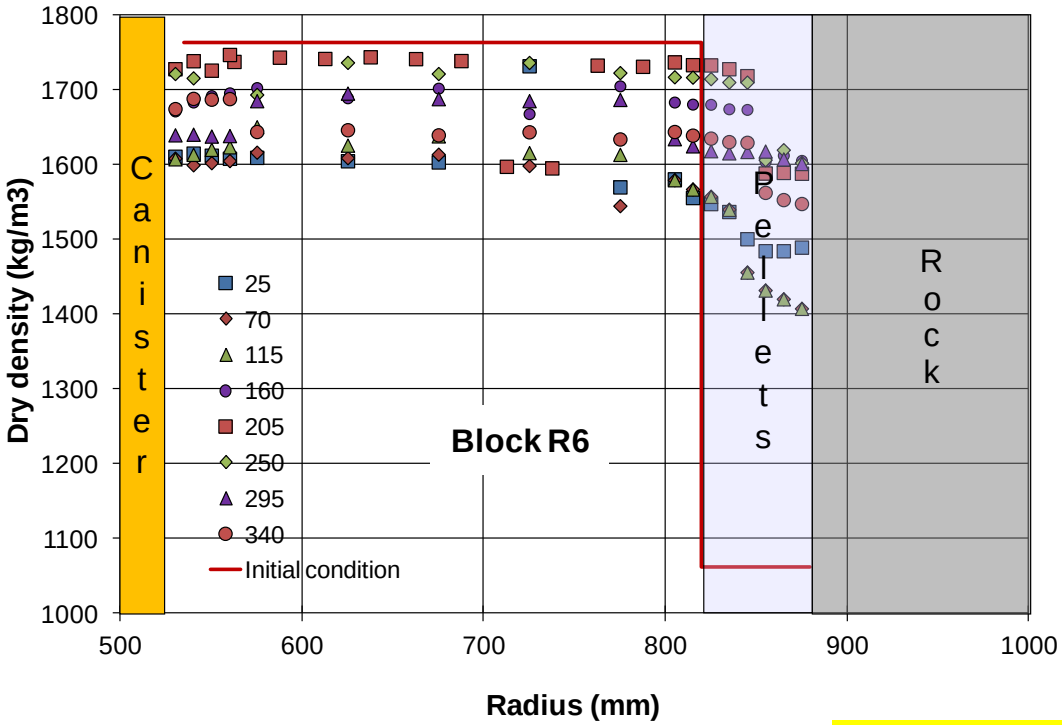
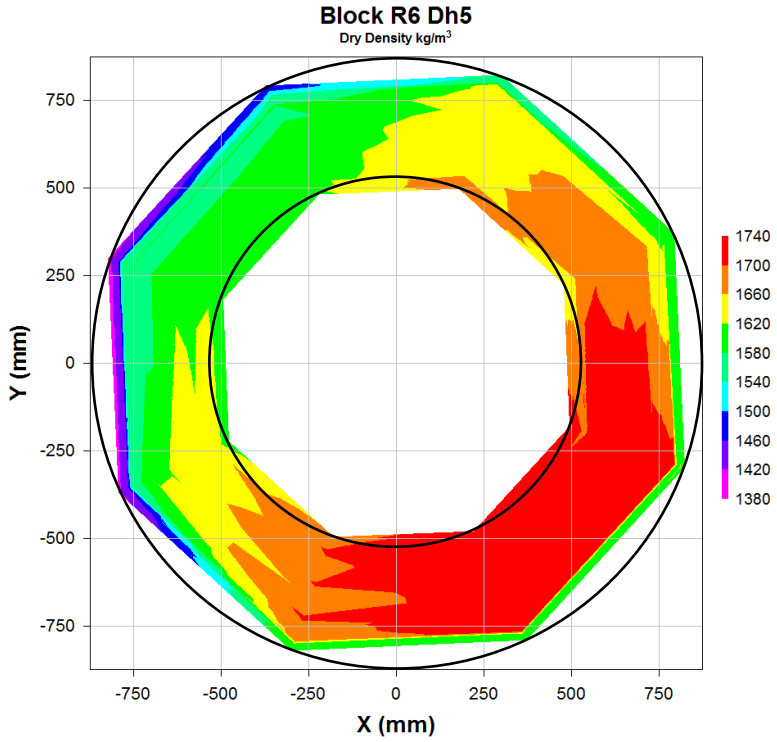


DH5:R6



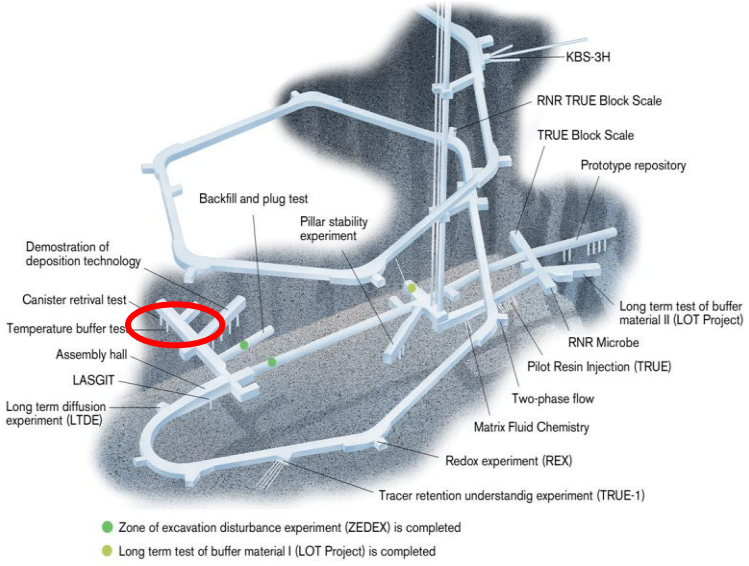


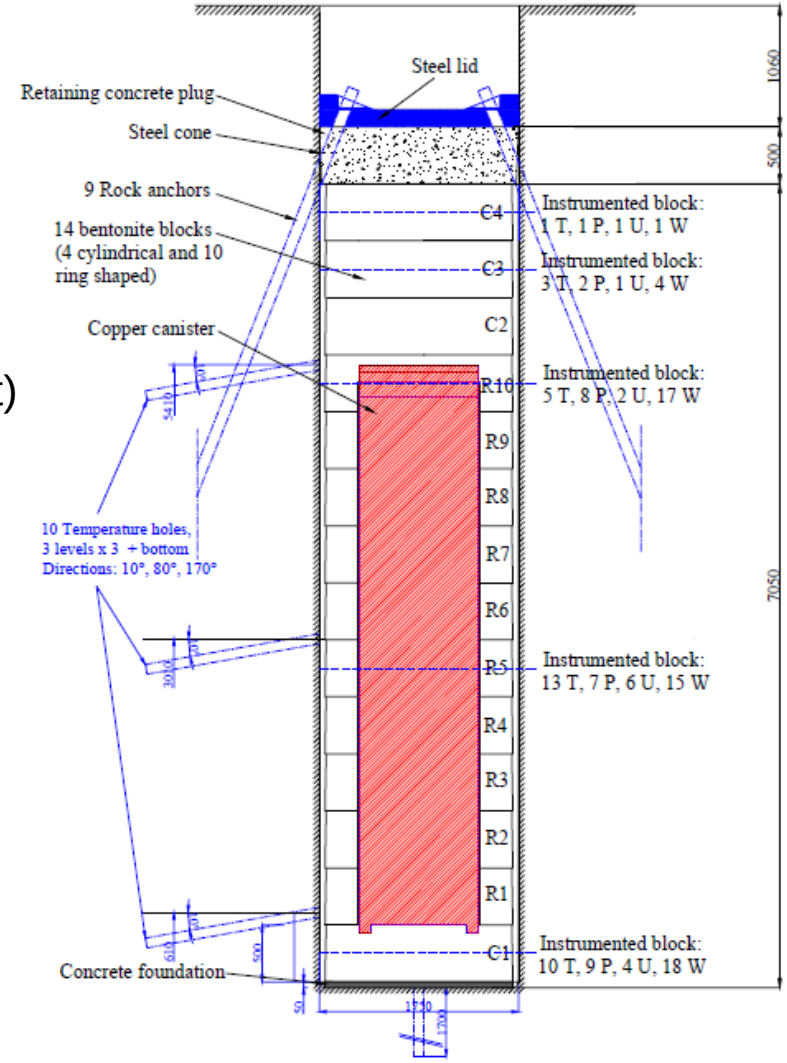
dry density

(Kristensson & Malmberg 2013)

Large-scale field experiments: non-isothermal

- Canister Retrieval Test (CRT)
  - Performed at Aspö Rock Laboragtory
- Installation
  - Located in the 420m level at Aspo
  - 8.55 m deep, 1.75 m diameter
  - 16 filter mats for artificial hydration
  - MX-80 bentonite blocks (d.d. = 1.71-1.79 g/cm^3)
  - Average initial w/c: 17%
  - Block diameter: 1.65 m (5cm thick pellet filled slot)
  - Canister diameter: 1.05m, weight 21.4 t
  - Thermal test





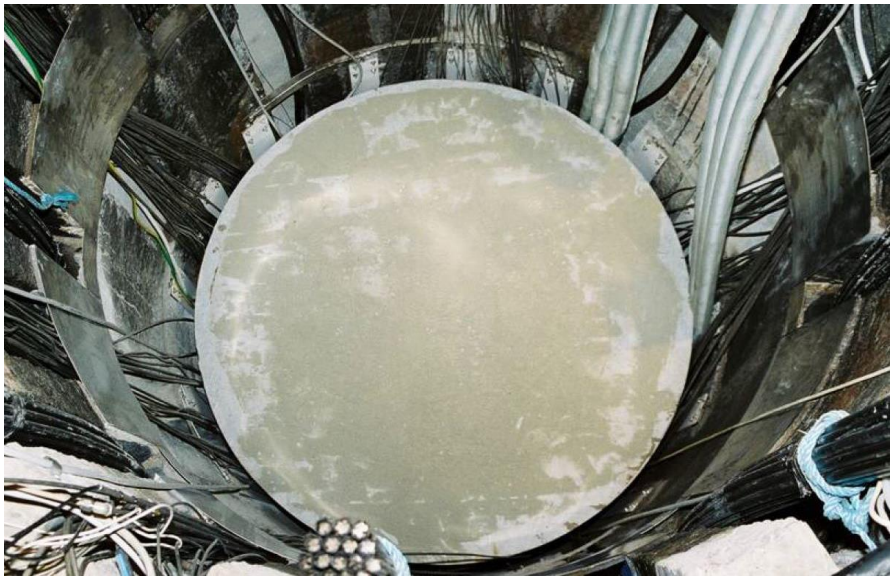
(Thorsager et al., 2002)

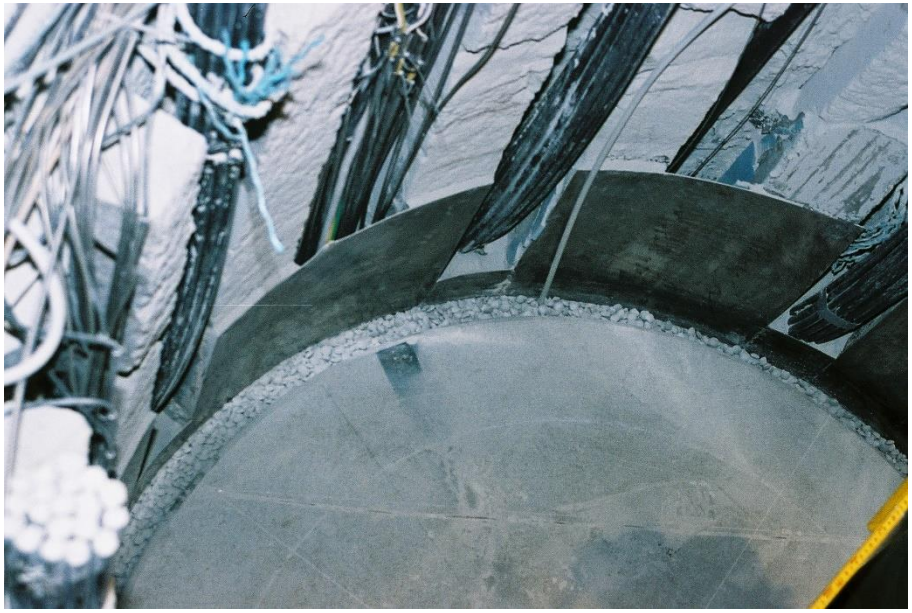
Large-scale field experiments: non-isothermal

- Canister Retrieval Test (CRT)

(Thorsager et al., 2002)

  - Installation



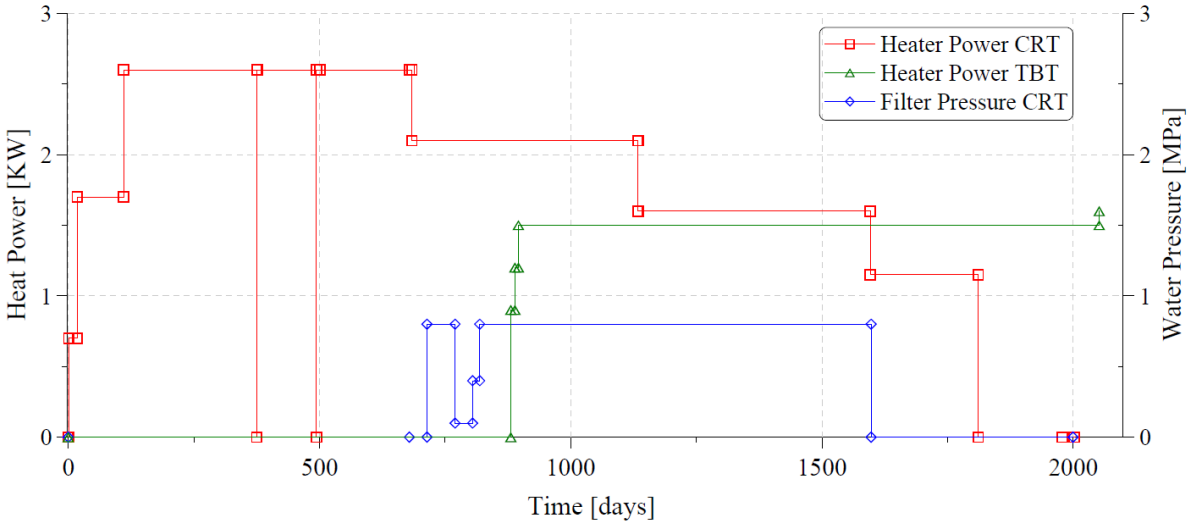


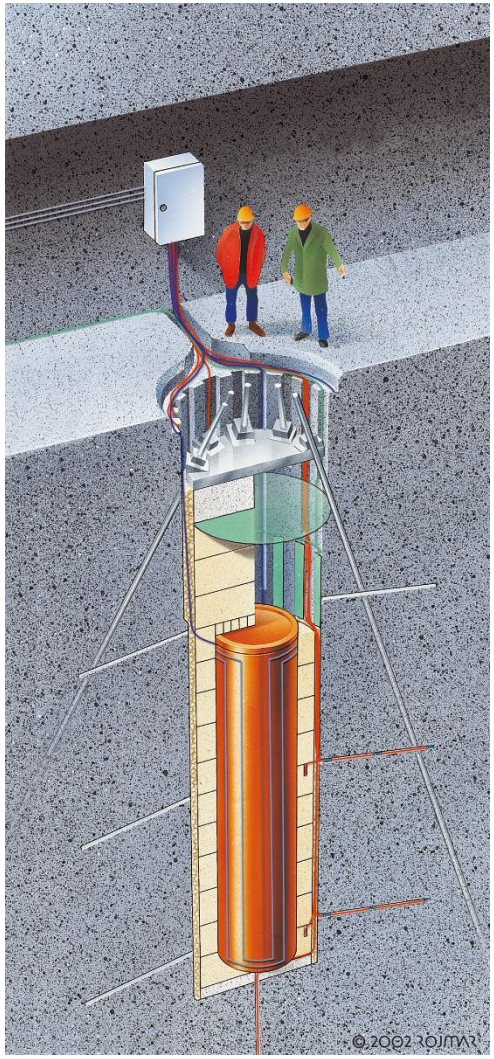
Large-scale field experiments: non-isothermal

- Canister Retrieval Test (CRT)
  - Installation

Three stages:

1. Boring of deposition hole and installation of instrumented bentonite blocks and canister with heaters. **2000**
2. Saturation of the bentonite and evolution of the thermal regime with measurement of thermal, hydraulic and mechanical processes. **2000-2005**
3. Sampling and test of freeing the canister from the bentonite and retrieving it. **2006**





(Thorsager et al., 2002)

Large-scale field experiments: non-isothermal

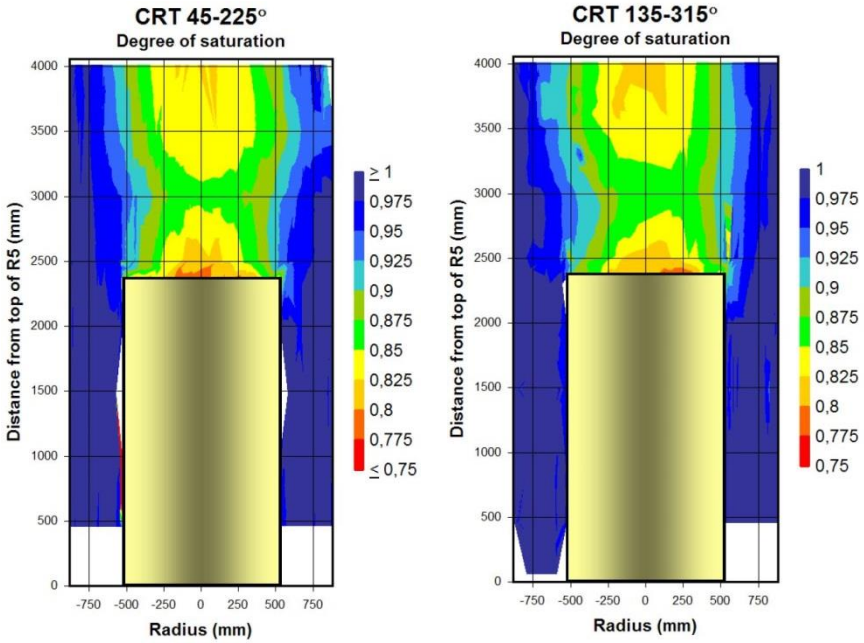
- Canister Retrieval Test (CRT)
  - Dsimantling

(Johannesson, 2007)

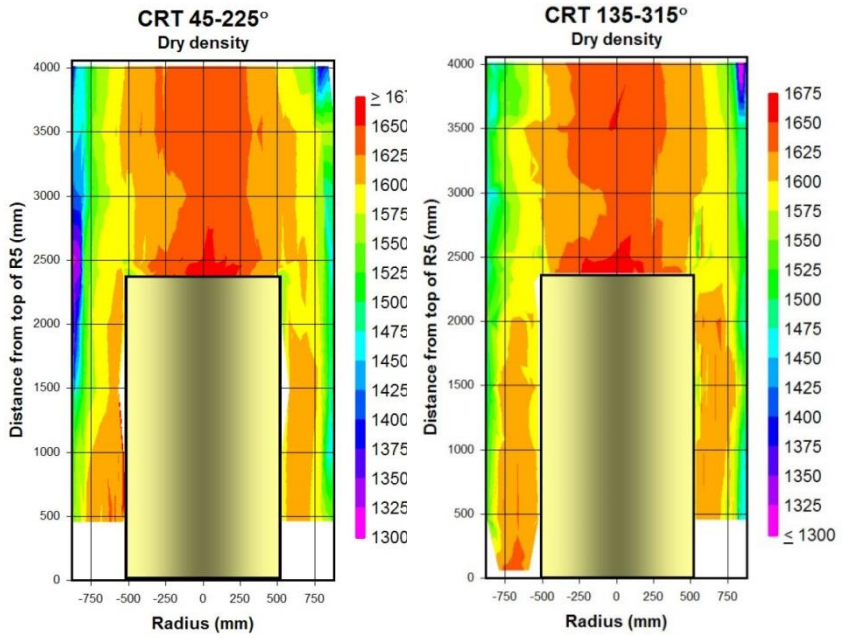
Large-scale field experiments: non-isothermal

- Canister Retrieval Test (CRT)
  - Dismantling

Final state



Degree of saturation



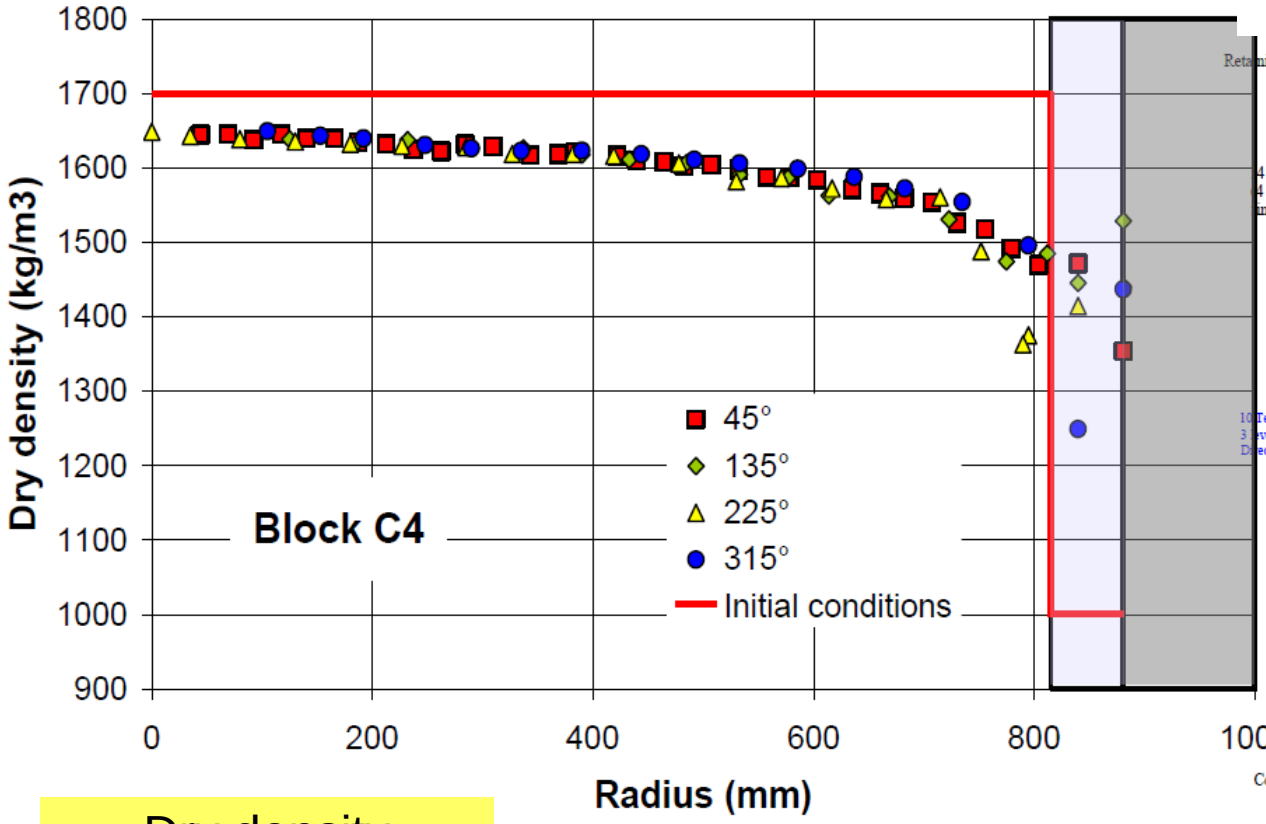
Dry density

(Johannesson, 2007)

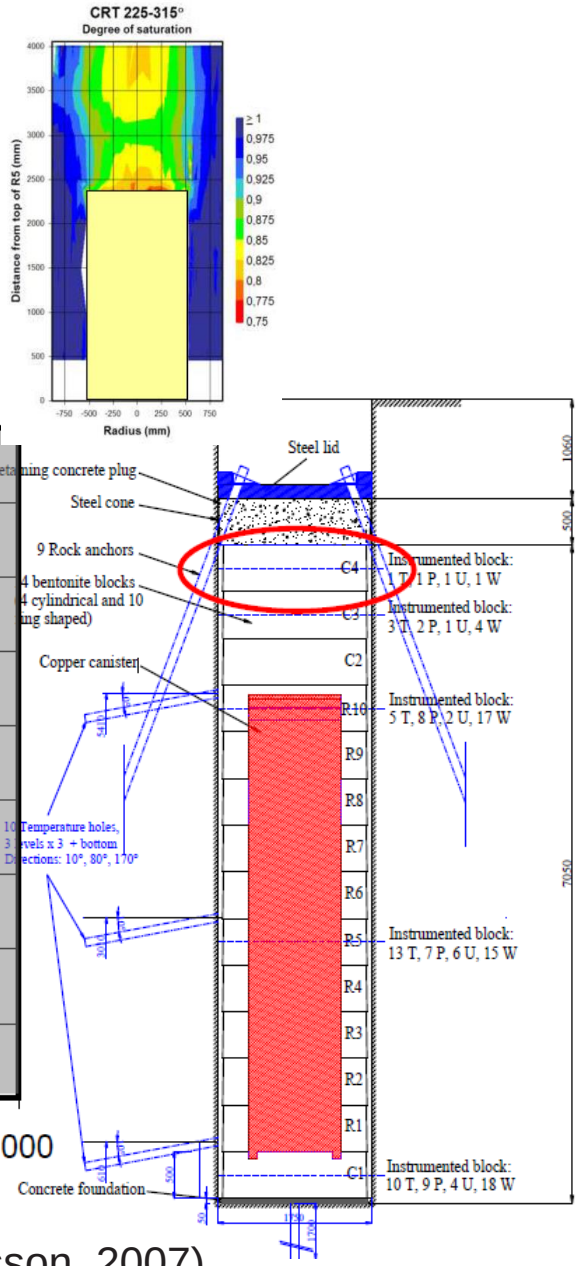
Large-scale field experiments: non-isothermal

- Canister Retrieval Test (CRT)
  - Dsimantling

Final state



Dry density

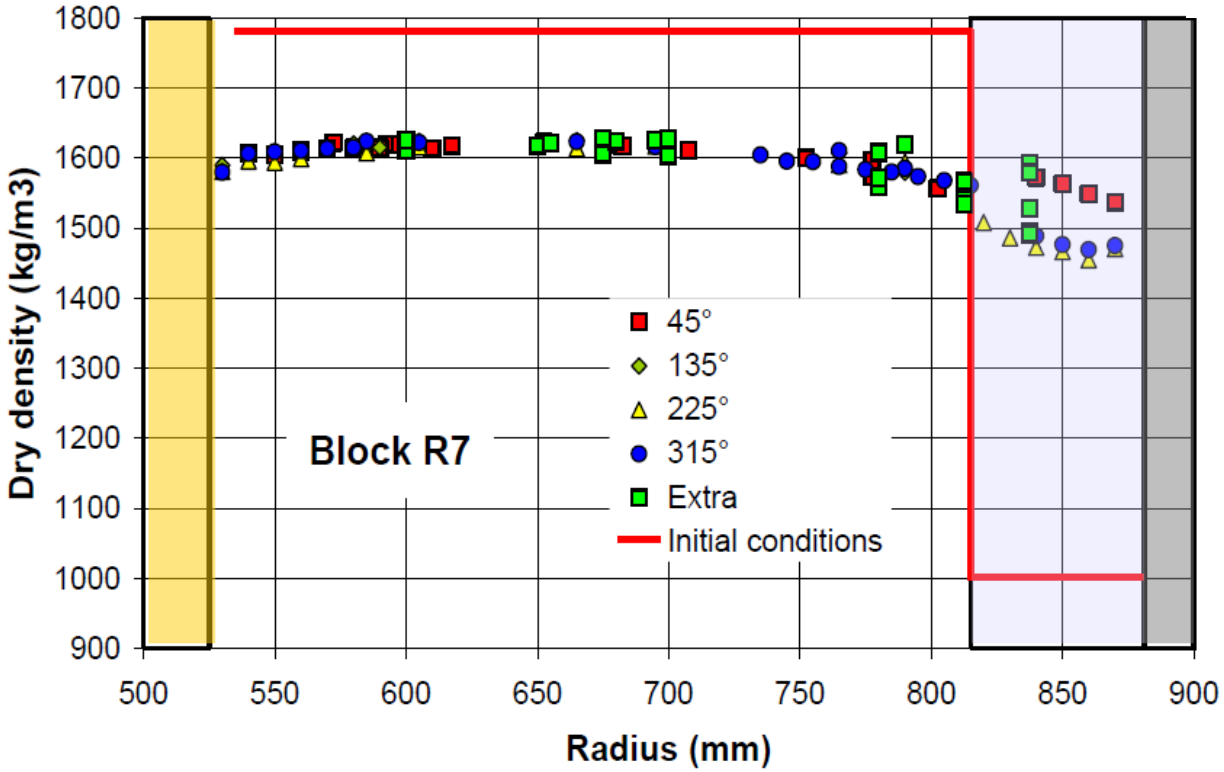


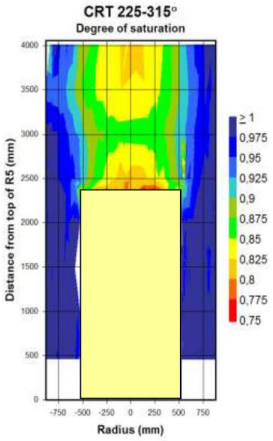
(Johannesson, 2007)

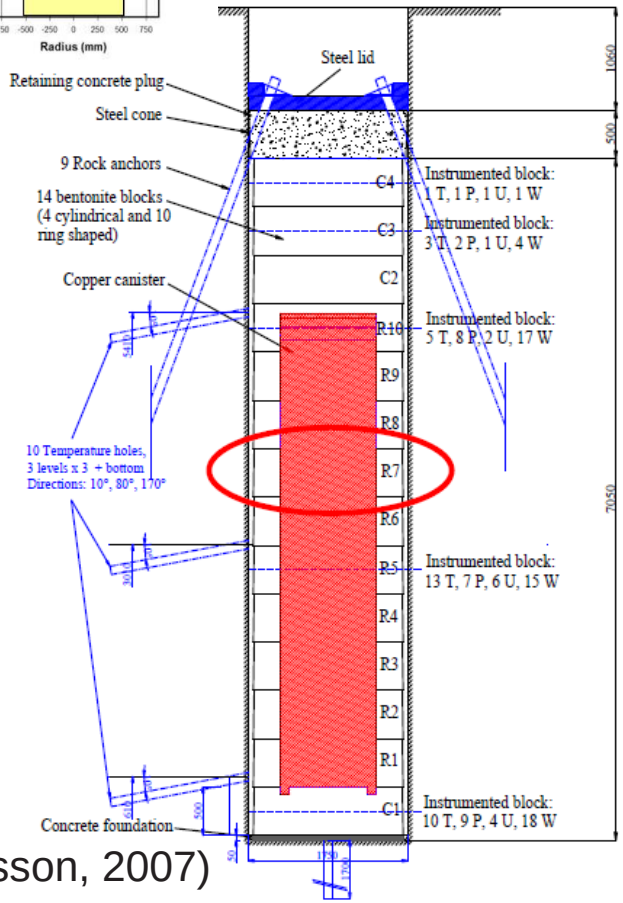
Large-scale field experiments: non-isothermal

- Canister Retrieval Test (CRT)
  - Dismantling

Final state





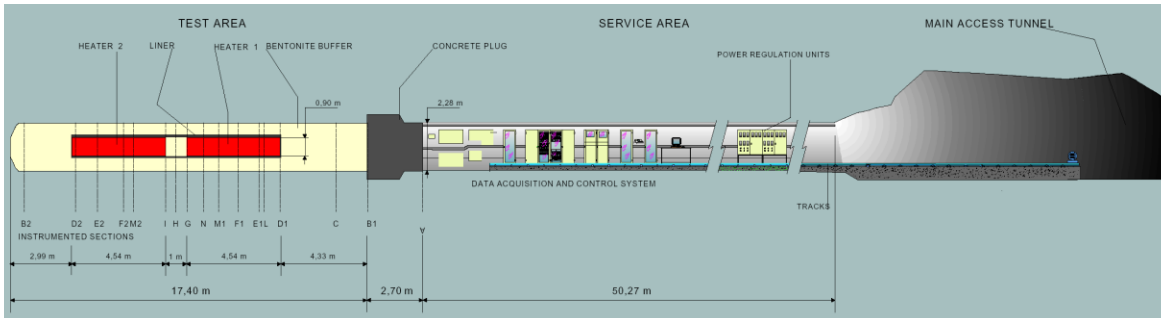


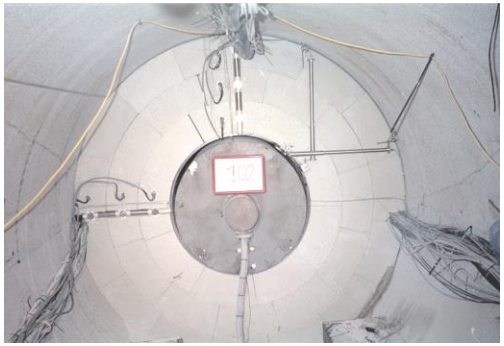
(Johannesson, 2007)

Large-scale field experiments: non-isothermal

Febex Test: main features

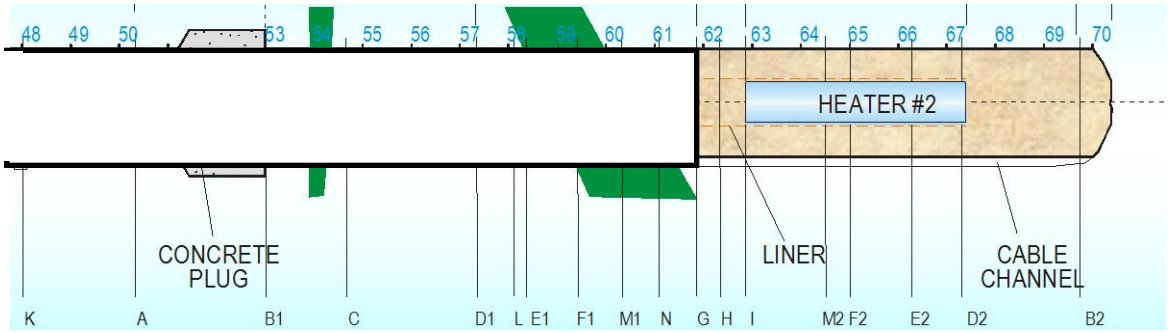
- Performed at the Grimsel Test Site (granite)
- Engineered barrier made up of compacted bentonite blocks
- Temperature-controlled test (maximum temperature 100ºC)
- Natural hydration
- Measurements of temperature, relative humidity and total stress in the barrier. Measurements available throughout the test
- Partial dismantling after 5 years of heating
- Total dismantling after 18 yeas of heating

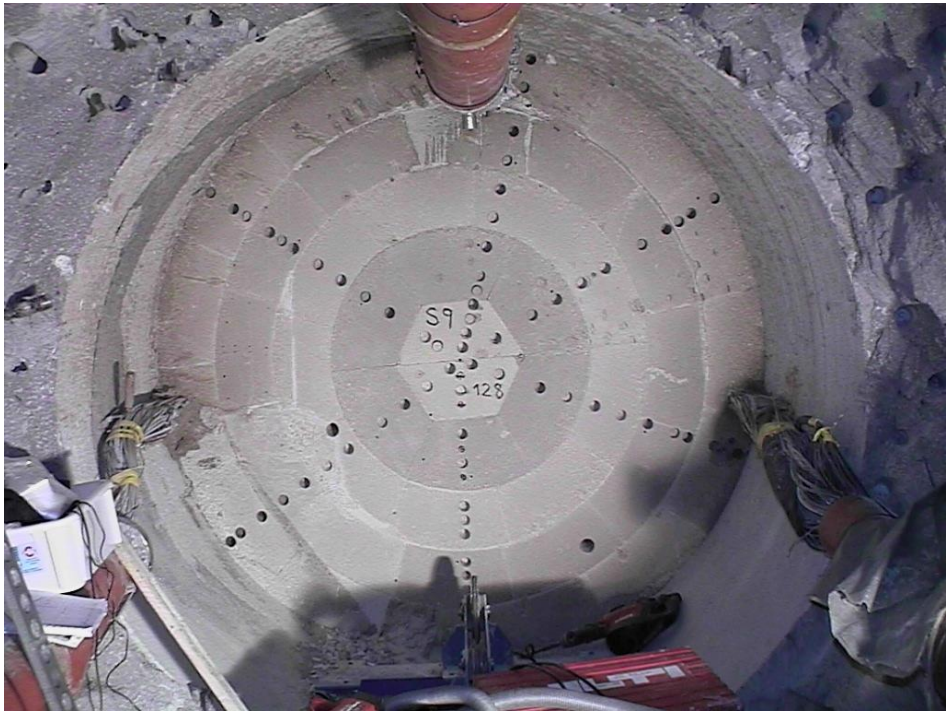




Large-scale field experiments: non-isothermal

- Febex Test: dismantling
  - Partial dismantling after 5 years of heating





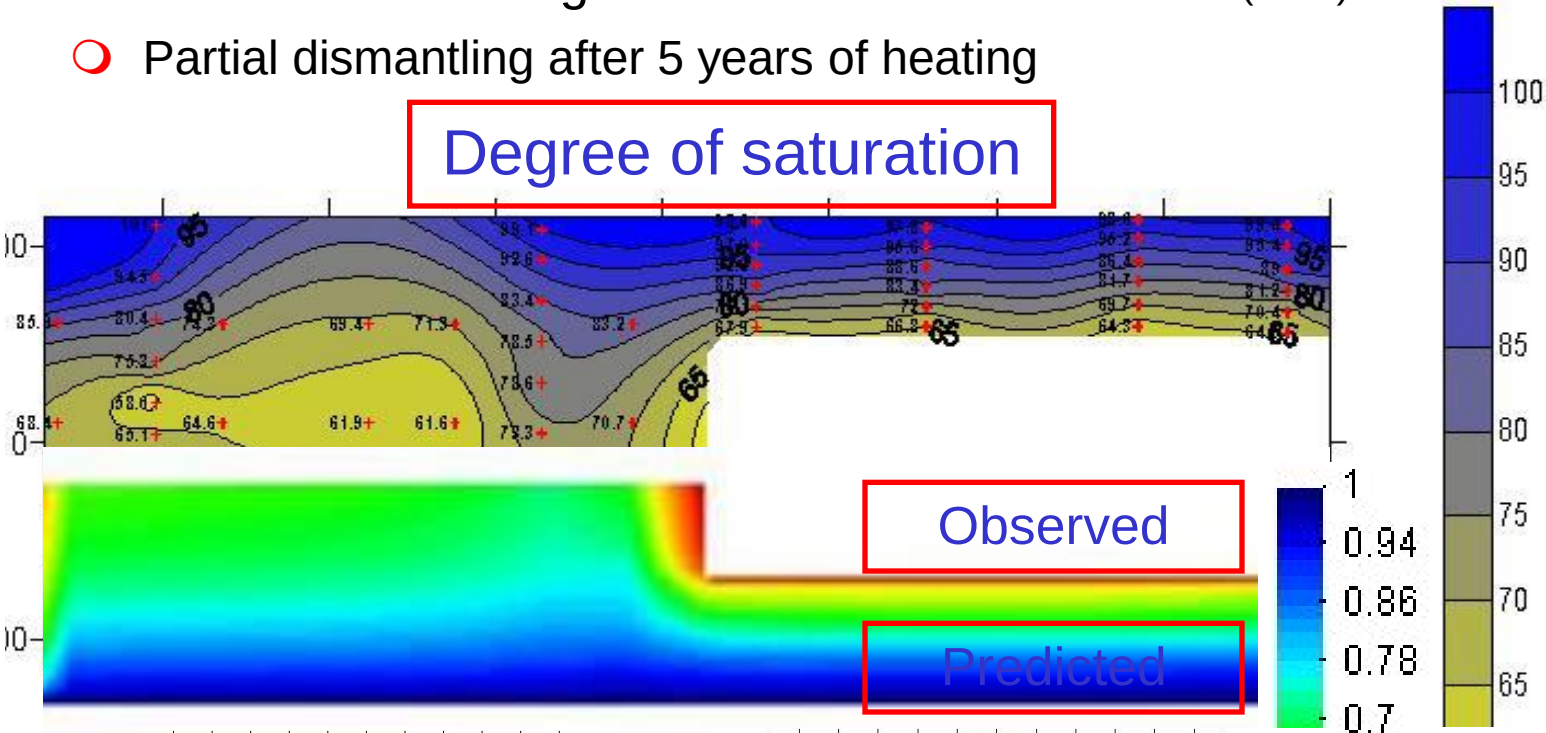
(Bárcena et al., 2003, Villar et al. 2005)

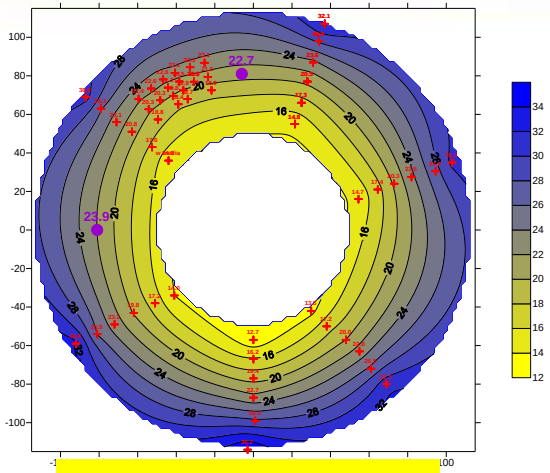
Large-scale field experiments: non-isothermal

- Febex Test: dismantling

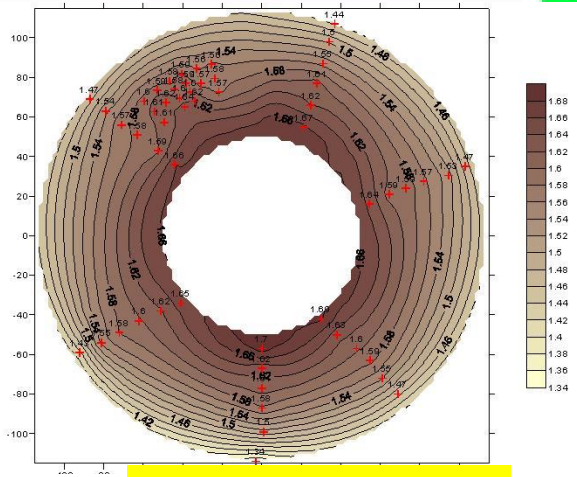
Lloret (2003) Villar et al. (2005)

  - Partial dismantling after 5 years of heating





water content

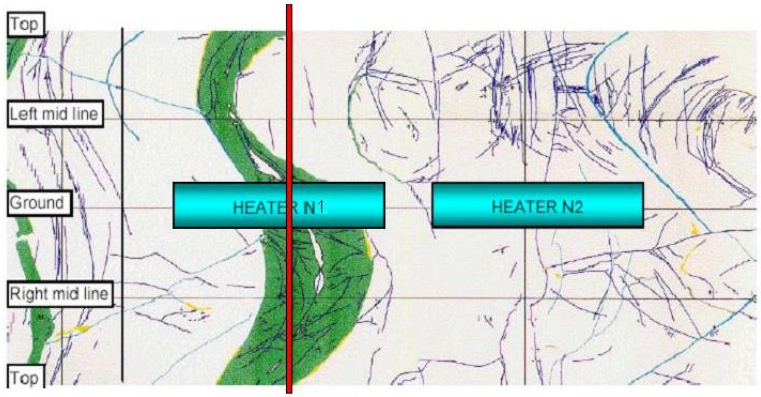


dry density

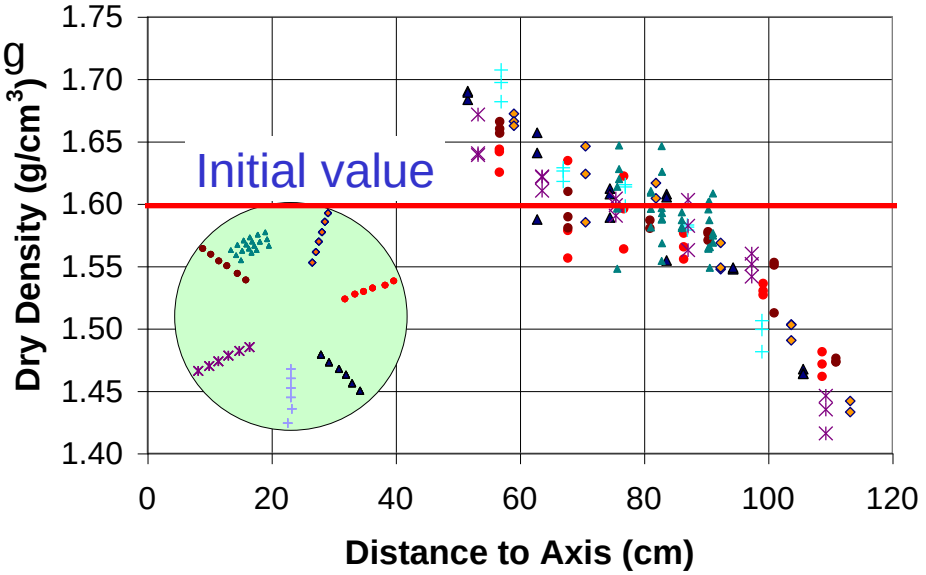
Large-scale field experiments: non-isothermal

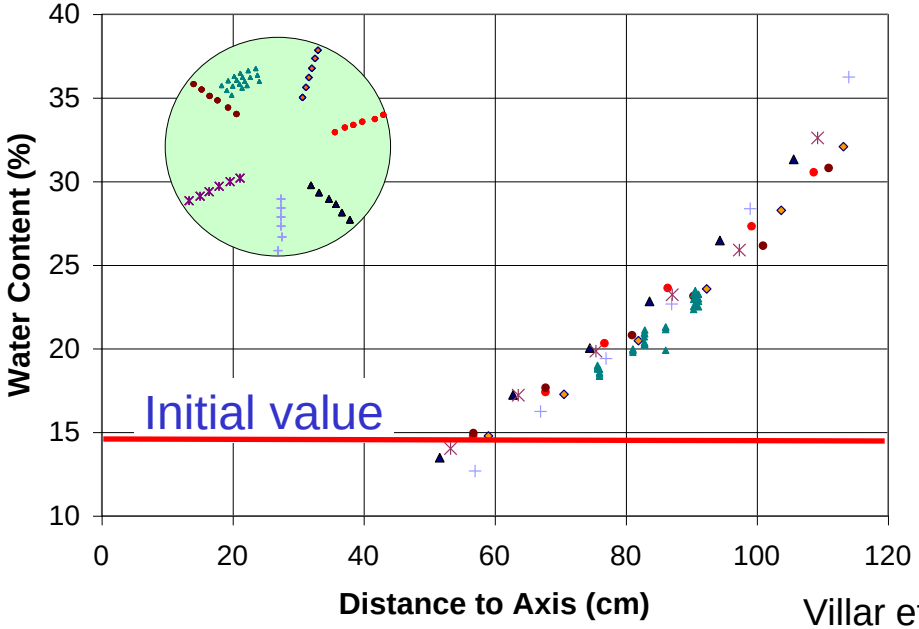
Febex Test: dismantling

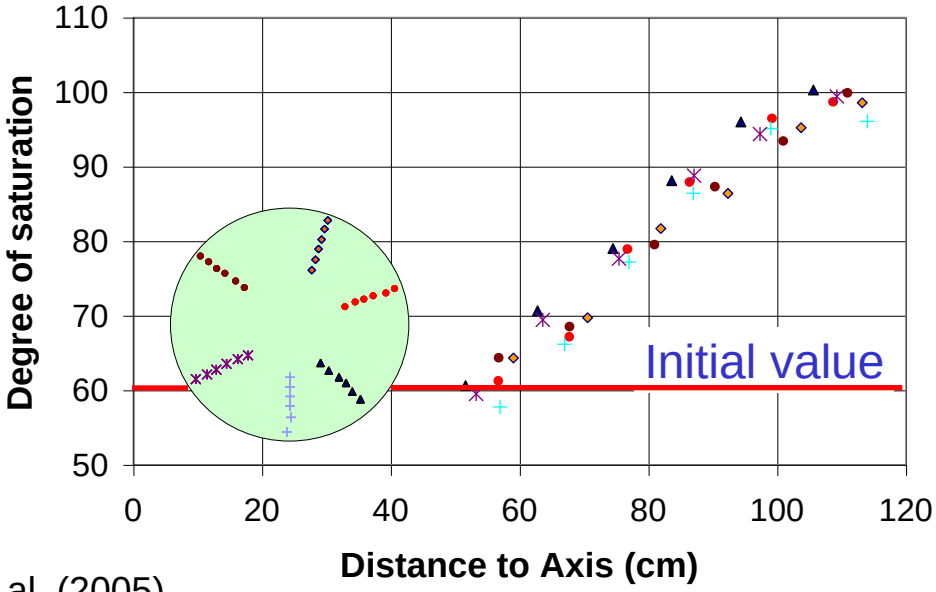
- Partial dismantling after 5 years of heating



X= 685 cm



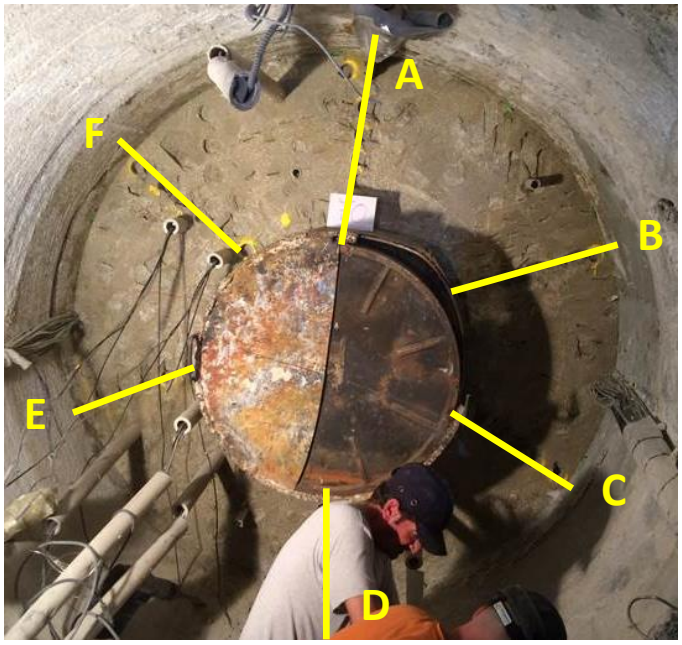


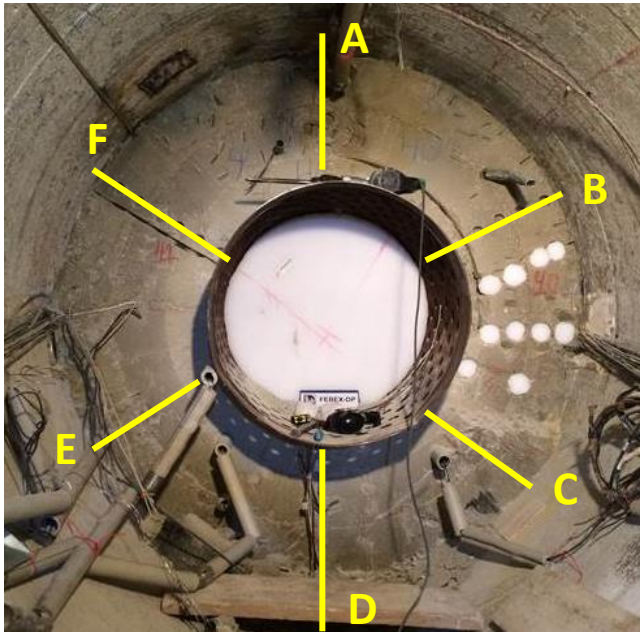


Villar et al. (2005)

Large-scale field experiments: non-isothermal

- Febex Test: dismantling
  - Total dismantling after 18 yeas of heating

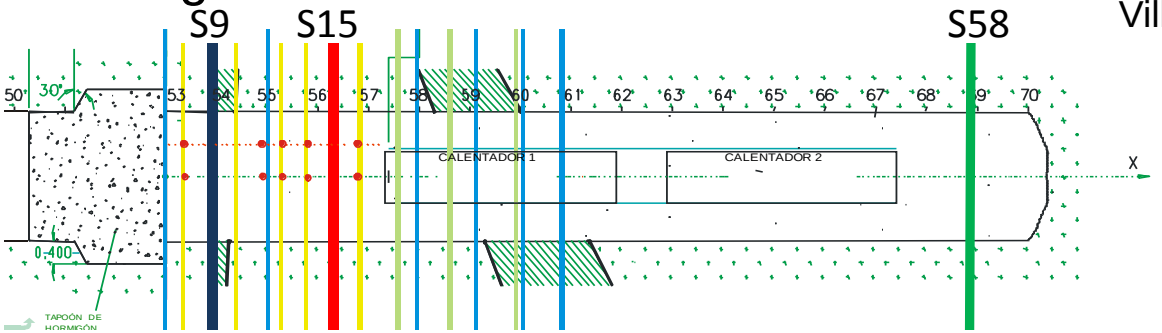




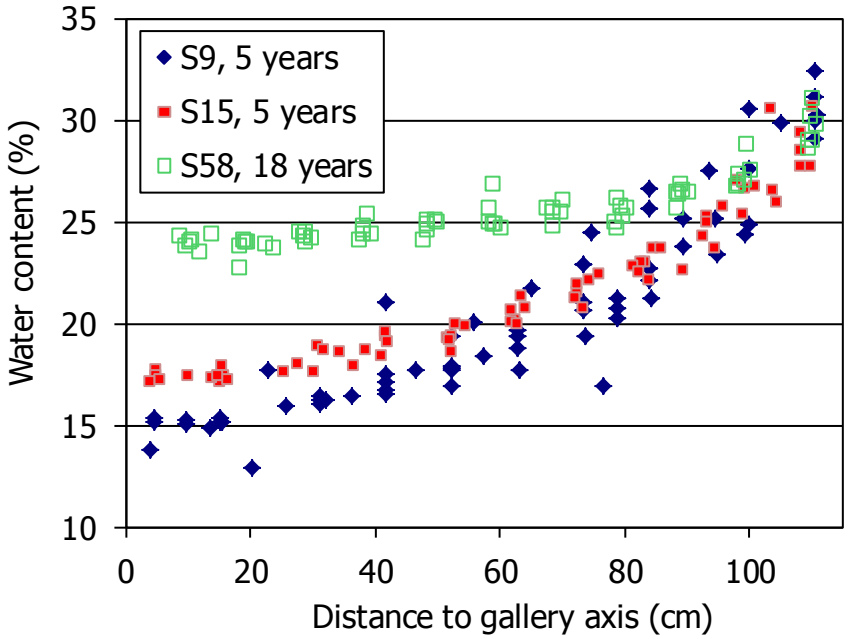
Large-scale field experiments: non-isothermal

- Febex Test: dismantling

Villar et al. (2015)



COLD SECTIONS

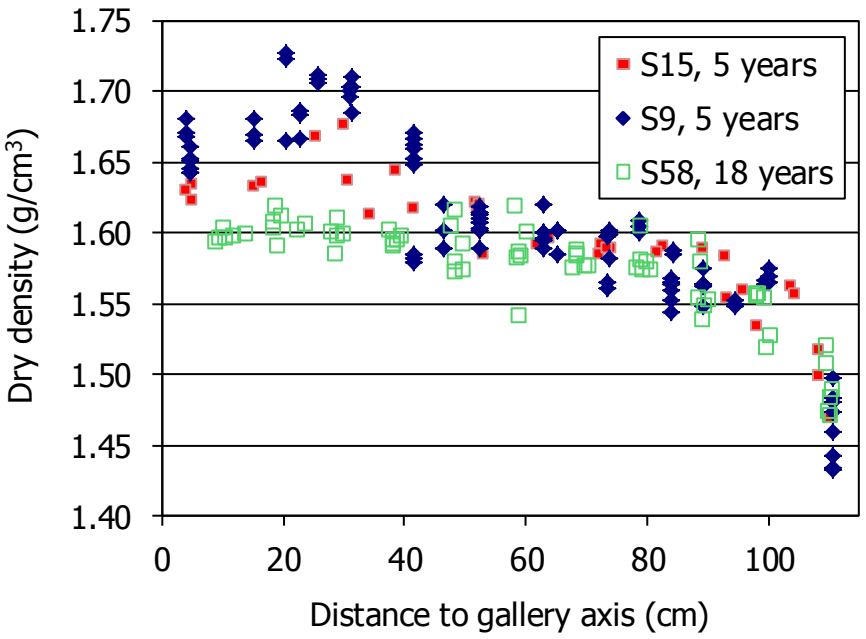


S9: 22.9%

S15: 22.8%

S58: 27.1%

COLD SECTIONS



S9: 85%

S15: 86%

S58: 98%

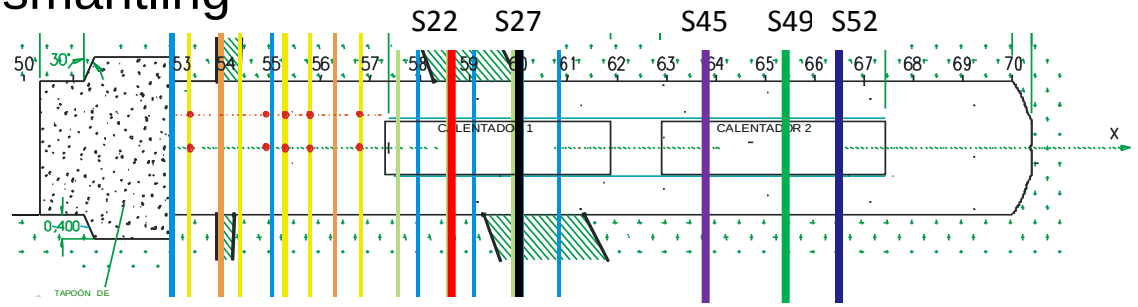
S9: 1.58 g/cm^3

S15: 1.58 g/cm^3

S58: 1.55 g/cm^3

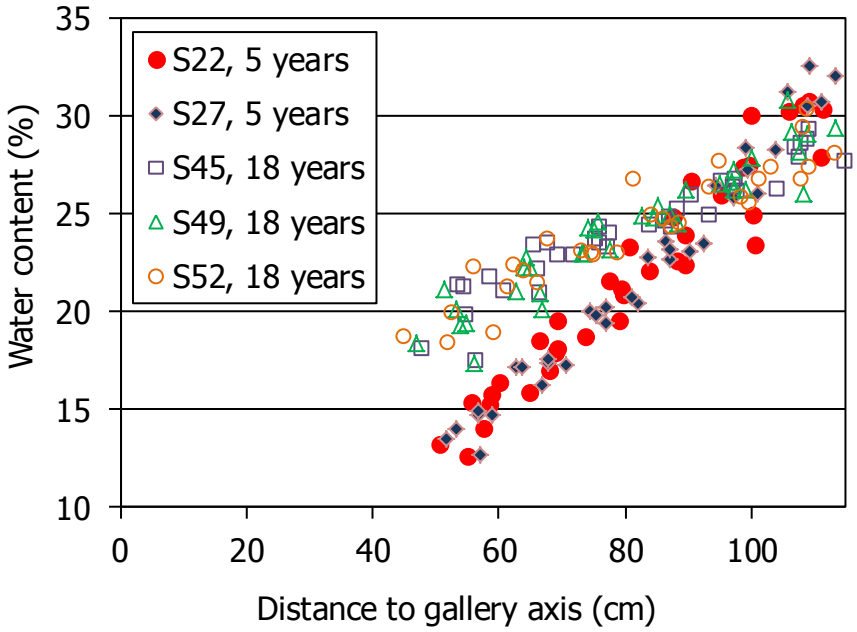
Large-scale field experiments: non-isothermal

- Febex Test: dismantling



Villar et al. (2015)

HOT SECTIONS



S22: 22.6%

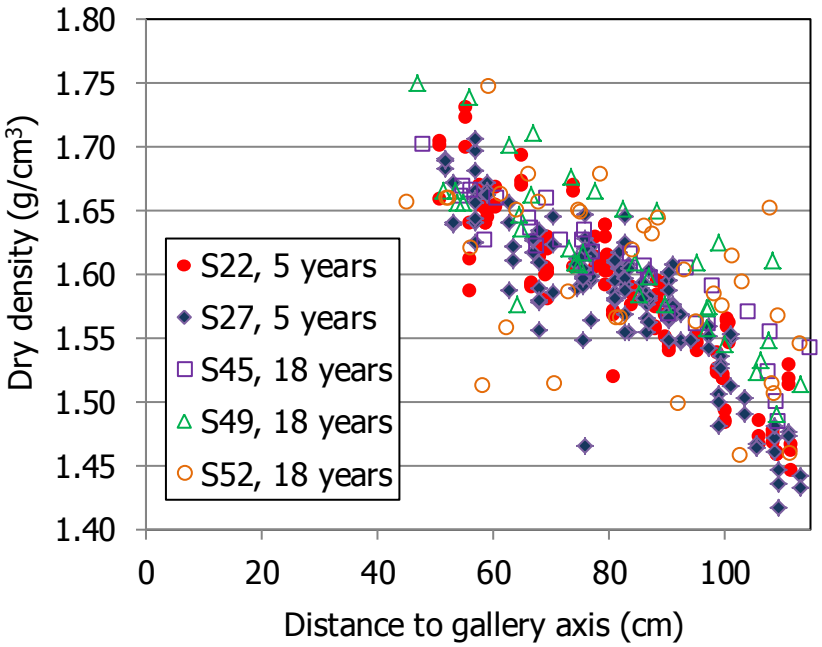
S27: 22.6%

S45: 25.7%

S49: 25.9%

S52: 25.6%

HOT SECTIONS



S22: 80 %

S27: 80 %

S45: 98%

S49: 99%

S52: 98%

S22: 1.57 g/cm³

S27: 1.56 g/cm³

S45: 1.59 g/cm³

S49: 1.59 g/cm³

S52: 1.59 g/cm³

Summary and concluding remarks

- The final state of an engineered barrier, including its degree of heterogeneity, depends on the mechanical behaviour of the bentonite and its interaction with hydraulic and thermal effects
- The mechanical behaviour of highly expansive clays is complex and often exhibits features such as stress path dependency and irreversibility
  - The occurrence and magnitude of Irreversibility and stress path dependency should be carefully characterized by means of well-designed and well-controlled tests on saturated and unsaturated bentonite
  - Irreversibility and stress path dependency should be reproduced by suitable constitutive models
- There exists a large amount of experimental evidence (from long-term laboratory and field tests) available to inspire and validate model development

Summary and concluding remarks

- The objective of the modelling with respect to bentonite homogenisation would be
  - Achieve and demonstrate process understanding
  - Attain and demonstrate predictive capabilities
- Focus would be on the mechanical constitutive model that should exhibit irreversibility and stress path dependency and encompass:
  - Saturated and unsaturated material for a wide range of densities
  - Isothermal and non-isothermal conditions
  - Blocks and pellet-based materials
- The mechanical constitutive model incorporated in coupled HM and THM formulations would be applied to:
  - Well-controlled laboratory tests at different scales (process understanding)
  - Past and ongoing large scale field tests: EB, Febex, SEALEX, CRT…
  - Case studies for the verification of the performance of current designs for buffers, backfills, seals and plugs
- Long term homogeneity/heterogeneity may depend on creep behaviour
  - Laboratory tests (limited duration); fundamental micro or nanoscale studies may be required

Acknowledgment

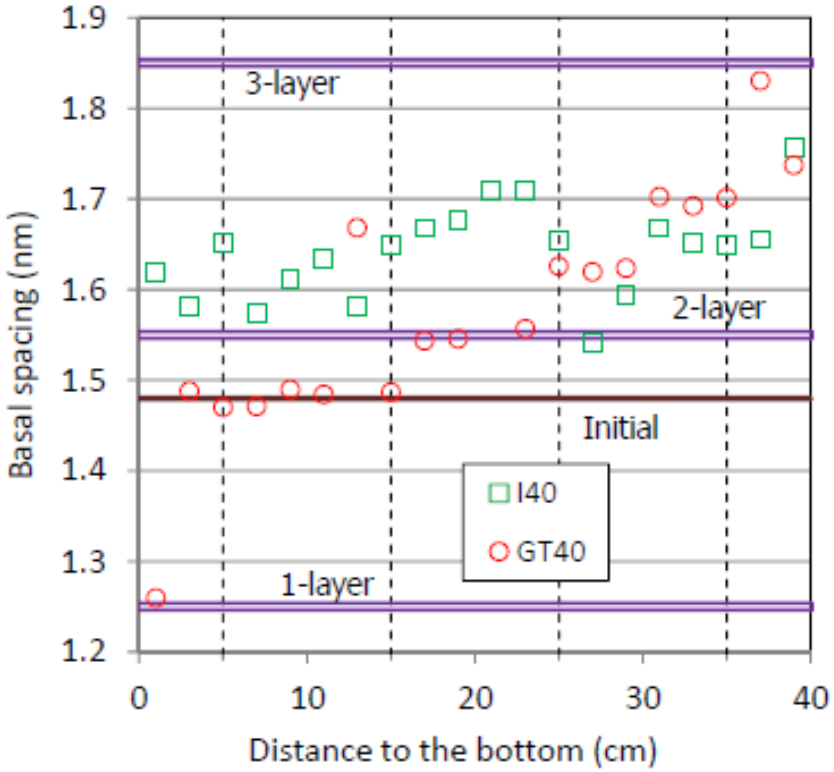
This project receives funding from the Euratom research and training programme 2014-2018 under grant agreement No 745942

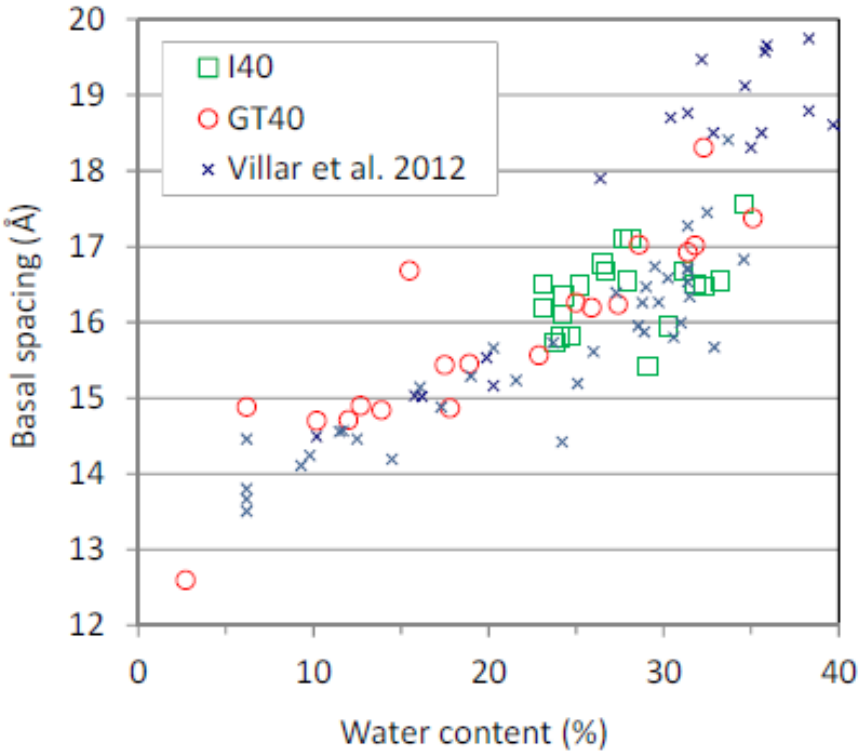
A Soil Mechanics perspective

Microstructural behaviour

(Villar et al. 2016)

- Results of two test of 12 years duration
  - **I40**: Hydration **GT40**: Heating/hydration





FEBEX bentonite

MX-80 bentonite