Considerations on the significance of the pre-hydration state for the long-term safety functions of bentonite –

Implementer’s Perspective

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With contributions from:

- Prof. Laloui / Prof. Ferrari and co-workers (EPFL)
- Prof. Romero and co-workers (UPC)
- Drs. Keller and Holzer (ZHAW)

BEACON Workshop
Mechanical properties of bentonite barriers
Kaunas, June 19-20, 2017

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Outline – Considerations on the role of the pre-hydration state …

- … with respect to the long-term safety functions of bentonite

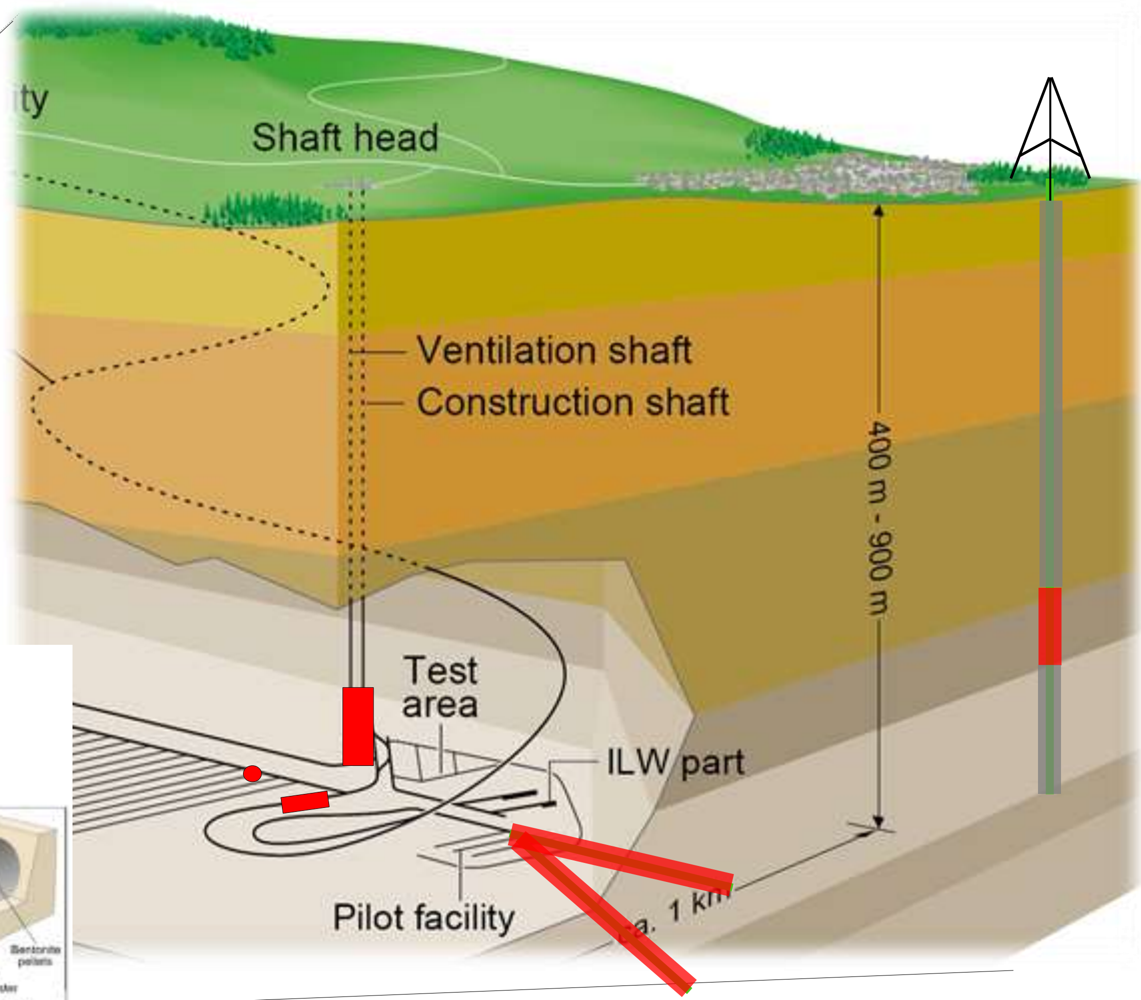
1. Bentonite based EBS - Spectrum of applications
2. Performance Assessment Issues
3. Role of the As-Compacted-State
4. A first glance on the Workshop Programme
5. Final remarks

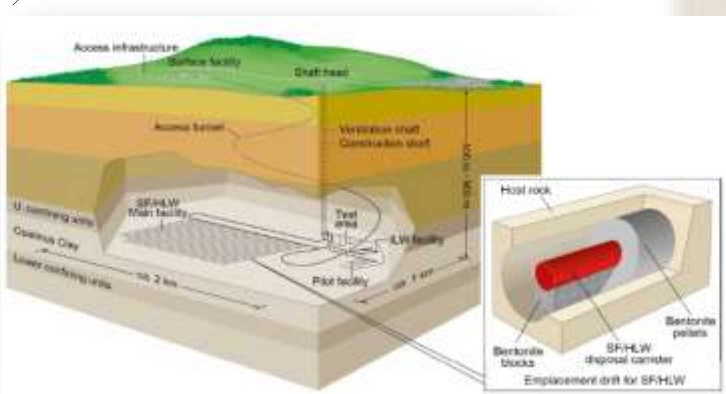
Implementer’s Perspective
(…chasing for advanced repository designs)

1 Spectrum of Applications – Bentonite-based material

- **Bentonite-based Sealing Material in Radioactive Waste Disposal – Applications**

- HLW near-field
- Tunnel seals & shaft seals
- Borehole (bh) sealing
  → surface bh
  → underground bh
  (horizontal, inclined)

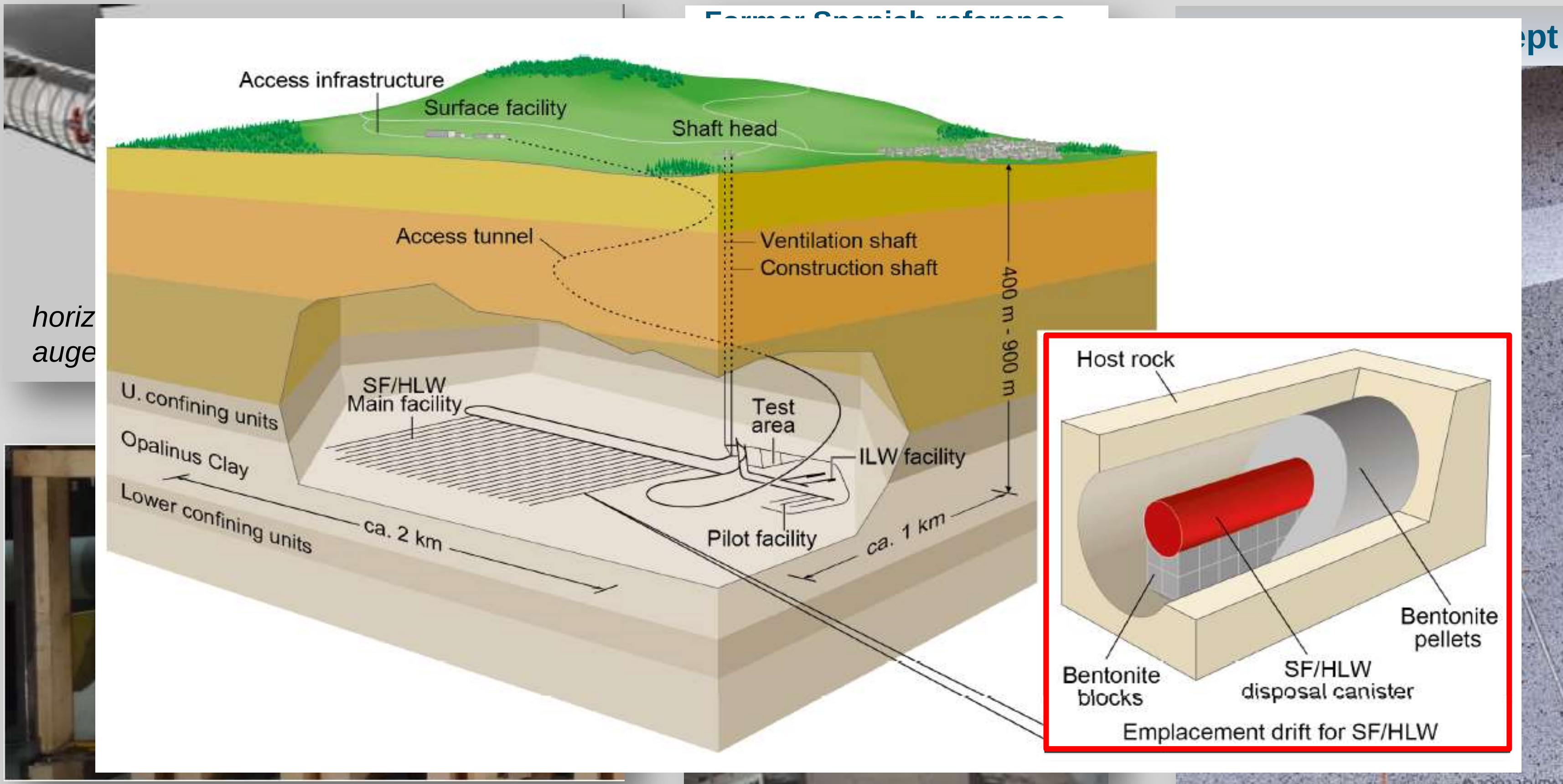




1 Spectrum of Applications – Bentonite-based material

- **HLW Near-field** – Issues related to the As-Built State (pre-hydration)

horiz
auge



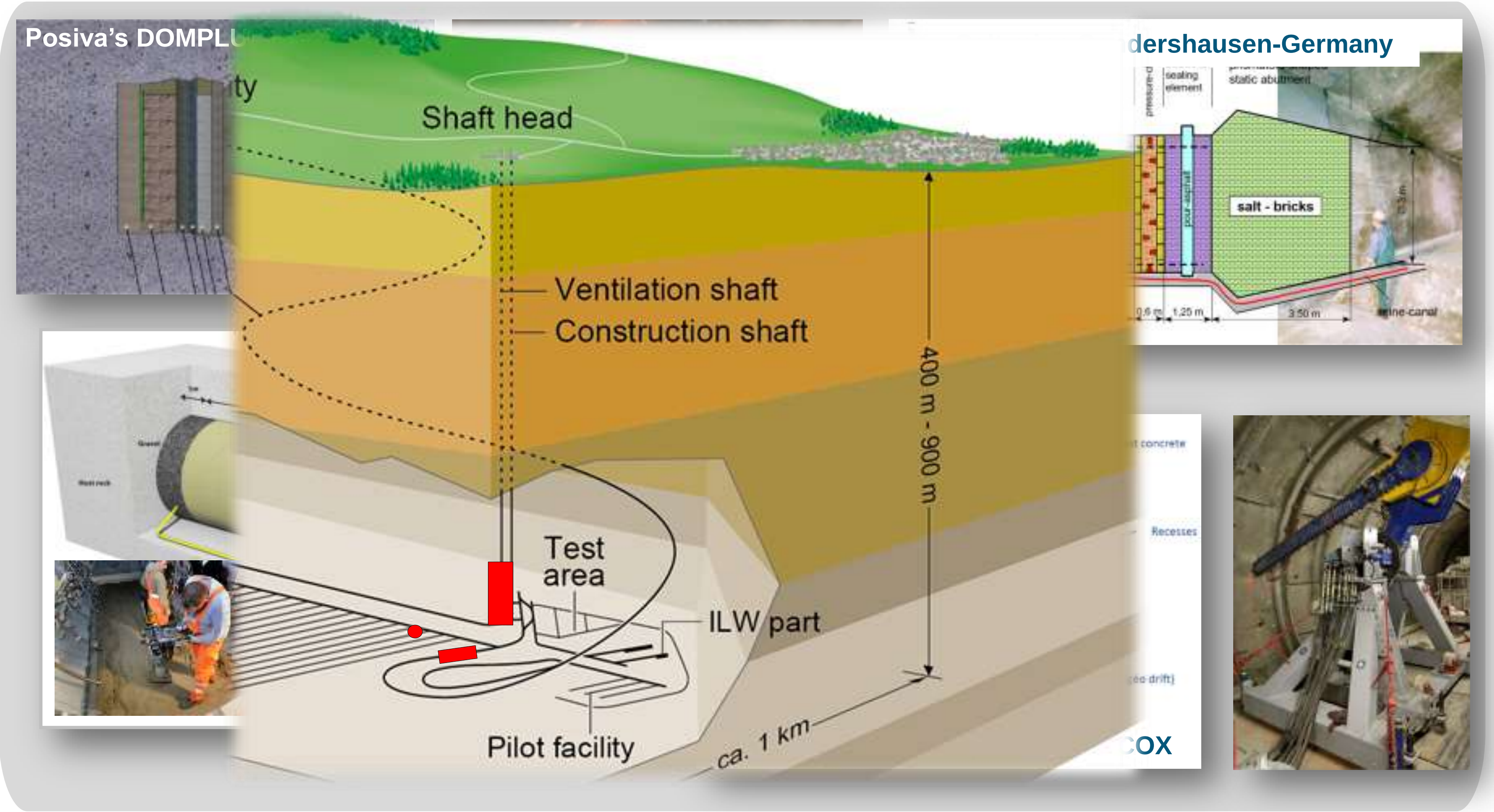
Emplacement tests: significant segregation

Construction gaps

Construction gaps

1 Spectrum of Applications – Bentonite-based material

- **Tunnel seals / shafts** – Wide range of designs (role of pre-hydration state?)



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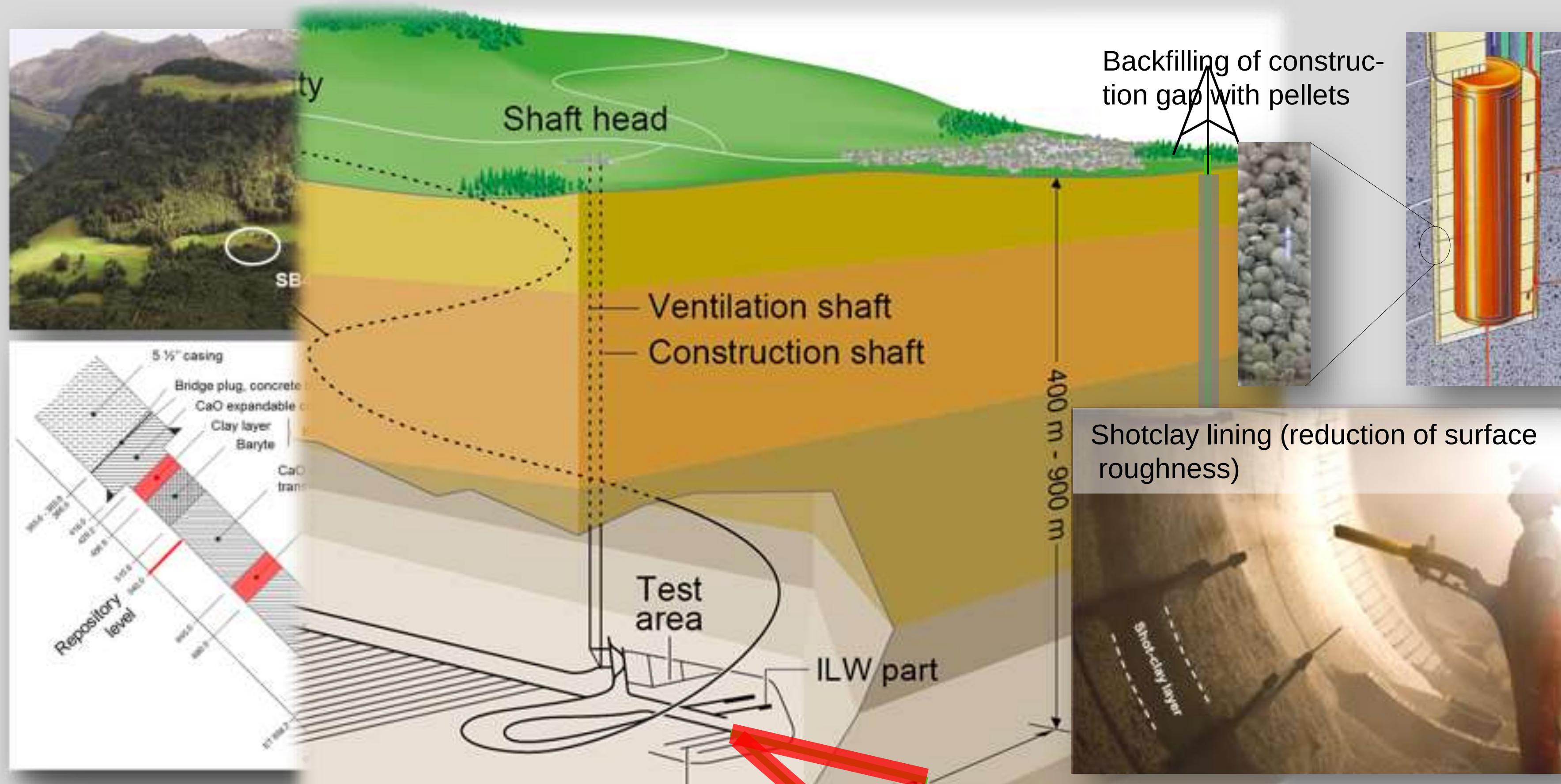
1 Spectrum of Applications – Bentonite-based material

- **Borehole sealing and special applications**



Sealing of an inclined borehole at Nagra's WLB site

underground (GTS, Grimsel)

Backfilling of breakout zones

1 Spectrum of Applications – Bentonite-based material

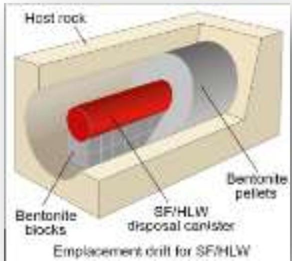
- **It's all applications in common:**

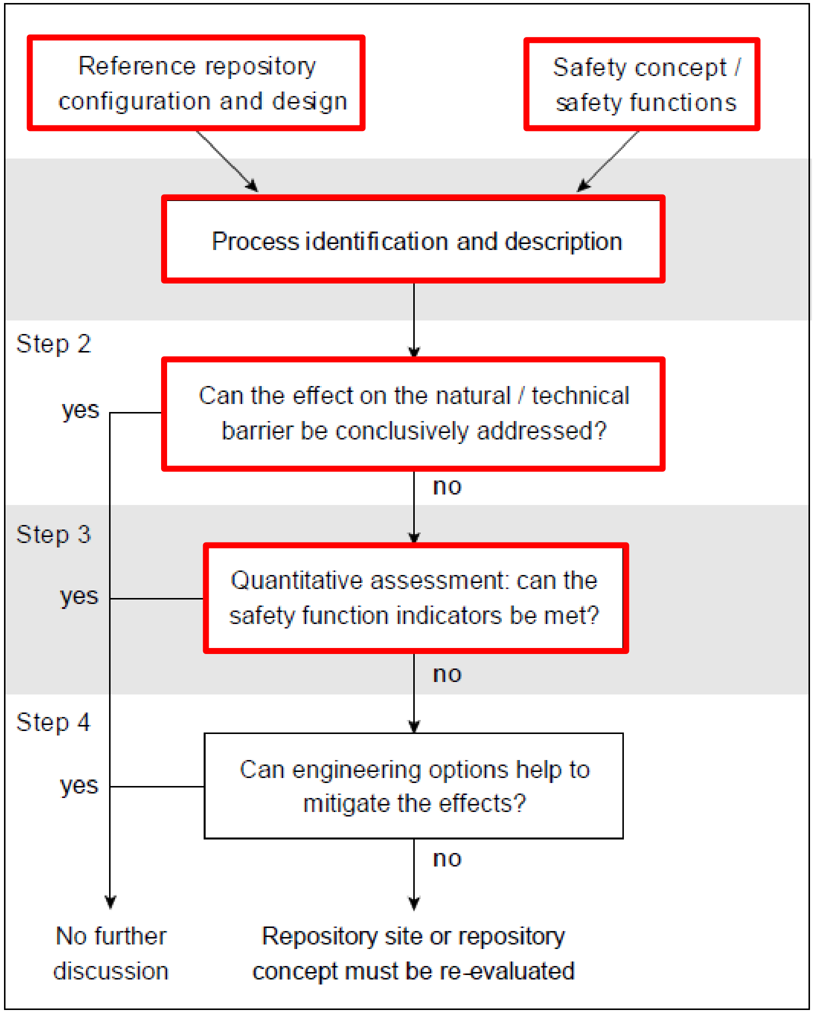
- How can sensible technical requirements and QA/QC procedures be formulated for emplacement?

- How can long-term performance be demonstrated?

2 Performance Assessment – A General Workflow

- **Generic PA-Workflow** – Criteria based indicator approach





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Safety functions

- mechanical confinement of cansiter
- retention of RN in the near-field
- attenuated release of RN
- …

Processes, detrimental effects

- Repository induced effects (THMC)
- Effects rel. to long-term evolution
- …

Functional indicators

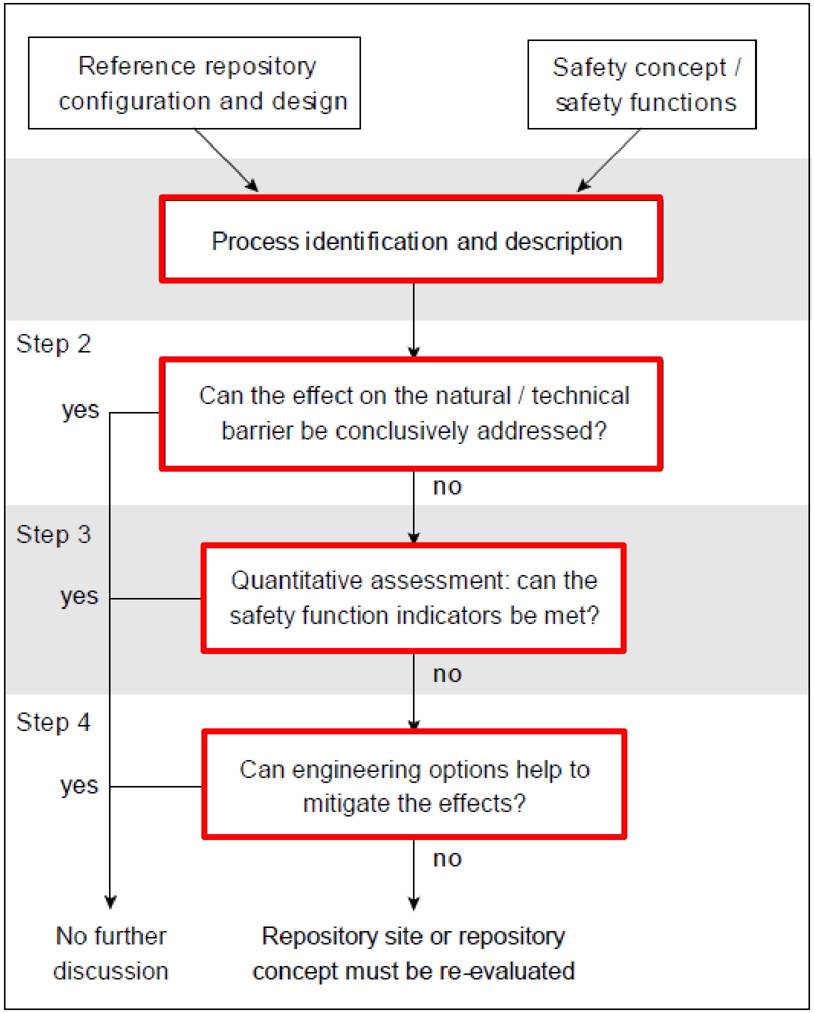
- canister displacement
- swelling pressure P_s
- bentonite dry density ρ_d
- bentonite temperature T_{bent}
- …

Performance measures
(compliance in entire assessment period)

- bentonite thickn. $M_{bent,min}$ < xy cm
- $P_{s,min}$ > xy MPa
- $\rho_{d,min}$ > xy Mg/m^3
- …

2 Performance Assessment – A General Workflow

- **Generic PA-Workflow** – Where do we need help from RD&D (BEACON!)?



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Processes, detrimental effects

- completeness of FEP list
- relevance for given repos. concept
- …

Concepts, Modelling tools

- reliable concept. frameworks (THM)
- verified codes & validated models
- robust appraisals for parameter estimation (multi-scale approaches)
- …

Model-based system analyses

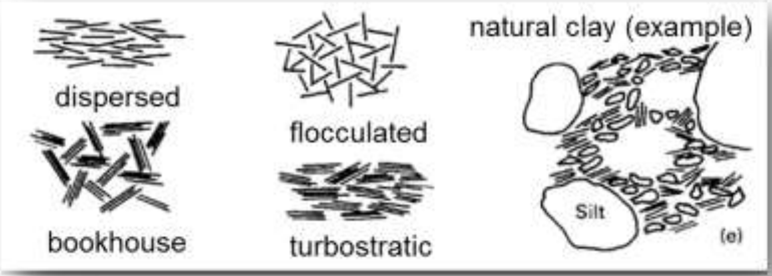
- Powerful THM-C modelling tools
- Tools for probabilistic assessments
- …

Repository Optimisation and QA/QC

- Novel emplacement techniques
- Guidance for balanced QA/QC
- …

3 The Role of the As-Compacted State – Considerations

- **Microstructure of bentonite** – Well-established conceptual frameworks describing natural state



Clay structures after Craig (2004)

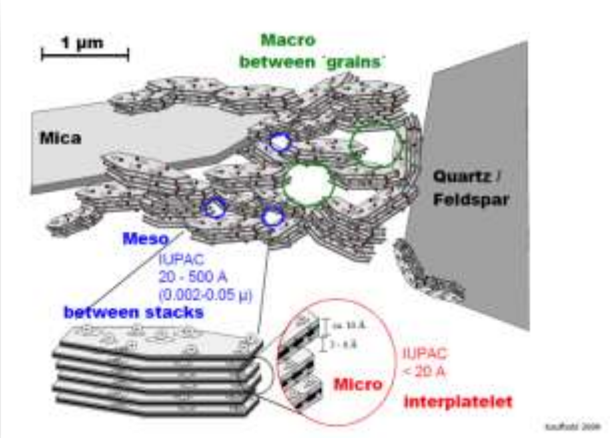
- microfabric of solid components:
  (classified in hierachical order)

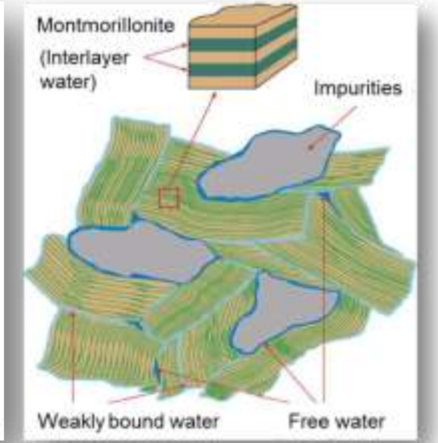
→ *Clay platelets*
→ *Stacks (… made-up of platlets)*
→ *Aggregates (… made-up of stacks)*
→ *Assemblage / cluster (…)*

- hierarchy of pore space (defined by the state of pore water):

→ *micropores (interlayer pw)*
→ *mesopores (weakly bound pw)*
→ *Macropores (free pw)*

Bradbury&Baeyens (2003)

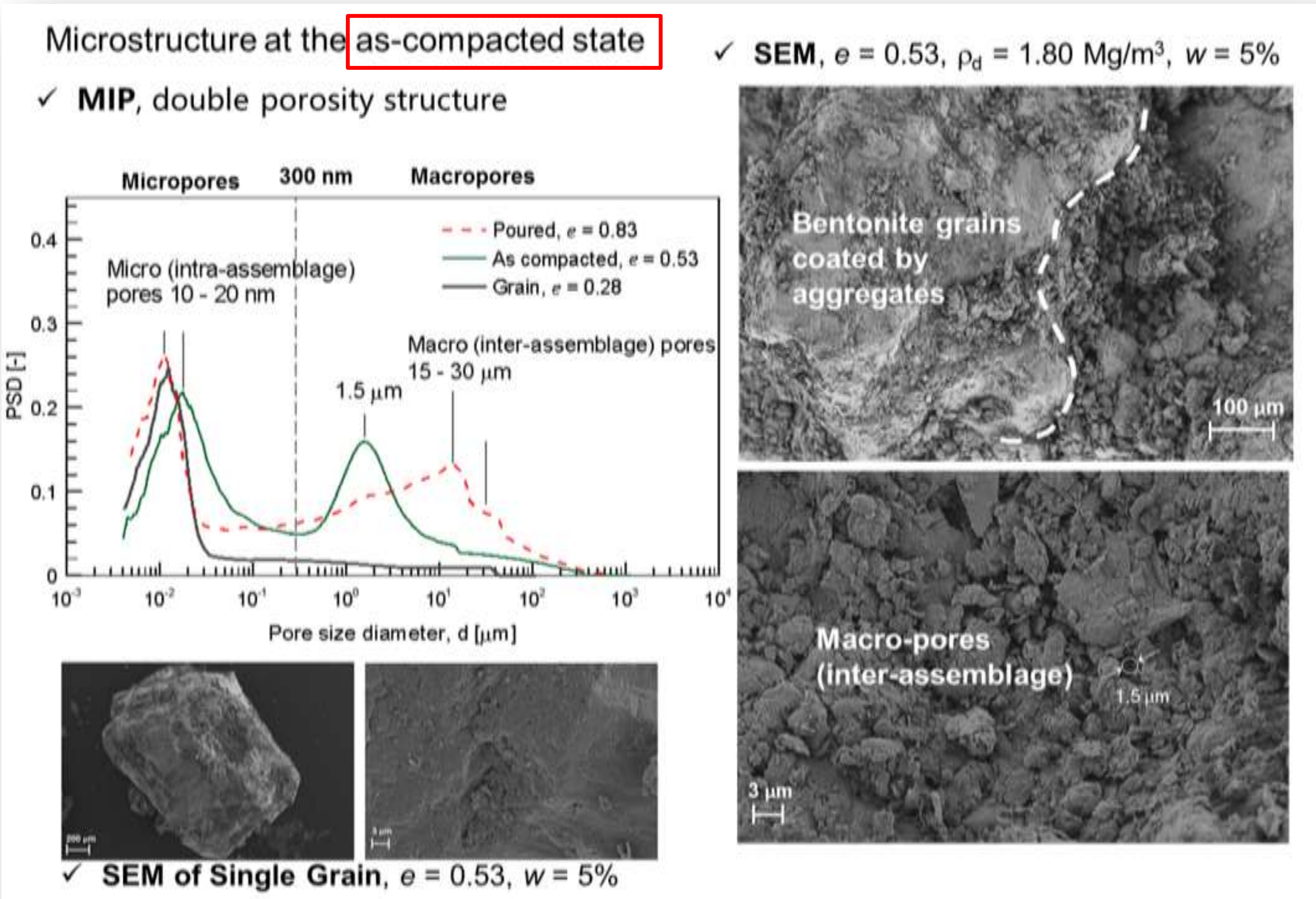




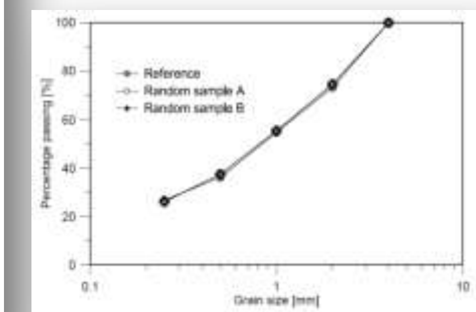
Kaufold (2009)

3 The Role of the As-Compacted State – Considerations

- **Well-established conceptual framework** – Confirmation by mercury intrusion porosimetry (MIP)



MX-80
granular bentonite
(Apparent grain size Distribution)



ρ_d = 2.10 Mg/m^3

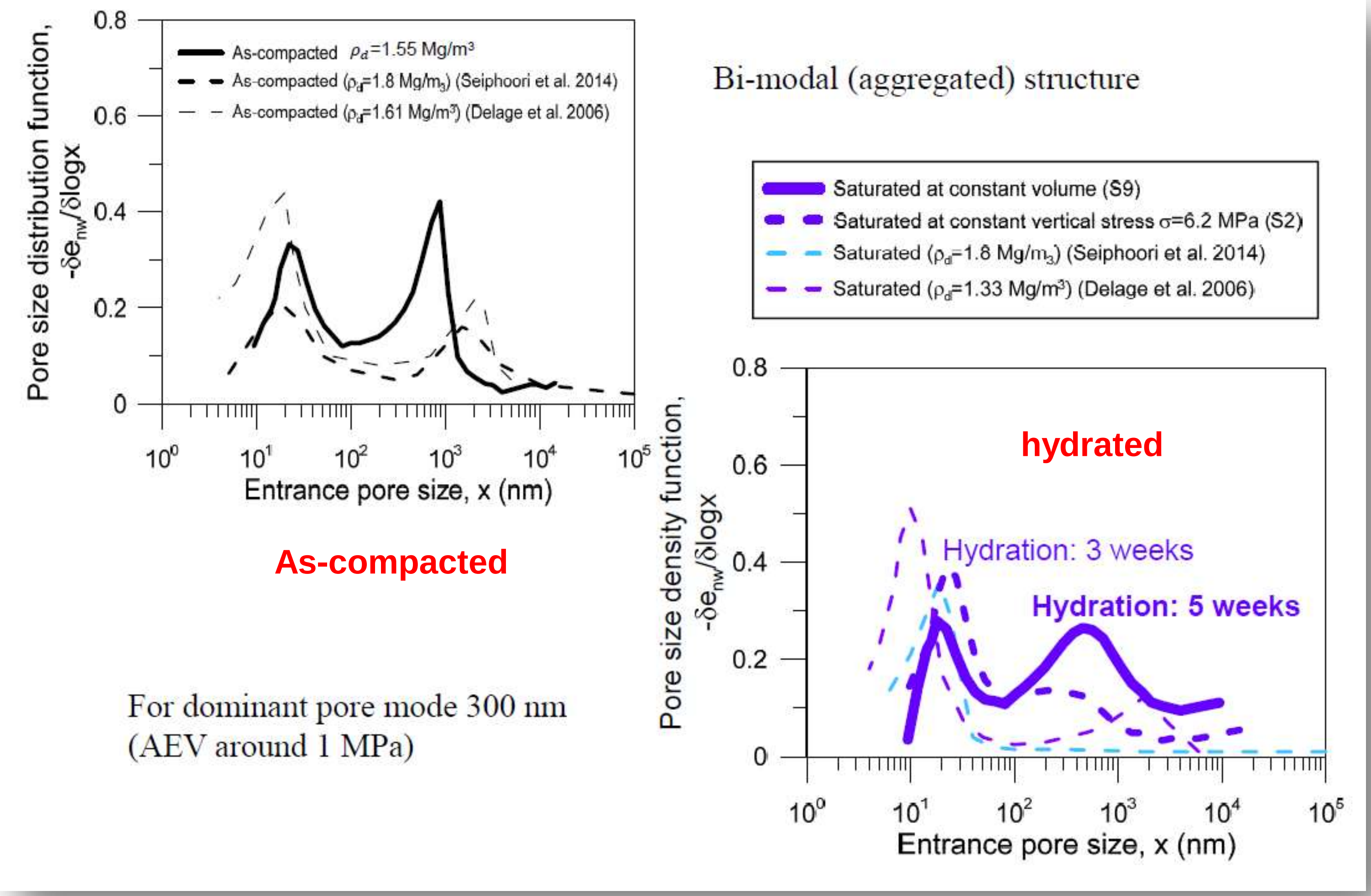
ρ_d = 1.80 Mg/m^3

ρ_d = 1.5 Mg/m^3

Seiphoori (2014)
Ferrari et al. 2015)

3 The Role of the As-Compacted State – Considerations

- **Hydration of the compacted material** – Evidence from mercury intrusion porosimetry (MIP)



Romero & co-workers

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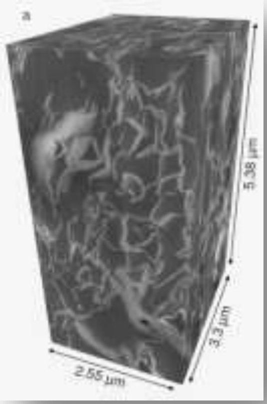
3 The Role of the As-Compacted State – Considerations

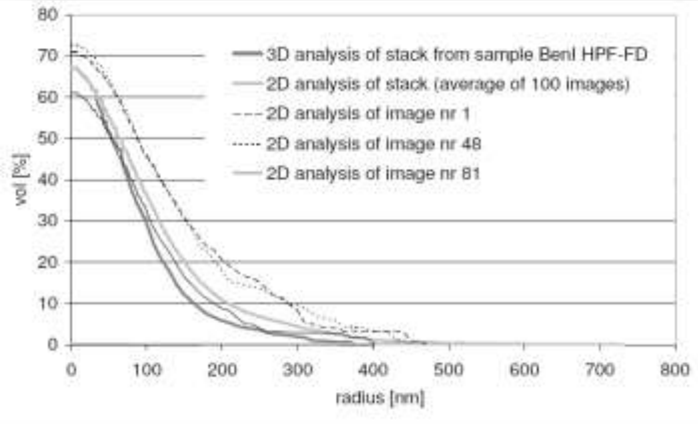
- **Hydration of the compacted material** – Independent evidence from 3-D imaging with cryo-FIB-nt

  - low and high density samples (0.39 Mg/m³ ,1.58 Mg/m³) imaged with a resolution of around 10 nm

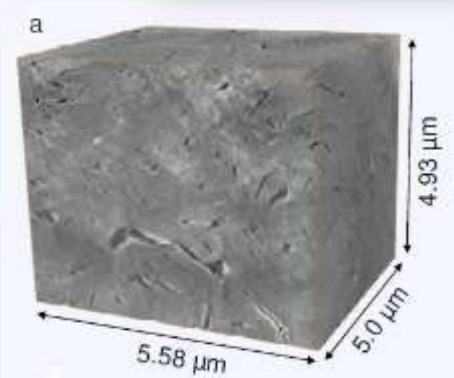
  - both samples fully saturated

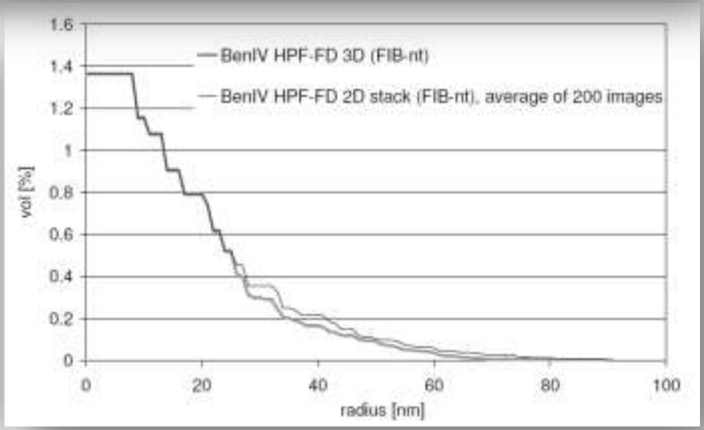
  - only 1 % macroporosity detected in the high density sample!





Sample name	wt.% of water	vol.% of water	Saturation	Dry density [kg/m^3]
Ben I	68.8	85.6	100%	0.39
Ben IV	21.5	42.4	96%	1.58





Holzer et al. (2009)

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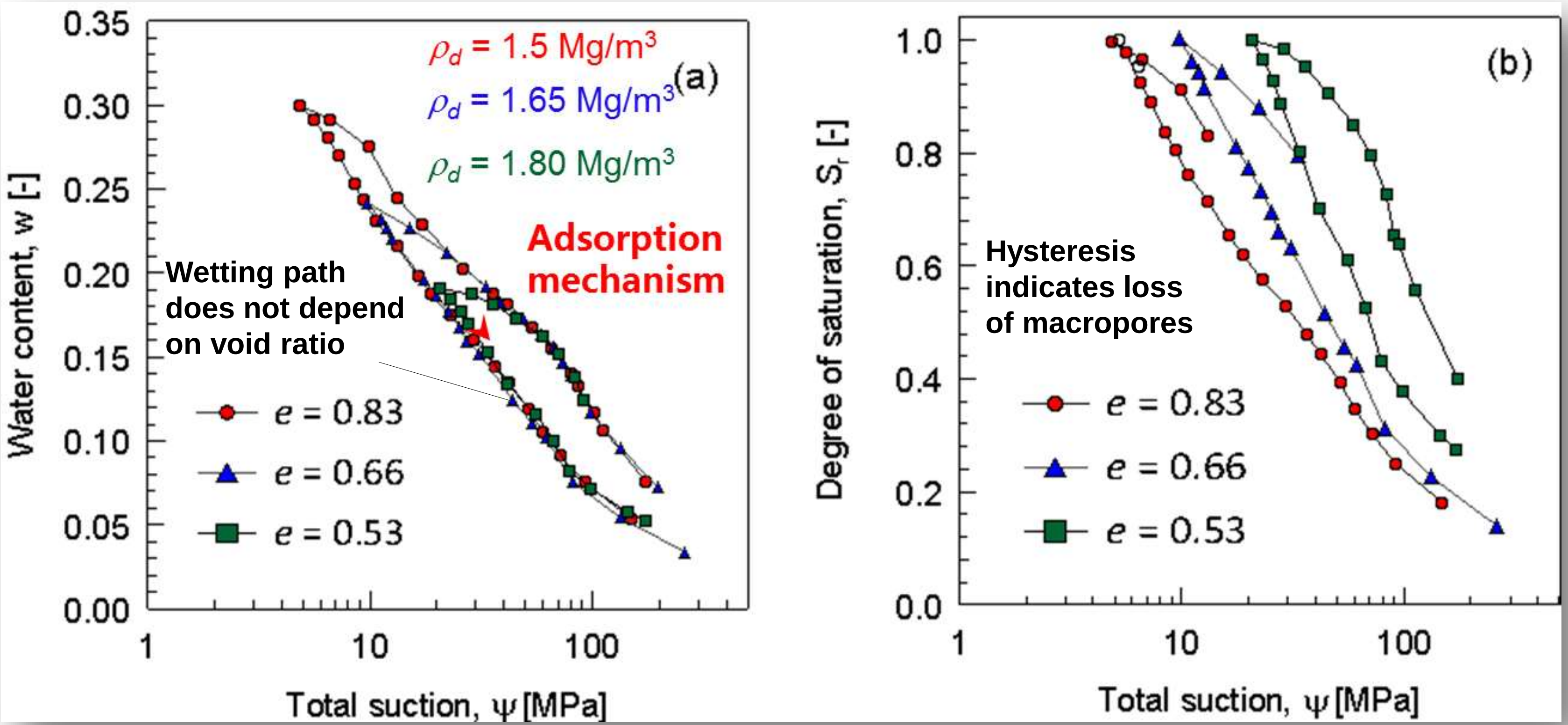
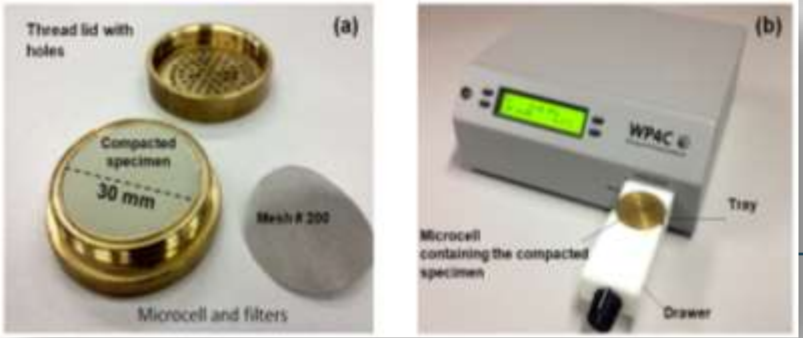
3 The Role of the As-Compacted State – Considerations

- **Hydration of the compacted material** – Suction measurements





Oral presentation by Aldo Madatschi

Seiphoori (2014)

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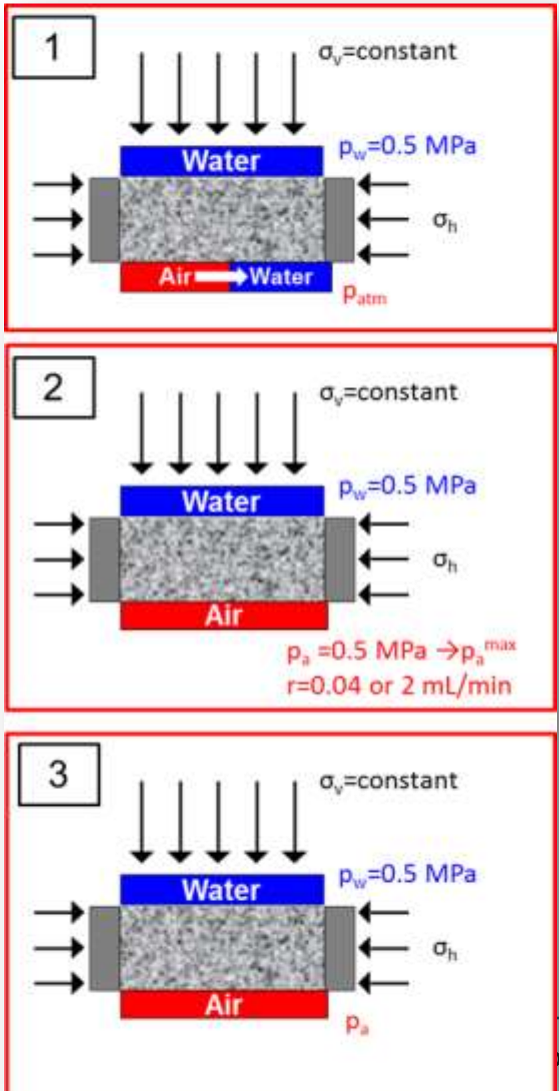
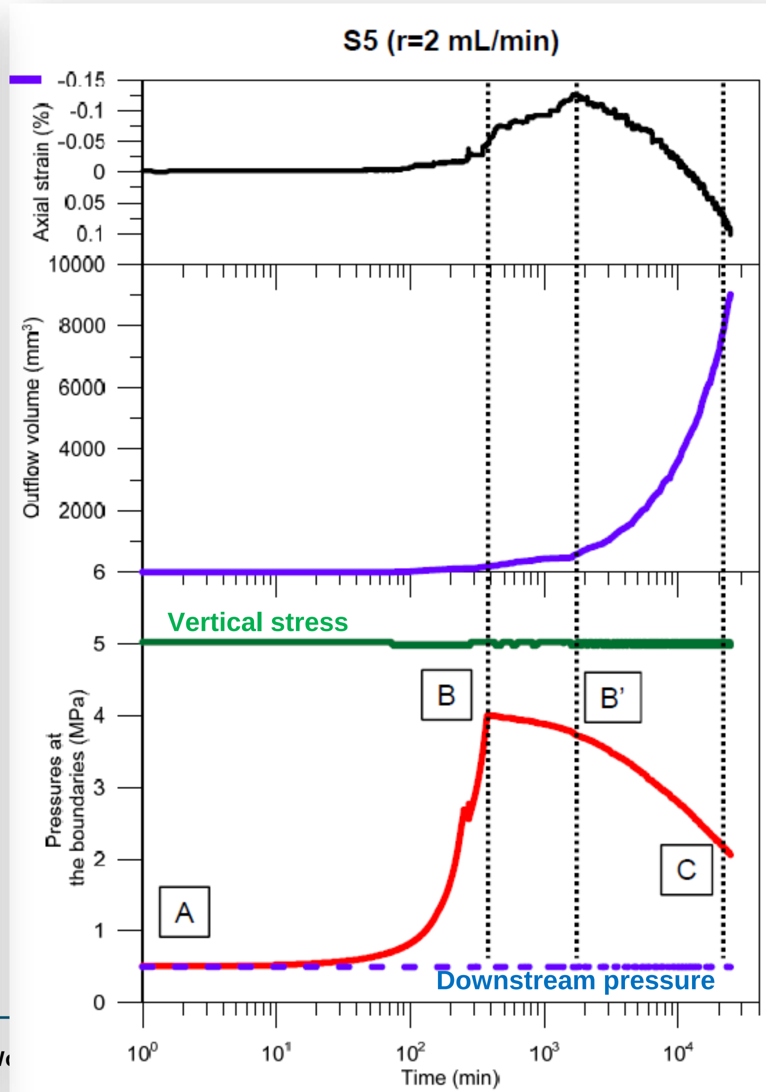
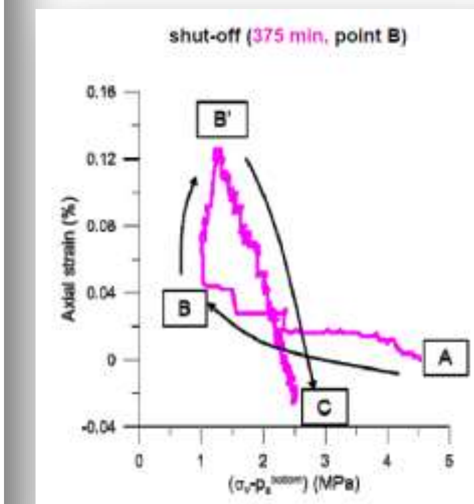
3 The Role of the As-Compacted State – Considerations

- **Hydration of the compacted material** – Air injection test under oedometric conditions







Romero et al. (2017)

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3 The Role of the As-Compacted State – Considerations

- **Some preliminary interpretations & conclusions**

- the evolution of micro-fabric during the hydration process is the driver for the homogenisation process

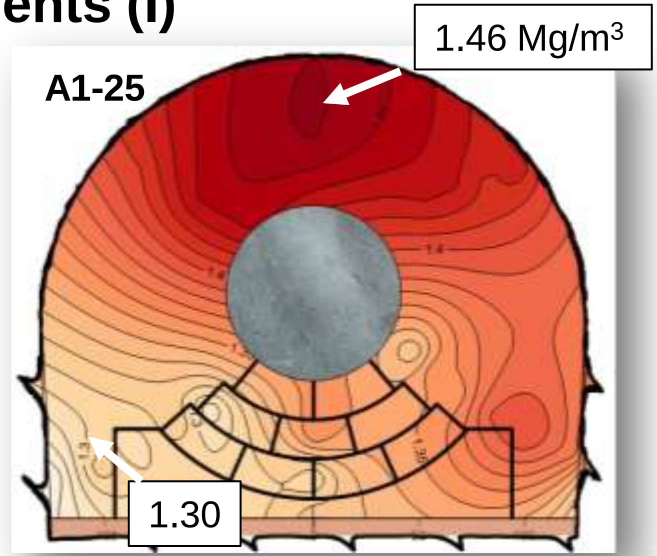
- in the density range between 1.5 and 1.6 Mg/m^3 the bi-modal structure goes lost after hydration

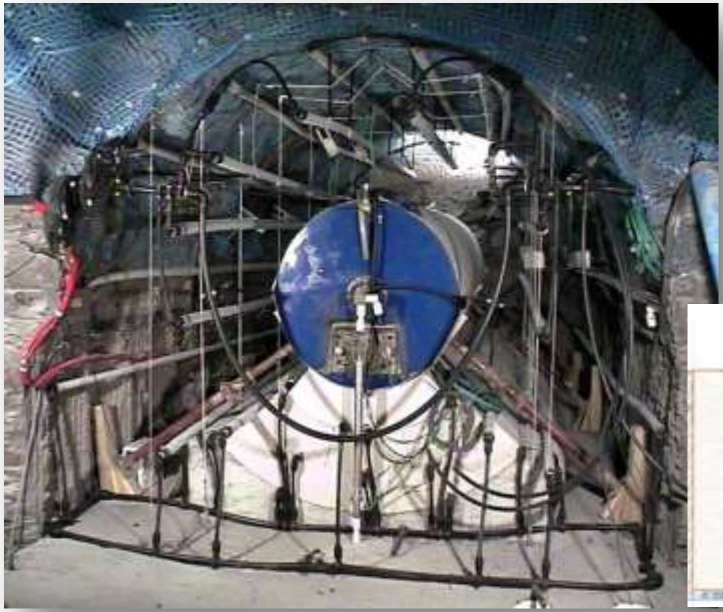
- the effect of the initial (as-compacted) density variation on the homogenisation of the hydrated material is yet to be investigated

4 A glance on the workshop programme – Highlights

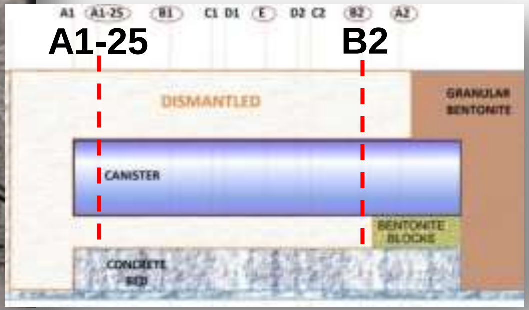
- **Evidence from Large Scale In-situ Experiments (I)**

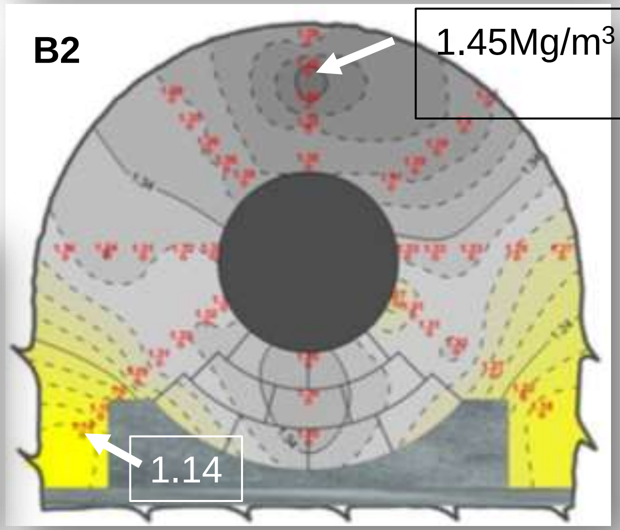
  - EB Experiment (Mont Terri)
    - → *artificial hydration started in 2002*
    - → *dismantling in 2013*
    - → *full saturation confirmed by comprehensive sampling*
    - → *significant variability in dry density after dismantling*
    - → *enhanced densities measured above the canister*





Plenary presentation
by Juan Carlos Mayor

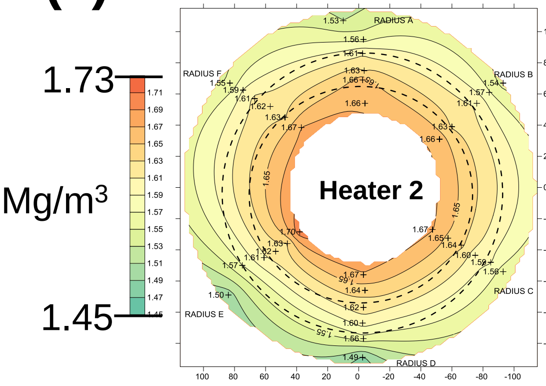


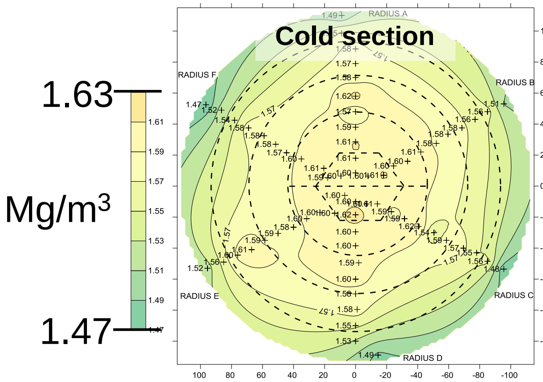


A glance on the workshop programme – Highlights

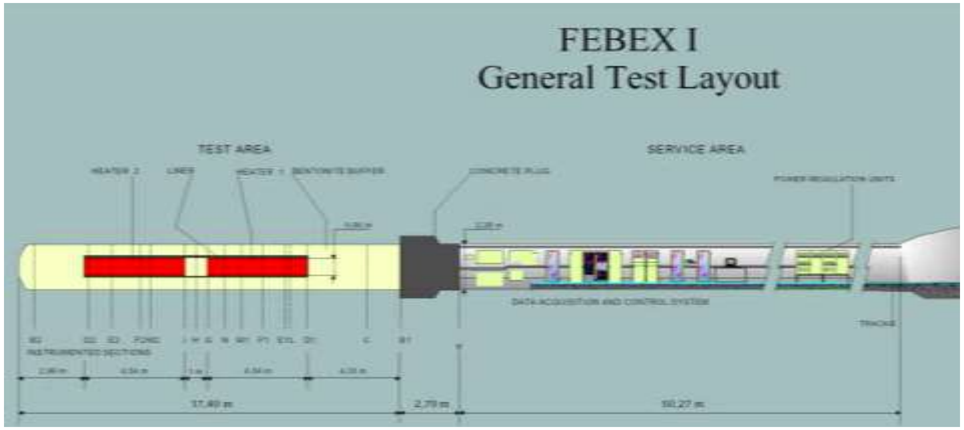
- **Evidence from Large Scale In-situ Experiments (II)**

  - FEBEX-DP Experiment (Grimsel Test Site)
    → *heating & hydration started in 1997*
    → *final shut-off and dismantling in 2015*
    → *full saturation reached in cold sections*
    → *incomplete saturation around canisters*
    → *construction joints closed, but visible!*
    → *moderate variability of densities in cold cross-sections*
    → *significant variability of densities in hot cross-sections*





Plenary presentation by Maria Victoria Villar

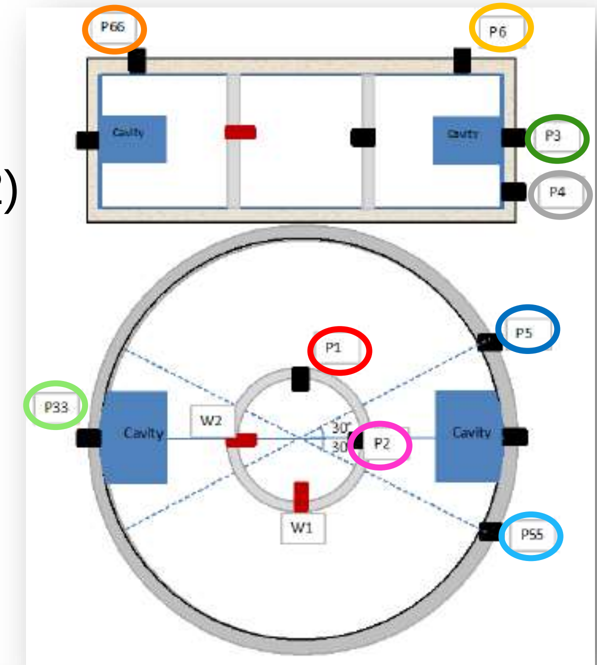


4 A glance on the workshop programme – Highlights

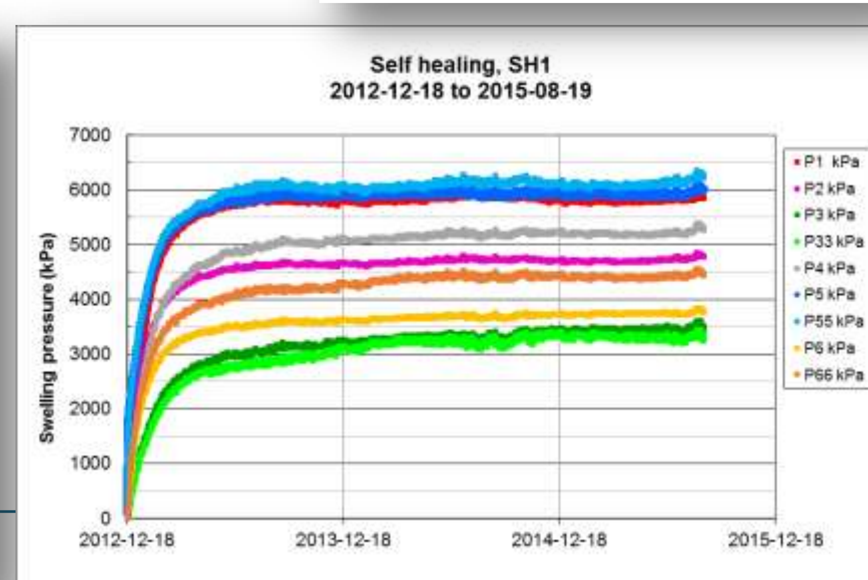
- **Experimental evidence (laboratory scale)**

  - Buffer homogenisation - Large scale test (SH1/SH2) by Clay-Tech (SKB's EBS-Task Force)

    → *comprehensive test programme (small/large scale)*
    → *SH2: dismantling after 1.5 y; SH1 ongoing*
    → *outstanding data set for model development (radial, axial swelling, …)*
    → *significant variability in swelling pressure after 2.5 y of hydration*



Plenary presentation by Ann Dueck



5 Messages and Remarks – Implementer's perspective

- **The as-built / pre-hydration state forms the initial conditions for the assessment of long-term performance of the (bentonite based) Engineered Barrier System**
- **Advise is seeked from the BEACON research team concerning:**

  - the drivers of the homogenisation process during hydration and the detrimental effect that could hinder the compliance with the specified performance measures

  - reliable prediction of homogenisation for the full range of considered detrimental effects (incl. heat, temperature, gas)

  - optimised emplacement procedures

thank you
for your attention