Boom clay drying behavior: experimental and numerical study

J. Hubert ¹ – N. Prime ³ – E. Plougonven ² – A. Leonard ² – F. Collin ¹

¹ Université de Liège – Dep.t ArGEnCo
² Université de Liège – Dept. Chimie appliquée
³Université Savoie Mont-Blanc LOCIE

Thesis director: Frédéric Collin

Wednesday 25th of May
SUMMARY OF THE PRESENTATION

- Nuclear waste disposal
- Material and method
- Drying kinetics
- Shrinkage
- Conclusions
**NUCLEAR WASTE DISPOSAL**

- High activity long life *radioactive wastes* need to be *isolated* for a long period of time ⇒ Deep geological disposal
  
  - Stable and low permeability rock formation required
    
    ⇒ in **Belgium** the studied formation is **Boom Clay**
Deep geological storage

- Burial shaft and multi barrier principle:

- Boom Clay
- Gallery retaining wall
- Stainless steel liner
- Buffer
- Overpack
- To be filled with a granular material
- Mechanical support

Craye et al., 2009
SUMMARY OF THE PRESENTATION

- Nuclear waste disposal
- Material and method
- Drying kinetics
- Shrinkage
- Conclusion
MATERIEL AND METHOD

- Samples preparation

<table>
<thead>
<tr>
<th>Initial core</th>
<th>Extracted samples</th>
<th>Saturation</th>
<th>Optimization</th>
<th>Finished samples</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>34 mm</td>
<td>39 mm</td>
<td></td>
<td>13 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15 mm</td>
</tr>
</tbody>
</table>
**MATERIAL AND METHOD**

- **Convective drying test**
  - Sample weighed every 30 seconds in the convective dryer

<table>
<thead>
<tr>
<th>Drying conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
</tr>
<tr>
<td>25°C</td>
</tr>
<tr>
<td>Humidity</td>
</tr>
<tr>
<td>3.5%</td>
</tr>
<tr>
<td>Air flow</td>
</tr>
<tr>
<td>0.8 m/s</td>
</tr>
</tbody>
</table>
MATERIAL AND METHOD

- Data acquisition and image processing
  - Shrinkage and cracking measurement

Identification of the bedding direction

Dimensions at saturated state

Dimensions until dry state

Hole filling and binarization

Skyscan 1172
SUMMARY OF THE PRESENTATION

- Nuclear waste disposal
- Material and method
- Drying kinetics
- Shrinkage
- Conclusion
Drying kinetics

- Theory of porous media drying kinetics

Léonard, 2002
**Drying Kinetics**

- Theory of porous media drying kinetics

---

Léonard, 2002
Drying kinetics

- Theory of porous media drying kinetics

Léonard, 2002
Drying kinetics

- Theory of porous media drying kinetics

Léonard, 2002
Drying kinetics

- Experimental results
Drying Kinetics

- Porous medium

Solid matrix
Air + vapor
Liquid water

Porous medium surface

Air + vapor
Liquid Water
Solid matrix
Drying kinetics

- Internal water transfer

- Solid matrix
- Air + vapor
- Liquid water

Porous medium surface

Air + vapor
Vapor diffusion
Evaporation
Liquid Water
Darcean flow
Solid matrix
Drying kinetics

- Boundary layer model

Heat flux:
\[ q_h = Lq_w - \beta(\T_{air} - \T_{surf}) \]

Water flux:
\[ q_w = \alpha(\rho_{v,\text{surf}} - \rho_{v,\text{air}}) \]
Numerical study of the drying kinetics

- **Integration of limit layer model** into a **FEM framework**:
  - Use of a special kind of finite element:
    - Boundary conditions
      - **Water pressure** at the environment node: \( p_c = -\frac{\rho RT}{M} \ln(HR) \)
      - **Temperature** at the environment node: \( T = 25^\circ C \)
      - Transfer coefficients:
        | \( \alpha \) [m/s] | \( \beta \) [W/m\(^2\)/K] |
        |-------------------|----------------------|
        | 0.048             | 53                   |
NUMERICAL STUDY OF THE DRYING KINETICS

- Numerical results:

\[ \text{Mass [g]} \]
\[ \text{Time [h]} \]
\[ \text{Drying rate [kg/(m²s)]} \]

\[ \text{Moisture content [-]} \]
\[ \text{Drying rate [kg/(m²s)]} \]
\[ \text{Time [h]} \]

\[ \text{Sample 1} \]

\[ \text{Numerical results} \]
SUMMARY OF THE PRESENTATION

- Nuclear waste disposal
- Material and method
- Drying kinetics
- Shrinkage
- Conclusion
Drying Shrinkage

- Experimental results
NUMERICAL STUDY OF THE DRYING SHRINKAGE

- Numerical mechanical model
  - 3D Orthotropic hydro-mechanical model

<table>
<thead>
<tr>
<th>MECHANICAL PARAMETERS (DIZIER, 2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\parallel}$</td>
</tr>
<tr>
<td>$E_{\perp}$</td>
</tr>
<tr>
<td>$v_{\parallel}$</td>
</tr>
<tr>
<td>$v_{\perp}$</td>
</tr>
<tr>
<td>$G_{\parallel\perp}$</td>
</tr>
<tr>
<td>$\rho_s$</td>
</tr>
</tbody>
</table>

Bedding planes

6.1 mm

6.72 mm
Numerical Study of the Drying Shrinkage

- Numerical results

![Graph showing numerical results over time and surface area.]

![Scatter plot comparing experimental and numerical results for different samples.]

- Sample 1
  - Numerical result

- Experimental parallel shrinkage
- Experimental perpendicular shrinkage
- Mean parallel shrinkage
- Mean perpendicular shrinkage
- Numerical parallel shrinkage
- Numerical perpendicular shrinkage
CONCLUSION

- Dessication cracking

![Images of sample with cracks over time](image)

![Graph showing depth of sample vs. fractured percentage of surface](image)
REFERENCES


Thank you!

This work was possible thanks to the FRS-FNRS

julien.hubert@ulg.ac.be
**Saturation Control**

- Skempton coefficient
MATERIALS AND METHODS

- X-Ray tomography characteristics
  - Cross section acquisition using a X-Ray microtomography

![Skyscan 1172](image)

Source Voltage = 100 kV
Filter = Al 0.5 mm
4x4 binning = 900x666 pixel radiograms

Pixel size = 27.27 µm
Exposure time = 510 ms
Rotation Step (deg) = 0.65

180° rotation
2 vertically-connected scans
Scan duration = 8 minutes
Experimental results

- Numerical filter
**Water Retention Curve**

- Samples put into chamber with controlled suction (saline solution)
- Water content measured ⇒ saturation degree deduced

Van Genuchten formulation:

$$S_{r,w} = S_{res} + (S_{sat} - S_{res}) \left[ \left( 1 + \frac{p_c}{\alpha} \right)^{n_{vg}} \right]^{-m_{vg}}$$

**Van Genuchten Formulation**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{res}$</td>
<td>0 [-]</td>
</tr>
<tr>
<td>$S_{sat}$</td>
<td>1 [-]</td>
</tr>
<tr>
<td>$\alpha_{vg}$</td>
<td>15 [MPa]</td>
</tr>
<tr>
<td>$m_{vg}$</td>
<td>0.449 [-]</td>
</tr>
<tr>
<td>$n_{vg}$</td>
<td>1.70 [-]</td>
</tr>
</tbody>
</table>

[Graph showing water retention curve with experimental results and fitted Van Genuchten's model].

Drying
Drying Shrinkage

- Quickly homogeneous on the whole sample
NUMERICAL STUDY

- Parameters used:

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>VALUES</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HYDRAULIC PARAMETERS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k_{sat,\perp}$</td>
<td>$8 \times 10^{-12}$</td>
<td>[m/s]</td>
</tr>
<tr>
<td>$k_{sat,\parallel}$</td>
<td>$2 \times 10^{-12}$</td>
<td>[m/s]</td>
</tr>
<tr>
<td>$n$</td>
<td>0.39</td>
<td>[-]</td>
</tr>
<tr>
<td><strong>MECHANICAL PARAMETERS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_{\parallel}$</td>
<td>700</td>
<td>[MPa]</td>
</tr>
<tr>
<td>$E_{\perp}$</td>
<td>350</td>
<td>[MPa]</td>
</tr>
<tr>
<td>$\nu_{\parallel}$</td>
<td>0.25</td>
<td>[-]</td>
</tr>
<tr>
<td>$\nu_{\parallel\perp}$</td>
<td>0.125</td>
<td>[-]</td>
</tr>
<tr>
<td>$G_{\parallel\perp}$</td>
<td>1.4</td>
<td>[MPa]</td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>2670</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td><strong>THERMAL PARAMETERS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$c_s$</td>
<td>2080</td>
<td>[J/kg*K]</td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>2670</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td>$c_w$</td>
<td>4185</td>
<td>[J/kg*K]</td>
</tr>
<tr>
<td>$\rho_w$</td>
<td>1000</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td>$c_a$</td>
<td>1004</td>
<td>[J/kg*K]</td>
</tr>
<tr>
<td>$\rho_a$</td>
<td>1.2</td>
<td>[kg/m³]</td>
</tr>
</tbody>
</table>
NUMERICAL MODEL

- Thermal model
  - Storage

\[ S_T = nS_{r,w}\rho_w c_{p,w}(T - T_0) + nS_{r,g}\rho_a c_{p,a}(T - T_0) + nS_{r,g}\rho_v c_{p,v}(T - T_0) + (1 - n)\ \rho_s c_{p,s}(T - T_0)\ ] + nS_{r,g}\rho_v c_{p,v}L \]

Liquid water  Air  Vapor  Solid  Vapor latent heat

- Heat flux

\[ V_T = -\Gamma \nabla T + c_{p,w}\rho_w f_w (T - T_0) + c_{p,a}\rho_a f_g (T - T_0) + c_{p,v}(\rho_v f_v + i_v) (T - T_0) + (\rho_v f_v + i_v)L \]

Conduction  Convection