Convective drying: experimental campaign and numerical modelling

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Monday 19th of June
SUMMARY OF THE PRESENTATION

- Scope of the study
- Experimental campaign
- Experimental results
- Model
- Numerical results
- Conclusion
NUCLEAR WASTE DISPOSAL

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

- Burial shaft and multi barrier principle:

![Diagram of burial shaft and multi barrier principle](image)

*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

- Scope of the study
- Material and method
- Experimental results
- Model
- Numerical results
- Conclusion
EXPERIMENTAL CAMPAIGN

- Samples preparation
EXPERIMENTAL CAMPAIGN

- Convective drying tests

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

- Data acquisition

Identification of the bedding direction
Dimensions at saturated state
Dimensions until dry state

Hole filling and binarization

Skyscan 1172
SUMMARY OF THE PRESENTATION

- Scope of the study
- Material and method
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Drying kinetics

- Theory of porous media convective drying

![Graphs showing drying kinetics](image)
Drying kinetics

- Theory of porous media convective drying
Drying kinetics

- Theory of porous media convective drying

![Graphs showing drying kinetics](image)
Drying kinetics

- Theory of porous media convective drying
EXPERIMENTAL RESULTS

- Drying kinetics

![Drying kinetics graphs](image)
EXPERIMENTAL RESULTS

- Shrinkage
SUMMARY OF THE PRESENTATION

- Scope of the study
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MODEL

- Porous medium
**MODEL**

- **Internal Water transfer**

  - **Porous medium surface**

  - **Solid matrix**

  - **Air + vapor**

  - **Liquid water**

  - **Liquid water**

  - **Air + vapor**

  - **Vapor diffusion**

  - **Evaporation**

  - **Darcean flow**

  - **Fick’s law**

    \[ i_v = D_{atm} \tau_v n s_{r,v} \nabla (\rho_v) \]

  - **Darcy’s law**

    \[ f_w = - \frac{k_{rel}(s_{r,w})k_{sat}}{\mu_w} \left( \nabla (\rho_w) + \rho_w g \nabla (z) \right) \]
MODEL

- Boundary layer model

Fick’s law

\[ i_v = -D_{atm} \tau_{v} n S_{r,v} V(\rho_v) \]

Boundary layer model

\[ q_h = L q - \beta(T_{air} - T_{surf}) \]

\[ q = \alpha(\rho_{v,\text{surf}} - \rho_{v,\text{air}}) \]

Darcy’s law

\[ f_w = -\frac{k_{rel}(S_{r,w}) k_{sat}}{\mu_w} (\nabla(p_w) + \rho_w g \nabla(z)) \]
Thermal model

Heat flux

\[ V_T = -\Gamma \nabla T + \rho_i c_{p,i} f_i (T - T_0) + (\rho_v f_v + i_v) L \]

Heat storage

\[ S_T = nS_{r,i} \rho_i c_{p,i} (T - T_0) + nS_{r,g} \rho_v L \]


**MODEL**

- Mechanical model
  - Expressed in effective stress

\[
\sigma'_{ij} = \sigma_{ij} - p_g \delta_{ij} + S_{r,w}(p_g - p_w)\delta_{ij}
\]

- 3D orthotropic elastic model

- Non linear elasticity:

\[
E = E_0 + E_{ref}\left(\frac{p'}{p_{ref}}\right)^b
\]

\[
\epsilon_{ij} = D_{ijkl}^e \sigma'_{ij}
\]

\[
D_{ijkl}^e = \begin{pmatrix}
\frac{1}{E_\parallel} & -\frac{\nu_{\parallel,\parallel}}{E_\parallel} & -\frac{\nu_{\parallel,\cdot}}{E_\parallel} & 0 & 0 & 0 \\
-\frac{\nu_{\parallel,\parallel}}{E_\parallel} & \frac{1}{E_\parallel} & -\frac{\nu_{\cdot,\parallel}}{E_\parallel} & 0 & 0 & 0 \\
-\frac{\nu_{\parallel,\cdot}}{E_\parallel} & -\frac{\nu_{\cdot,\parallel}}{E_\parallel} & \frac{1}{E_\parallel} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{2G_{\parallel,\parallel}} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{2G_{\parallel,\cdot}} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{2G_{\cdot,\cdot}}
\end{pmatrix}
\]
NUMERICAL MODELING

- Meshing and parameters

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>VALUES</th>
<th>UNITS</th>
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</thead>
<tbody>
<tr>
<td>(k_{\text{sat},\perp})</td>
<td>(6.1 \times 10^{-12})</td>
<td>[m/s]</td>
</tr>
<tr>
<td>(k_{\text{sat},\parallel})</td>
<td>(3.1 \times 10^{-12})</td>
<td>[m/s]</td>
</tr>
<tr>
<td>(n)</td>
<td>0.39</td>
<td>[-]</td>
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<tr>
<td>HYDRAULIC PARAMETERS</td>
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<tr>
<td>(E_{\text{I,ref}})</td>
<td>350</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(E_{\text{L,ref}})</td>
<td>175</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(E_{\text{Z,ref}})</td>
<td>300</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(\nu_{\text{II}})</td>
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<td>[-]</td>
</tr>
<tr>
<td>(\nu_{\text{IL}})</td>
<td>0.0625</td>
<td>[-]</td>
</tr>
<tr>
<td>(\nu_{\text{IZ}})</td>
<td>0.0625</td>
<td>[-]</td>
</tr>
<tr>
<td>MECHANICAL PARAMETERS</td>
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<td></td>
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<tr>
<td>(G_{\text{II}})</td>
<td>140</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(G_{\text{IL}})</td>
<td>140</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(\rho_{s})</td>
<td>2670</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td>THERMAL PARAMETERS</td>
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<td></td>
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<tr>
<td>(c_{p,s})</td>
<td>2080</td>
<td>[J/kg/K]</td>
</tr>
<tr>
<td>(\rho_{s})</td>
<td>2670</td>
<td>[kg/m³]</td>
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<tr>
<td>(c_{p,w})</td>
<td>4185</td>
<td>[J/kg/K]</td>
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<tr>
<td>(\rho_{w})</td>
<td>1000</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td>(c_{p,a})</td>
<td>1004</td>
<td>[J/kg/K]</td>
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<tr>
<td>(\rho_{a})</td>
<td>1.2</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td>(c_{p,v})</td>
<td>1864</td>
<td>[J/kg/K]</td>
</tr>
<tr>
<td>(\rho_{v})</td>
<td>0.59</td>
<td>[kg/m³]</td>
</tr>
</tbody>
</table>
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**NUMERICAL RESULTS**

- Drying kinetics

![Graphs showing drying kinetics](image-url)
NUMERICAL RESULTS

- Shrinkage

![Graph 1: Surface vs. Time](image1)

![Graph 2: V/V₀ vs. Time](image2)
Numerical Results

- Shrinkage

After 1h

Dry sample

Sample height [mm]

Sample name [-]

Relative shrinkage [%]

R/R₀ [-]

Experimental parallel radius
Numerical parallel radius
Experimental perpendicular radius
Numerical perpendicular radius

Parallel shrinkage
Perpendicular shrinkage
Axial shrinkage
Numerical parallel shrinkage
Numerical perpendicular shrinkage
Numerical axial shrinkage
CONCLUSION

- Dessication cracking
REFERENCES


SCK-CEN. R and D for the geological disposal of medium and high level waste in the Boom clay, 2009. URLence.sckcen.be/en/Projects/Project/RD_waste_disposal/Geological_disposal

SENSITIVITY STUDY

Julien Hubert

QUESTIONS

19/06/2017
**Numerical Modeling**

- Boundary layer model in FEM code:

  ![Diagram](Gerard & al, 2008)

  - Water pressure at the environmental node $n_4$: $p_c = -\frac{\rho RT}{M} \ln(HR)$
  - Temperature at the environmental node $n_4$: $T = 25^\circ C$
  - Transfer coefficients:

<table>
<thead>
<tr>
<th>$\alpha [m/s]$</th>
<th>$\beta [W/m^2/K]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.048</td>
<td>53</td>
</tr>
</tbody>
</table>
WATER RETENTION CURVE

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

Van Genuchten formulation:

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

<table>
<thead>
<tr>
<th>VAN GENUCHTEN FORMULATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>(S_{\text{res}})</td>
</tr>
<tr>
<td>(S_{\text{sat}})</td>
</tr>
<tr>
<td>(\alpha_{\text{vg}})</td>
</tr>
<tr>
<td>(m_{\text{vg}})</td>
</tr>
<tr>
<td>(n_{\text{vg}})</td>
</tr>
</tbody>
</table>

Experimental results

Delage et al., 2011

Fitted using Van Genuchten’s model

Drying
# Boom Clay Composition

<table>
<thead>
<tr>
<th>Composition MINÉRALOGIQUE en [%]</th>
<th>Al-Mukhtar et al., 1996</th>
<th>Wouters et Vandenberghe, 1994</th>
<th>Decler et al., 1983</th>
<th>Horseman et al., 1986</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>20-25</td>
<td>20</td>
<td>23.8-58.3</td>
<td>30</td>
</tr>
<tr>
<td>Interstratifié illite-smectite</td>
<td>33</td>
<td>40-50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Illite</td>
<td>16</td>
<td>25-35</td>
<td>3-23</td>
<td>19</td>
</tr>
<tr>
<td>Smectite</td>
<td></td>
<td></td>
<td>19-42</td>
<td>22</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>13</td>
<td>15-25</td>
<td>1-9</td>
<td>29</td>
</tr>
<tr>
<td>Feldspaths:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microcline</td>
<td>4-5</td>
<td></td>
<td>6.5-11.3</td>
<td></td>
</tr>
<tr>
<td>Plagioclase</td>
<td>4-5</td>
<td></td>
<td>3.2-6.2</td>
<td></td>
</tr>
<tr>
<td>Chlorite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyrite</td>
<td>4-5</td>
<td>1-5</td>
<td>0.7-2.5</td>
<td></td>
</tr>
<tr>
<td>Carbonates</td>
<td>traces</td>
<td>1-5</td>
<td>0.0-4.3</td>
<td></td>
</tr>
<tr>
<td>Matières organiques</td>
<td></td>
<td>1-5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tableau 3 : Revue bibliographique de la composition minéralogique de l’Argile de Boom
MATERIALS AND METHODS

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

<table>
<thead>
<tr>
<th>Source Voltage = 100 kV</th>
<th>Filter = Al 0.5 mm</th>
<th>4x4 binning = 900x666 pixel radiograms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel size = 27.27 µm</td>
<td>Exposure time = 510 ms</td>
<td>Rotation Step (deg)= 0.65</td>
</tr>
<tr>
<td>180° rotation</td>
<td>2 vertically-connected scans</td>
<td>Scan duration = 8 minutes</td>
</tr>
</tbody>
</table>

SkyScan 1172
EXPERIMENTAL RESULTS

- Numerical filter

### Questions

19/06/2017

Julien Hubert