UEE
Urban & Environmental Engineering

LIÈGE université

6th European Drying Conference

# Convective drying : experimental campaign and numerical modelling

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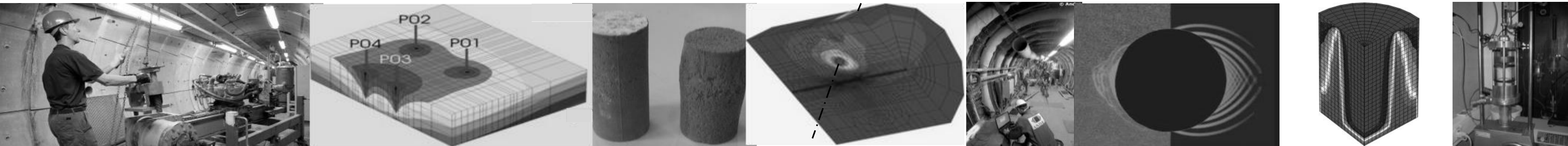
*Monday 19th of June*



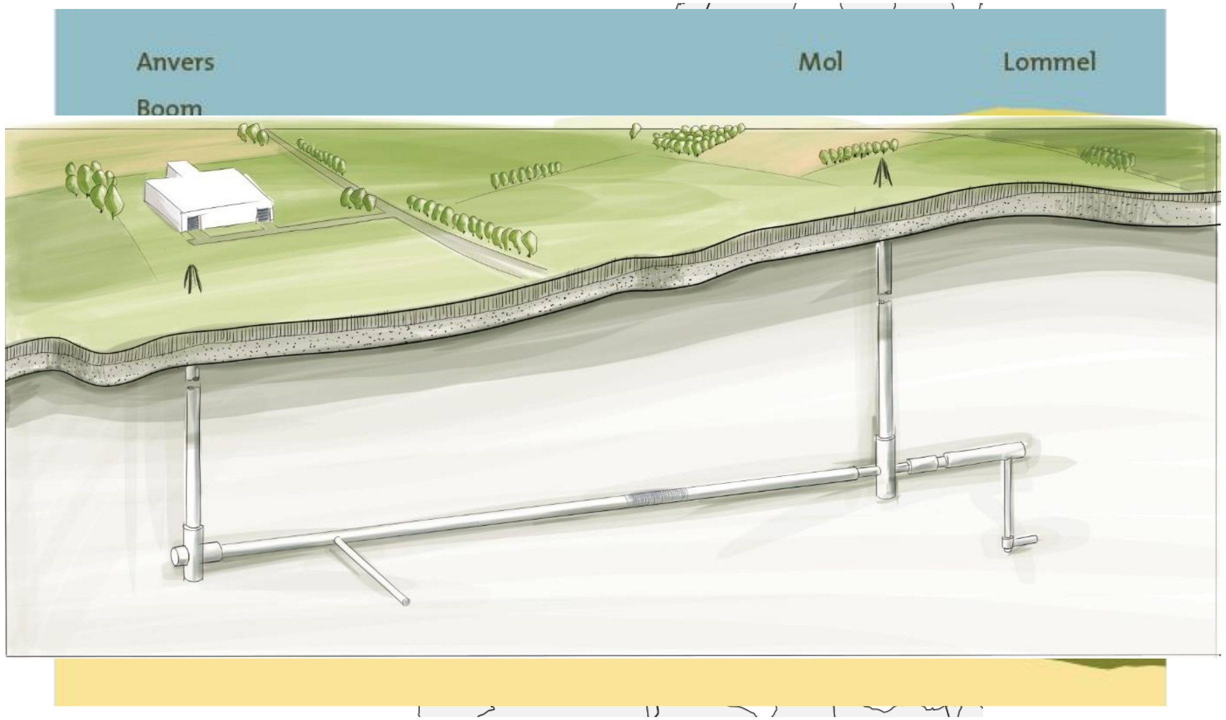
# Summary of the presentation

- 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

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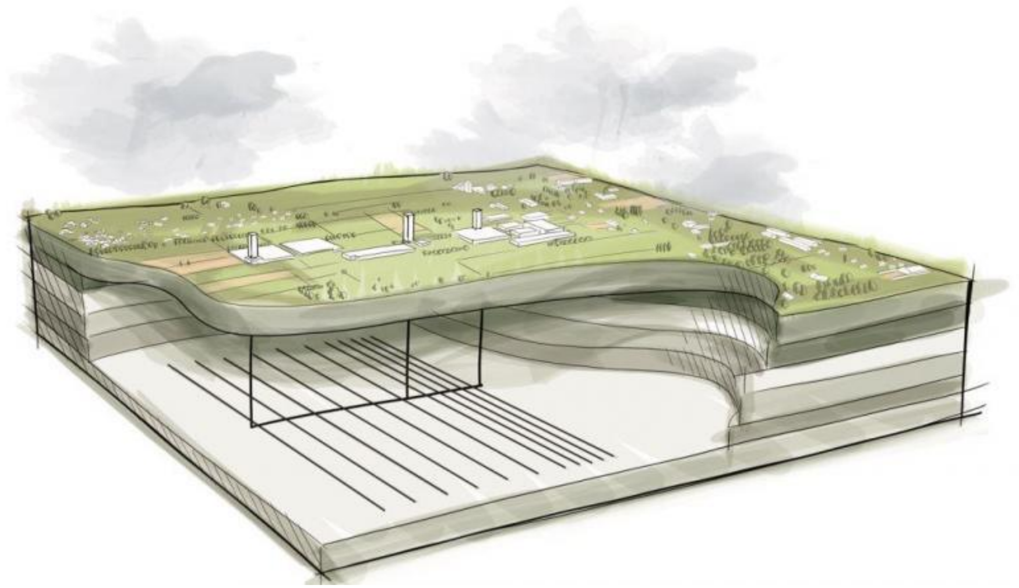
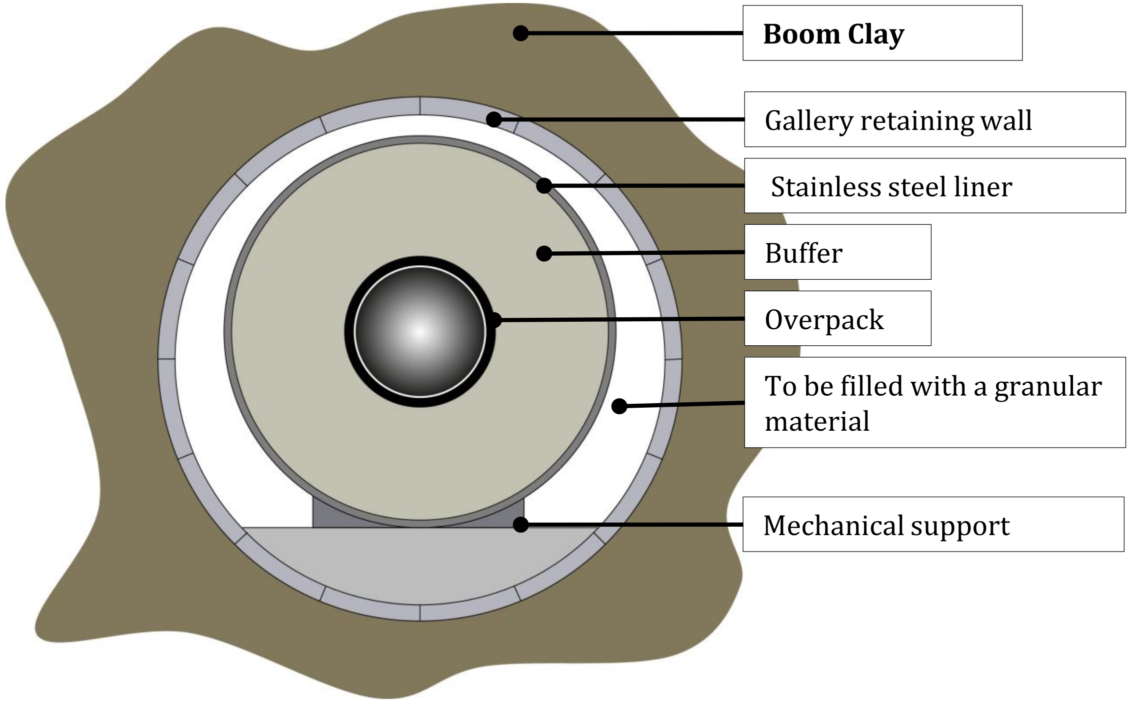
# Deep Geological Storage

- Burial shaft and multi barrier principle:



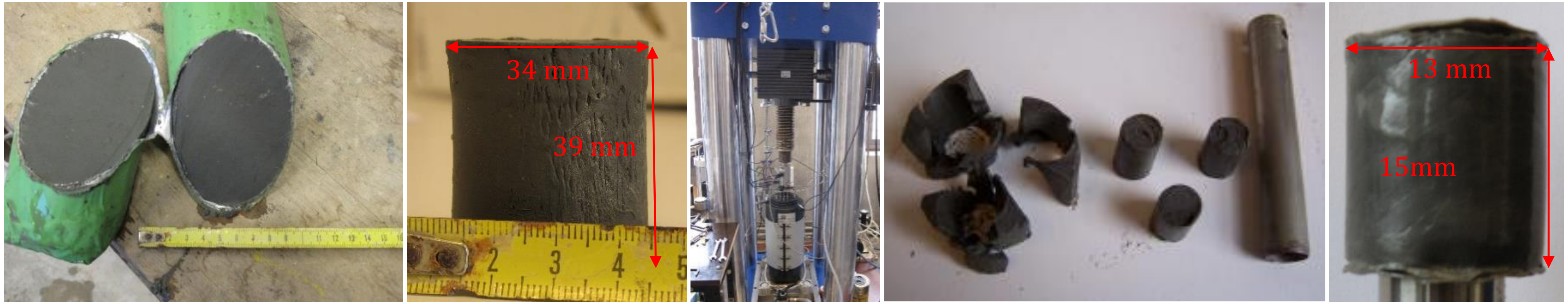



*Craye et al., 2009*

# SUMMARY OF THE PRESENTATION

# Experimental campaign

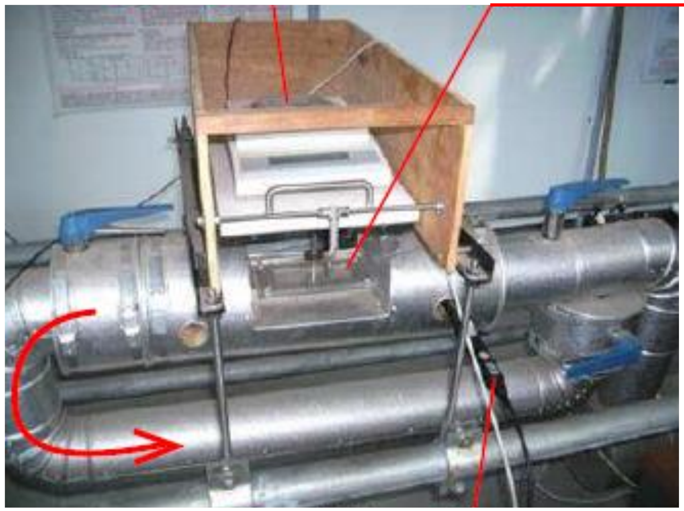
- Samples preparation

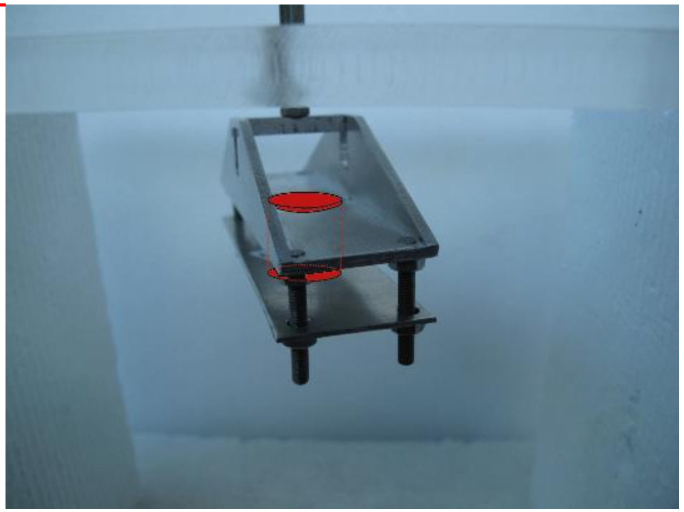



Initial core → Extracted samples → Saturation → Optimization → Finished samples

# EXPERIMENTAL CAMPAIGN

- Convective drying tests

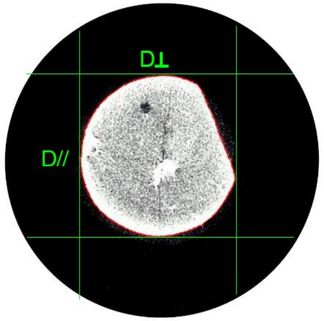


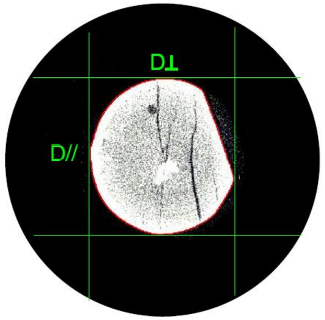


| Drying conditions | |
|---|---|
| Temperature | 25°C |
| Humidity | 3,5 % |
| Air flow | 0,8 m/s |

# EXPERIMENTAL CAMPAIGN

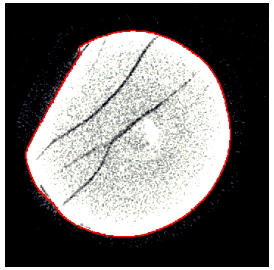
- Data acquisition

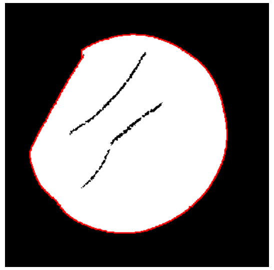




Identification of the bedding direction | Dimensions at saturated state | Dimensions until dry state

*Skyscan 1172*



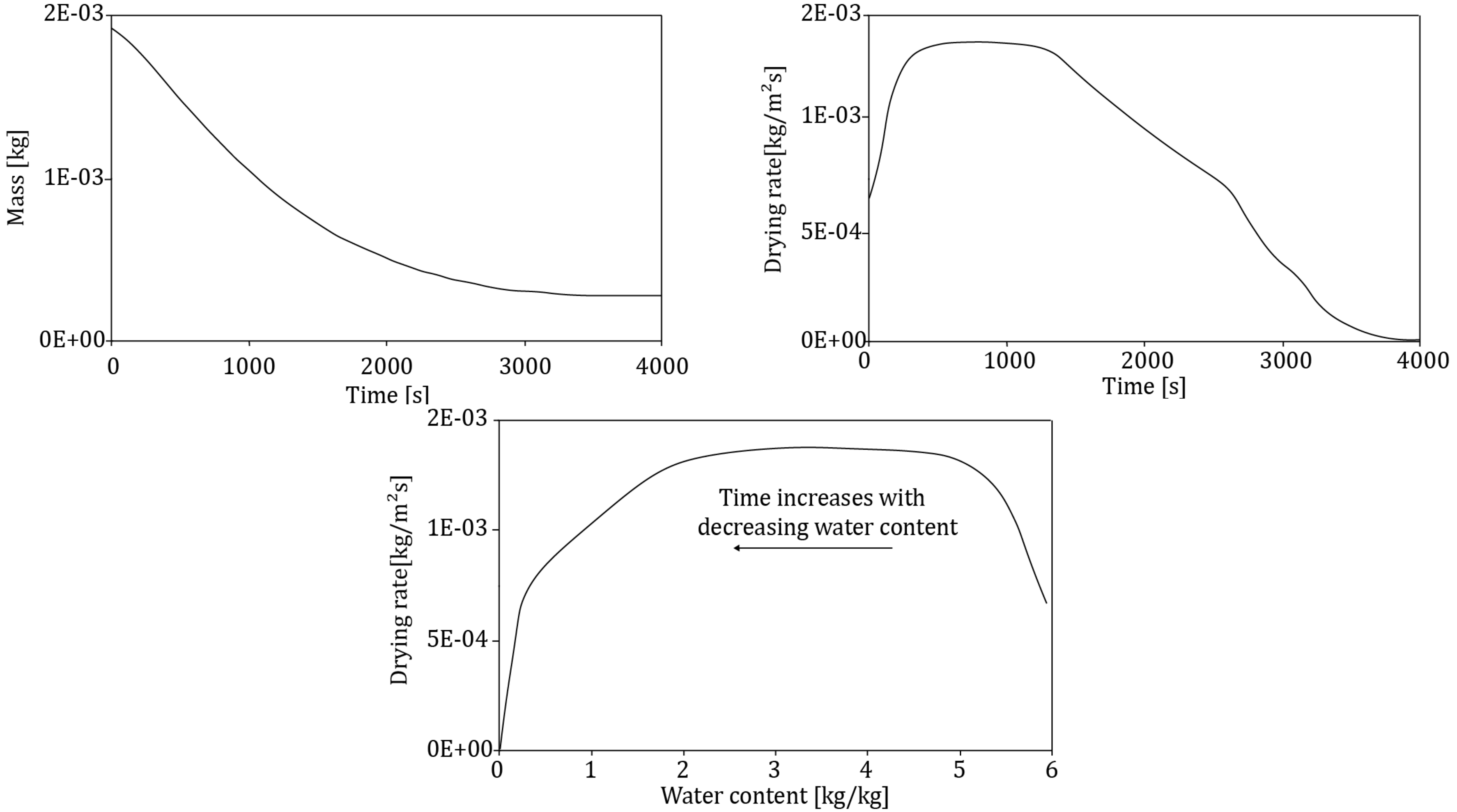
Hole filling and binarization



# Summary of the presentation

# DRYING KINETICS

- Theory of porous media convective drying



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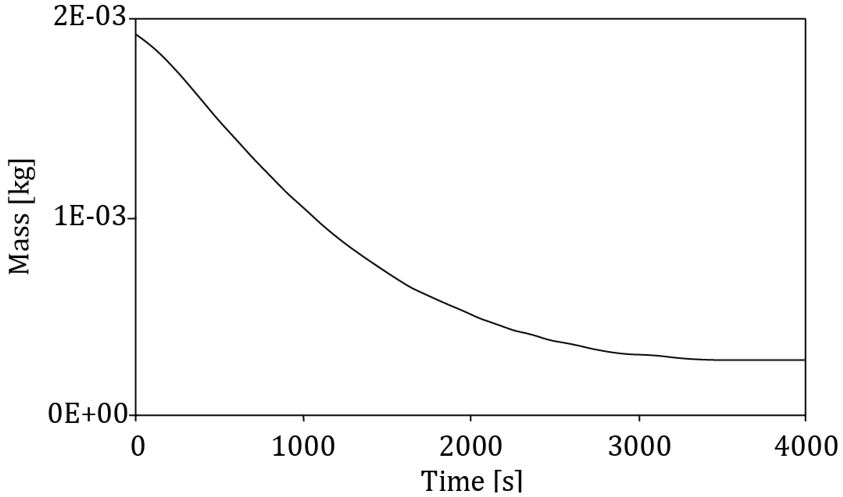


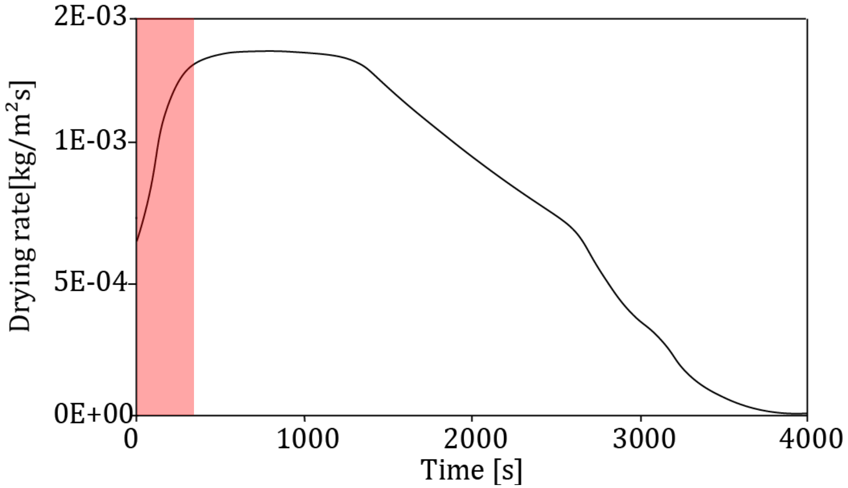


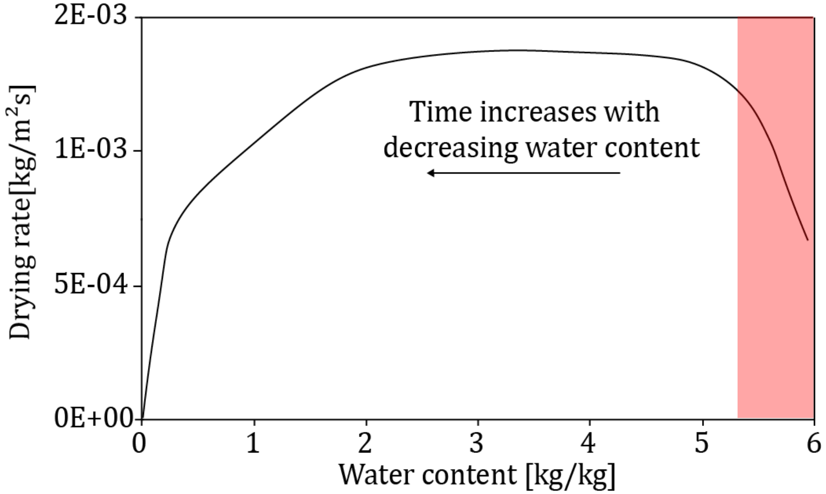

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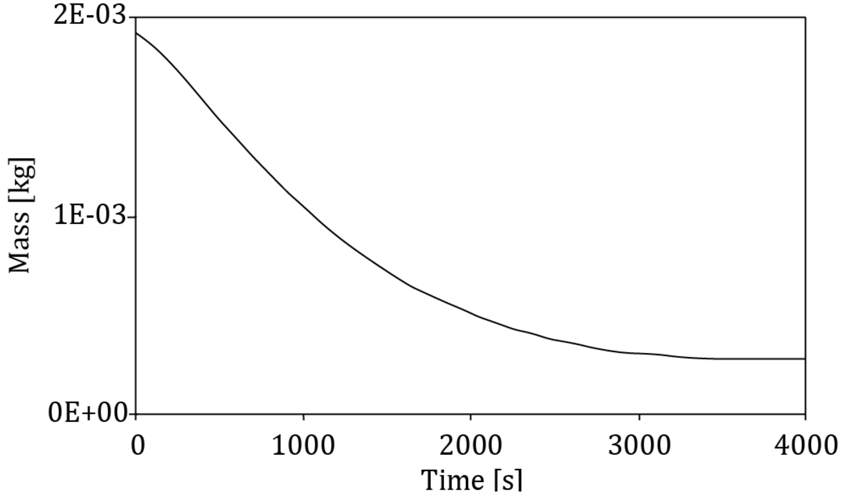


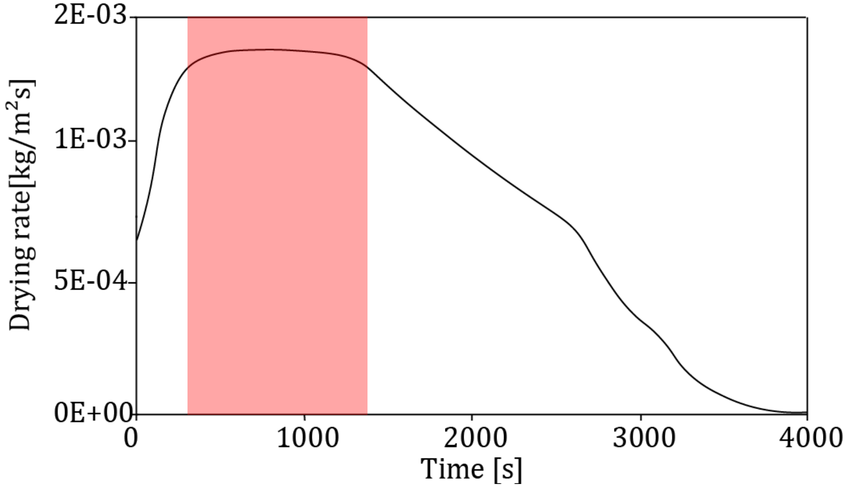


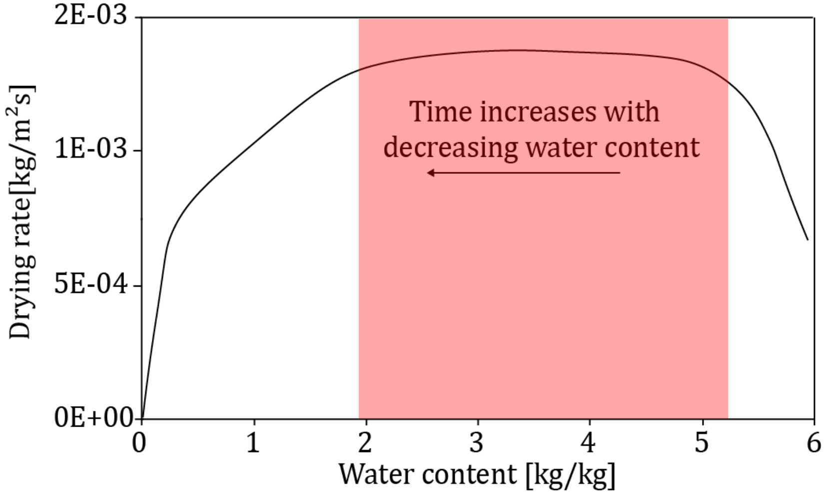


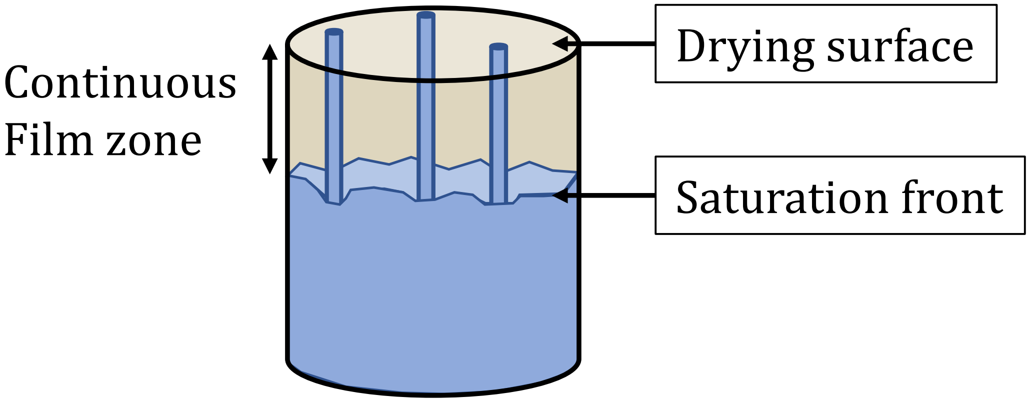

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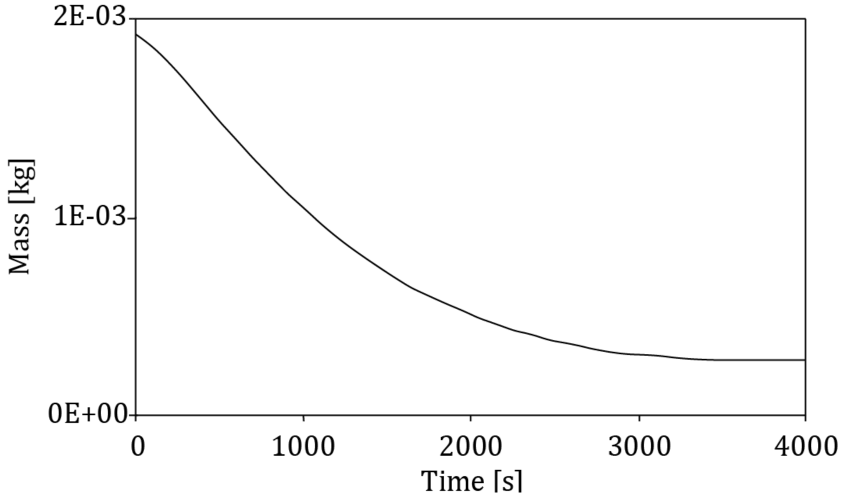
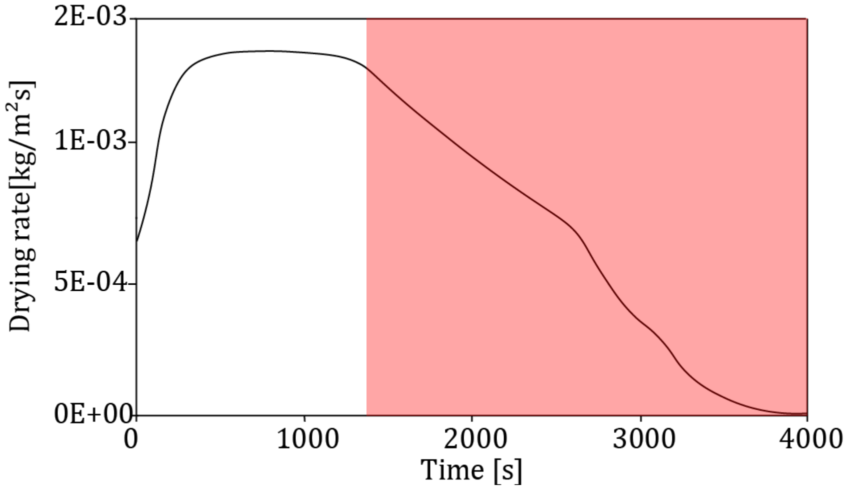
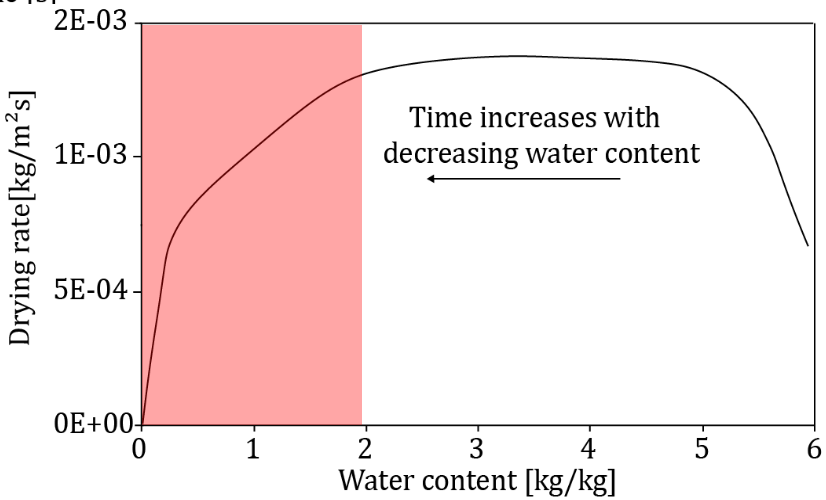
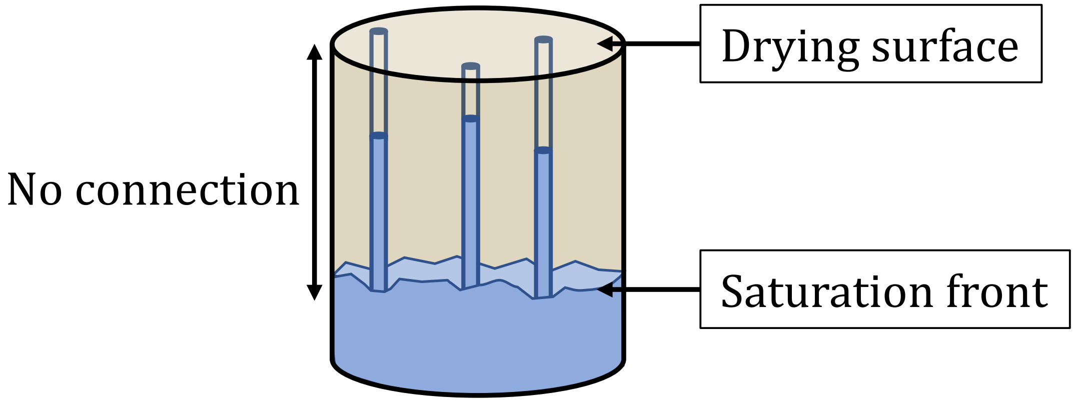
- Theory of porous media convective drying



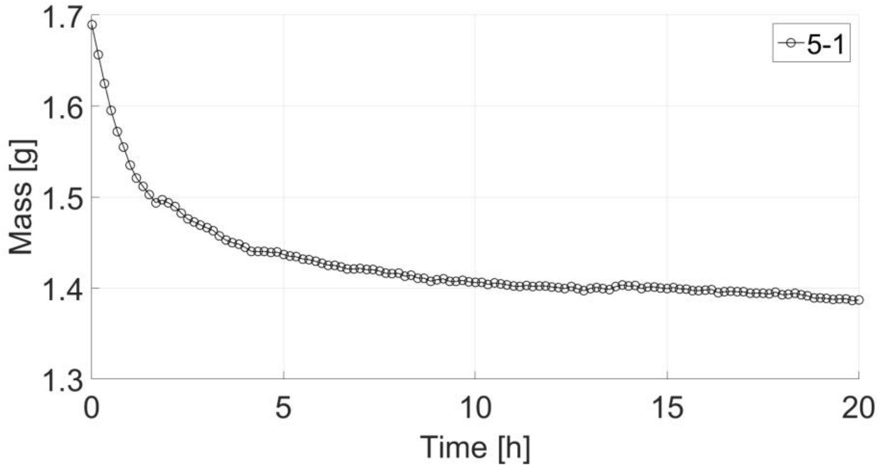



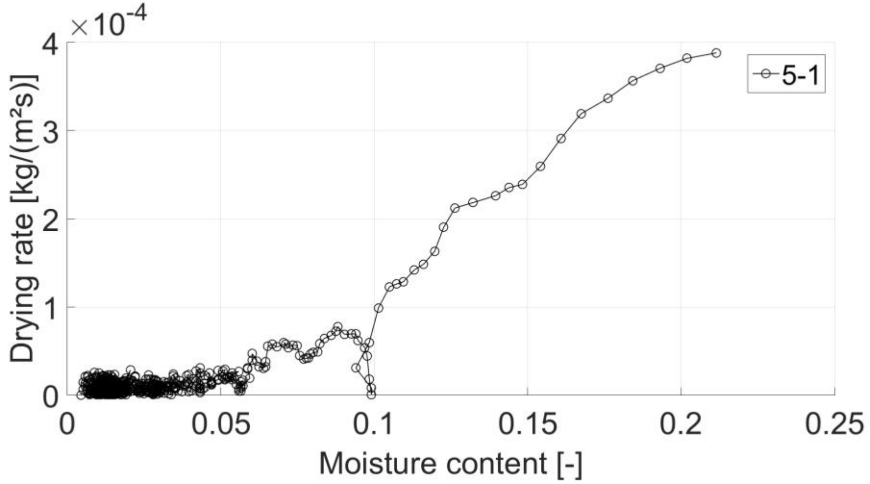



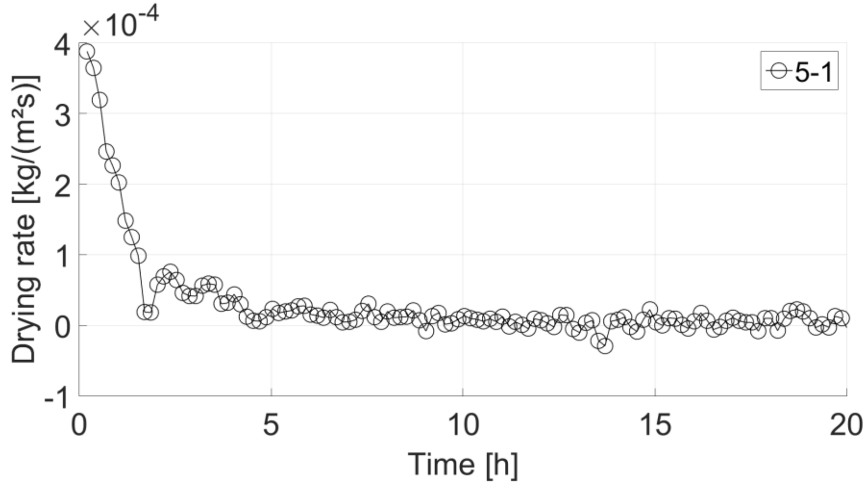



# Experimental results

- Drying kinetics

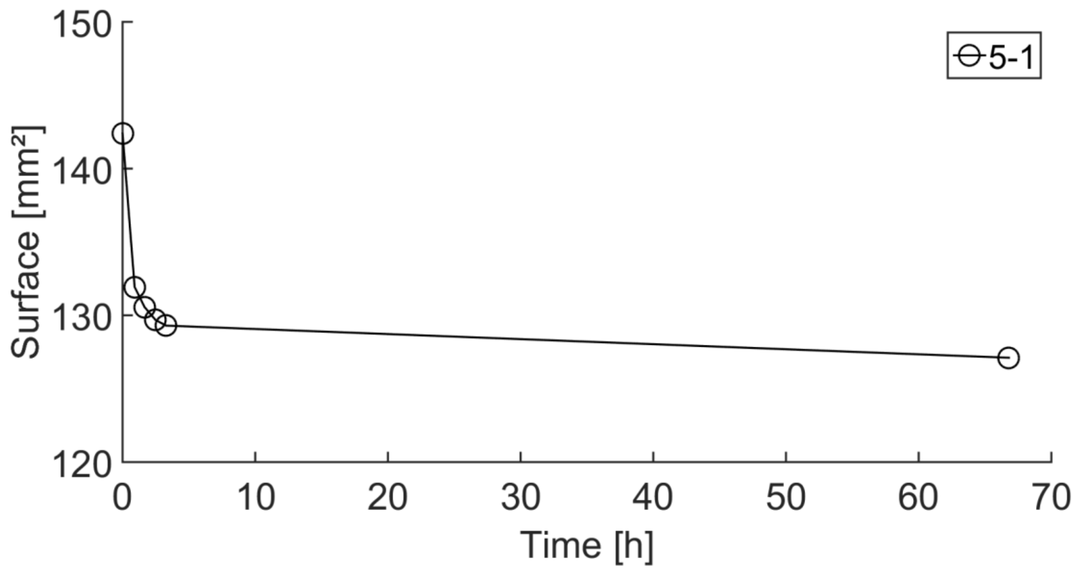


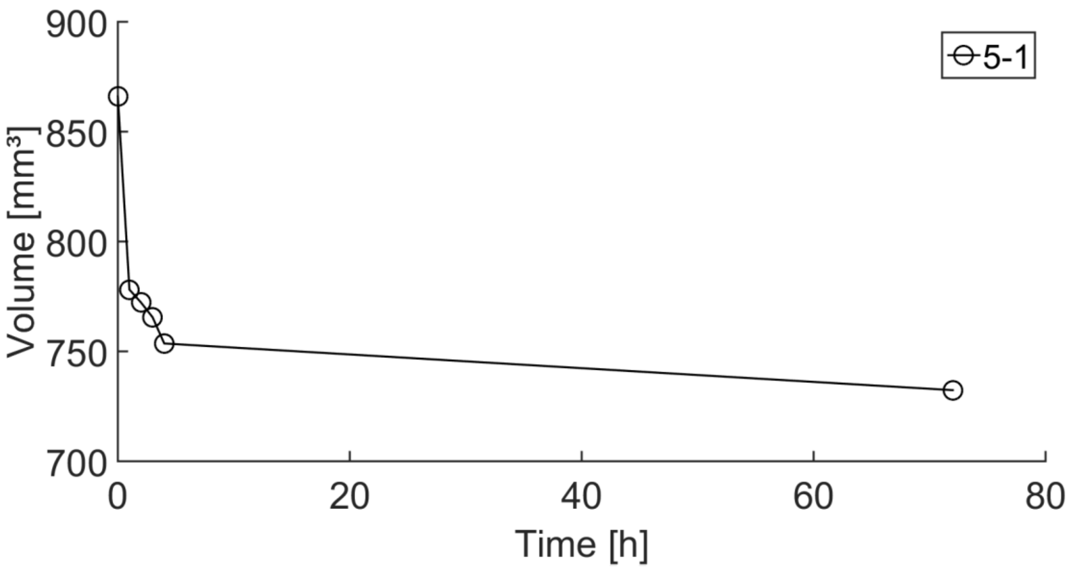



# Experimental results

- Shrinkage

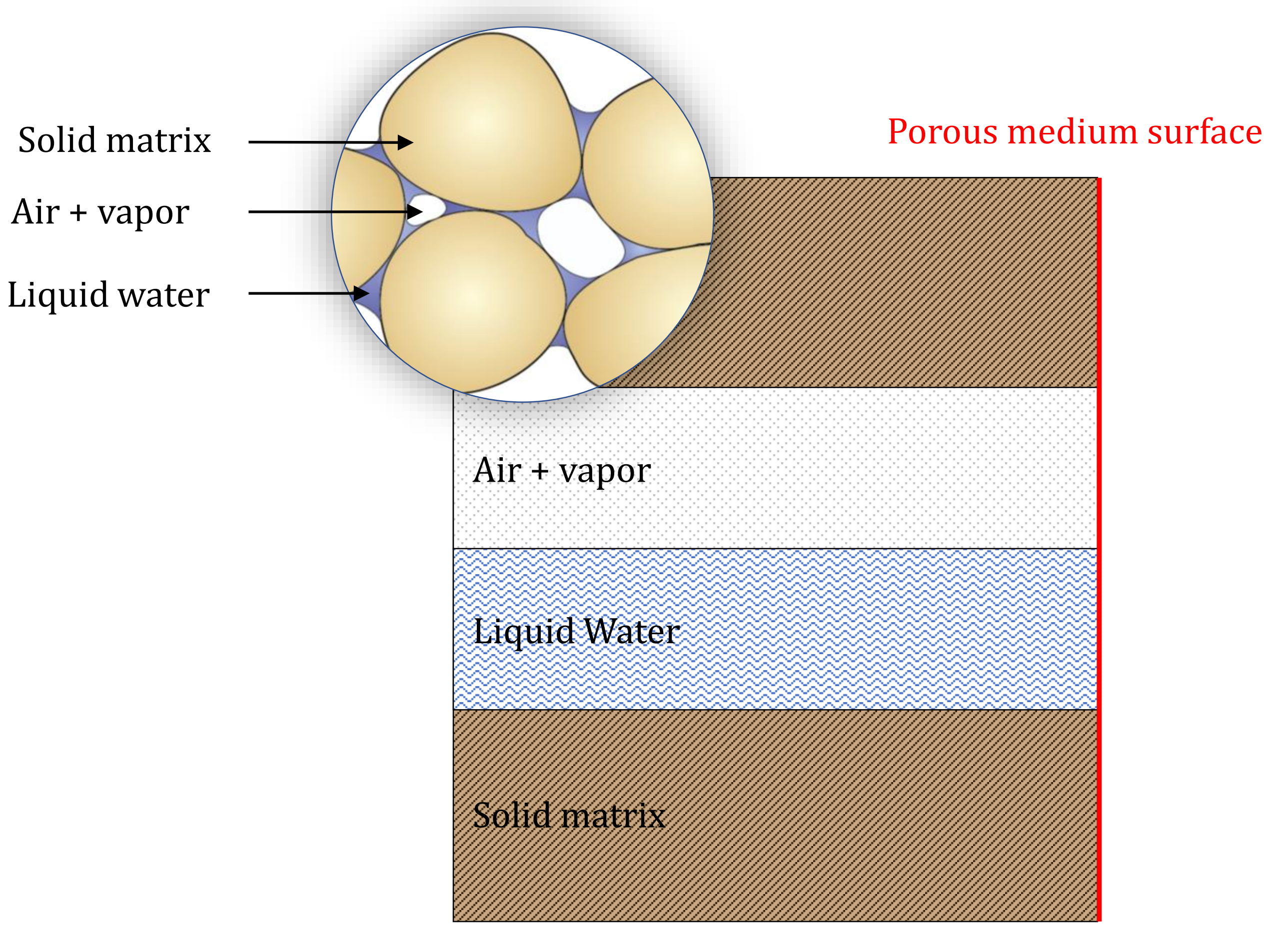


# SUMMARY OF THE PRESENTATION

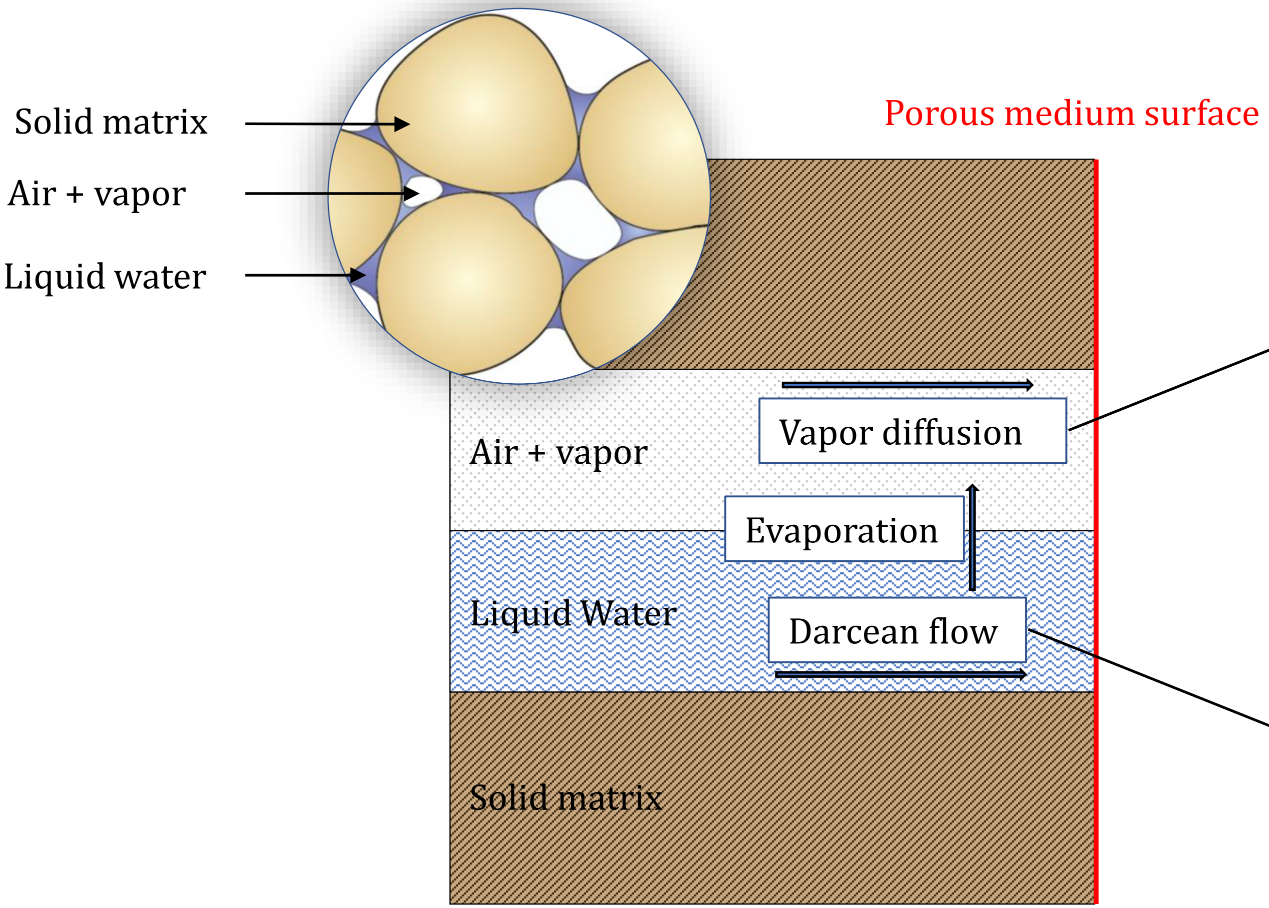
# Model

- Porous medium



# Model

- Internal Water transfer




Fick's law

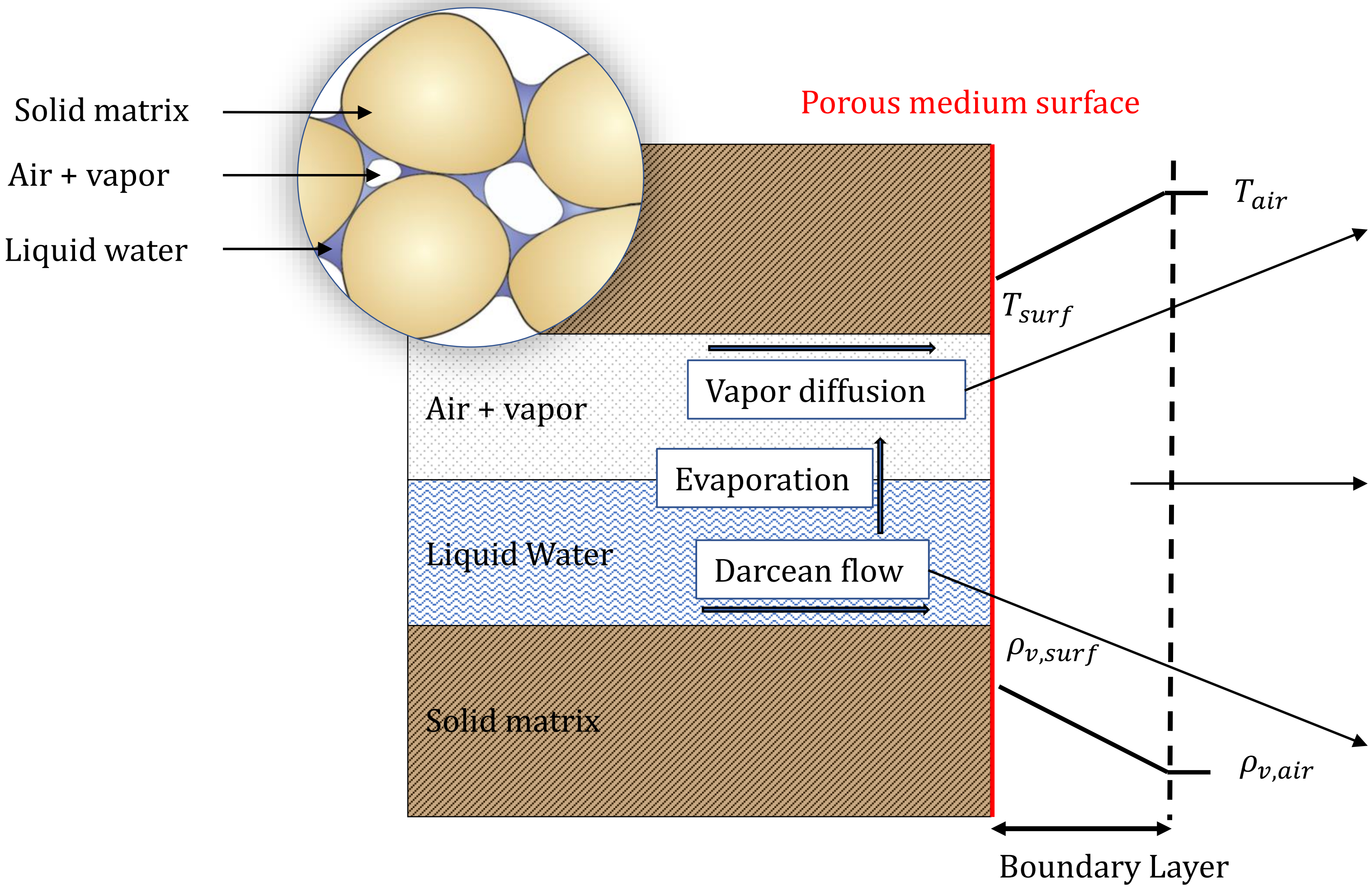
$$\underline{i}_v = D_{atm}\tau_v n S_{r,v} \nabla(\rho_v)$$

Darcy's law

$$\underline{f}_w = -\frac{k_{rel}(S_{r,w})k_{sat}}{\mu_w}\left(\underline{\nabla}(p_w) + \rho_w g \underline{\nabla}(z)\right)$$

# Model

- Boundary layer model




**Fick's law**

$$\underline{i}_v = -D_{atm}\tau_v n S_{r,v} \underline{\nabla}(\rho_v)$$

**Boundary layer model**

$$\underline{q}_h = L\underline{q} - \boldsymbol{\beta}(T_{air} - T_{surf})$$

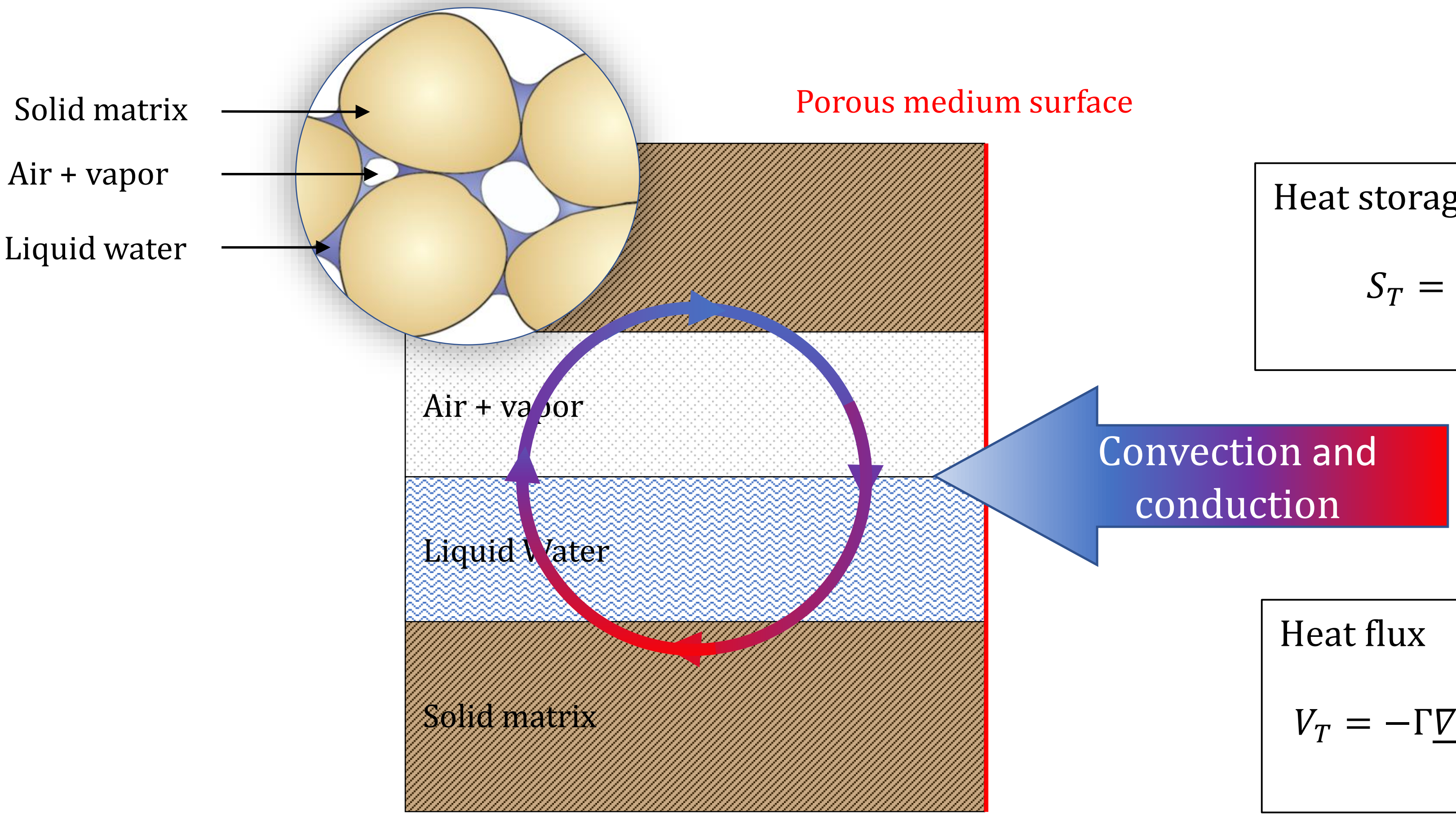
$$\underline{q} = \boldsymbol{\alpha}(\rho_{v,surf} - \rho_{v,air})$$

**Darcy's law**

$$\underline{f}_w = -\frac{k_{rel}(S_{r,w})k_{sat}}{\mu_w}\left(\underline{\nabla}(p_w) + \rho_w g \underline{\nabla}(z)\right)$$

# MODEL

- Thermal model




Heat storage

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

Heat flux

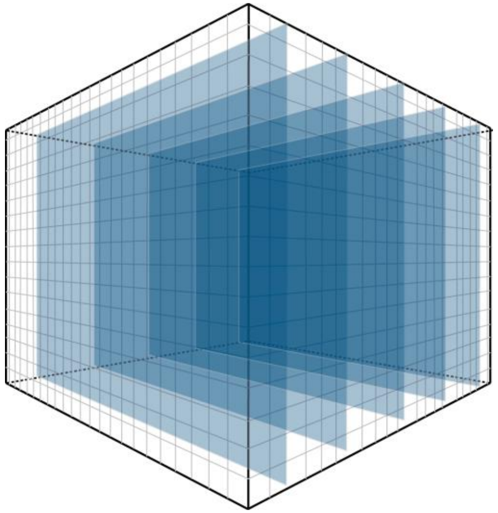
$$V_T = -\Gamma \underline{\nabla} T + c_{p,i}\rho_i \underline{f_i}(T - T_0) + (\rho_v f_v + i_v)\mathrm{L}$$

# 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 :

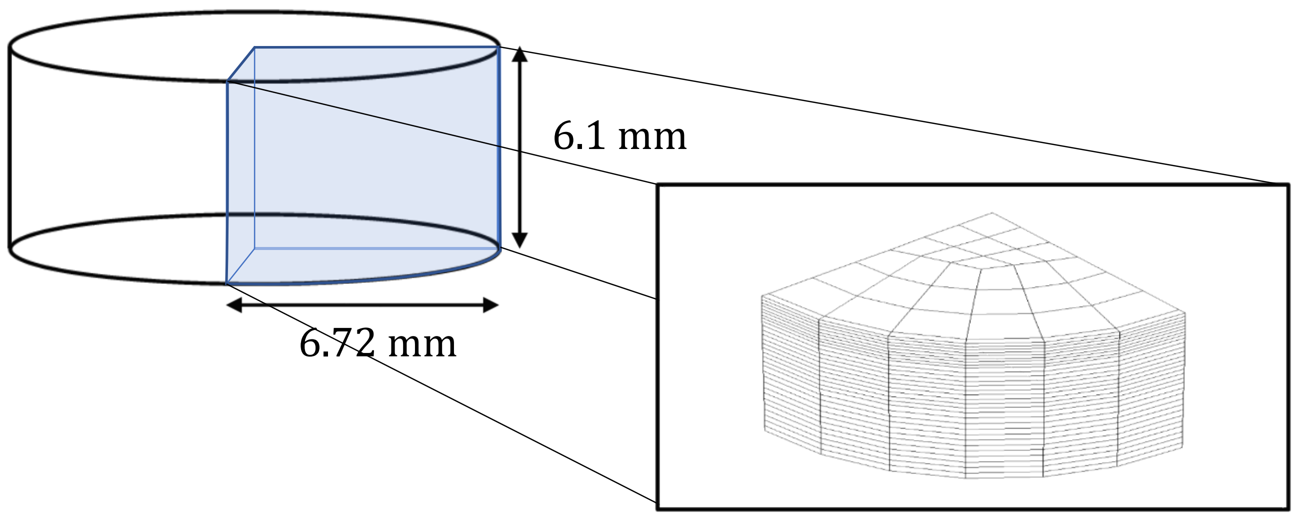
$$E = E_0 + E_{ref}\left(\frac{p'}{p_{ref}}\right)^b$$

$$\epsilon_{ij} = \mathrm{D}^{\mathrm{e}}_{\mathrm{ijkl}}\sigma'_{ij}$$

$$\mathrm{D}^{\mathrm{e}}_{\mathrm{ijkl}} = \begin{pmatrix} \frac{1}{E_\parallel} & -\frac{\nu_{\perp,\parallel}}{E_\perp} & -\frac{\nu_{z,\parallel}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{\parallel,\perp}}{E_\parallel} & \frac{1}{E_\perp} & -\frac{\nu_{z,\perp}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{\parallel,z}}{E_\parallel} & -\frac{\nu_{\perp,z}}{E_\perp} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{2G_{\parallel,\perp}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{2G_{\parallel,z}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2G_{\perp,z}} \end{pmatrix}$$

# NUMERICAL MODELING

- Meshing and parameters



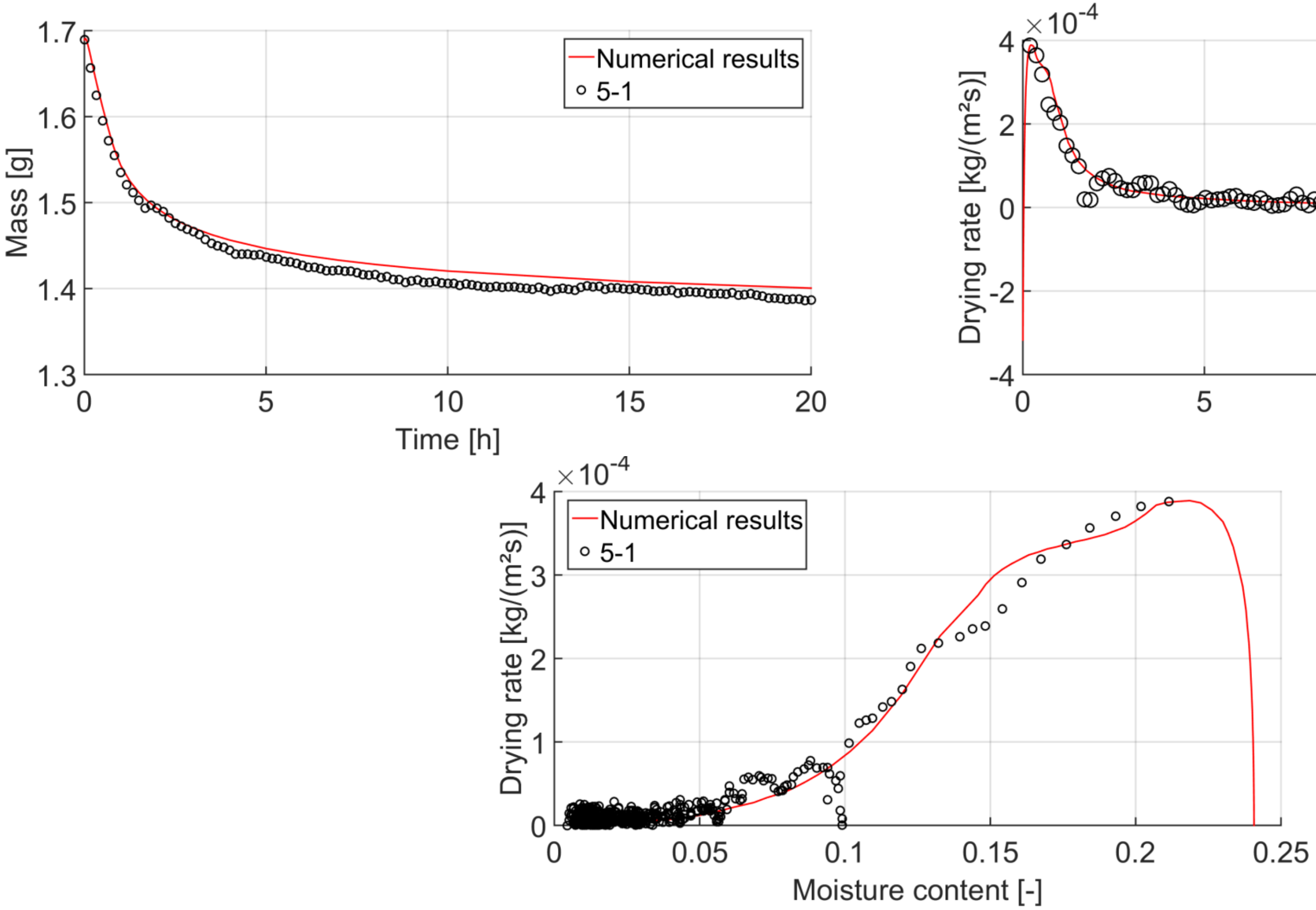

| PARAMETERS | VALUES | UNITS |
|---|---|---|
| | HYDRAULIC PARAMETERS | |
| $k_{sat,\perp}$ | $6.10^{-12}$ | $[m/s]$ |
| $k_{sat,\parallel}$ | $3.10^{-12}$ | $[m/s]$ |
| $n$ | 0.39 | $[-]$ |
| | MECHANICAL PARAMETERS | |
| $E_{\parallel,ref}$ | 350 | $[MPa]$ |
| $E_{\perp,ref}$ | 175 | $[MPa]$ |
| $E_{z,ref}$ | 300 | $[MPa]$ |
| $\nu_{\parallel\perp}$ | 0.125 | $[-]$ |
| $\nu_{\parallel z}$ | 0.0625 | $[-]$ |
| $\nu_{\perp z}$ | 0.0625 | $[-]$ |
| $G_{\parallel\perp}$ | 140 | $[MPa]$ |
| $G_{\perp z}$ | 140 | $[MPa]$ |
| $\rho_s$ | 2670 | $[kg/m^3]$ |
| | THERMAL PARAMETERS | |
| $c_{p,s}$ | 2080 | $[J/kg/K]$ |
| $\rho_s$ | 2670 | $[kg/m^3]$ |
| $c_{p,w}$ | 4185 | $[J/kg/K]$ |
| $\rho_w$ | 1000 | $[kg/m^3]$ |
| $c_{p,a}$ | 1004 | $[J/kg/K]$ |
| $\rho_a$ | 1.2 | $[kg/m^3]$ |
| $c_{p,v}$ | 1864 | $[J/kg/K]$ |
| $\rho_v$ | 0.59 | $[kg/m^3]$ |

# Summary of the presentation

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

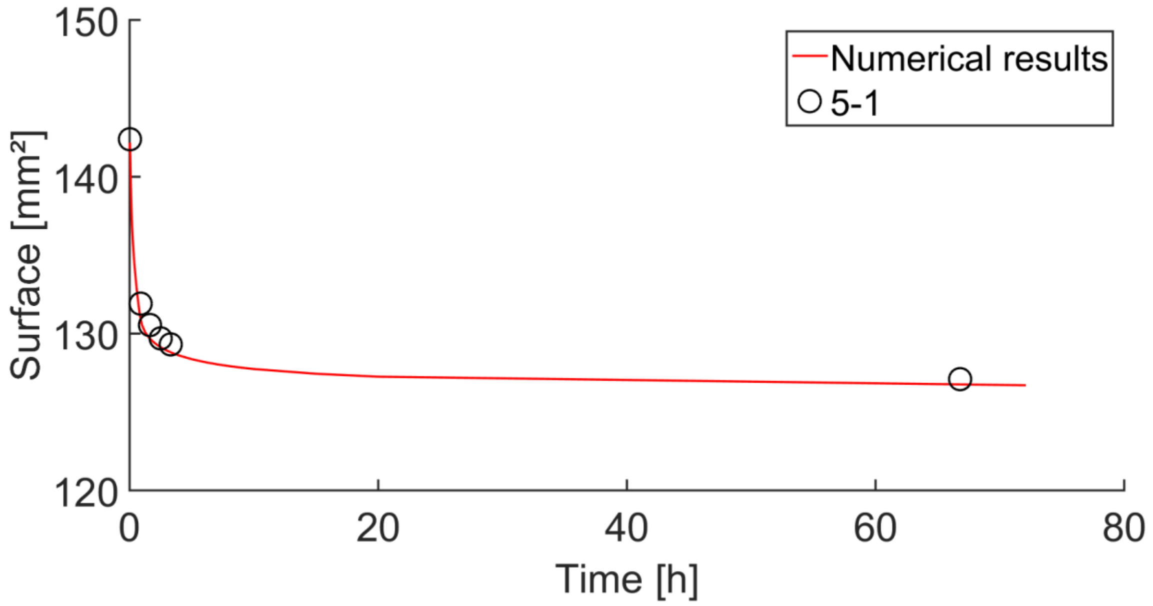
# NUMERICAL RESULTS

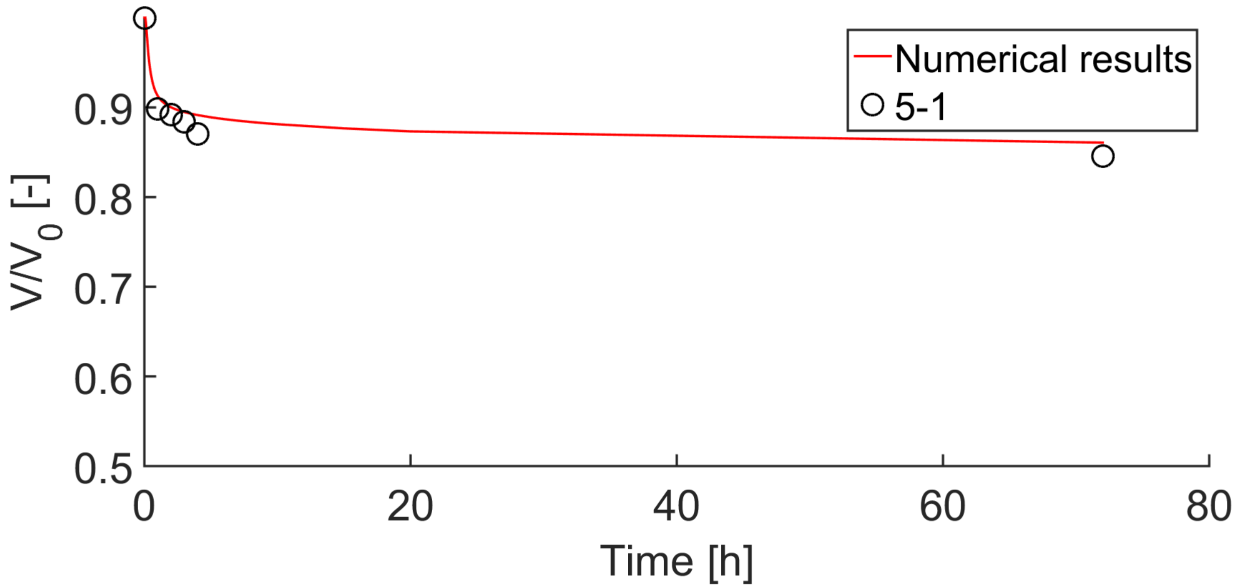
- Drying kinetics



# NUMERICAL RESULTS

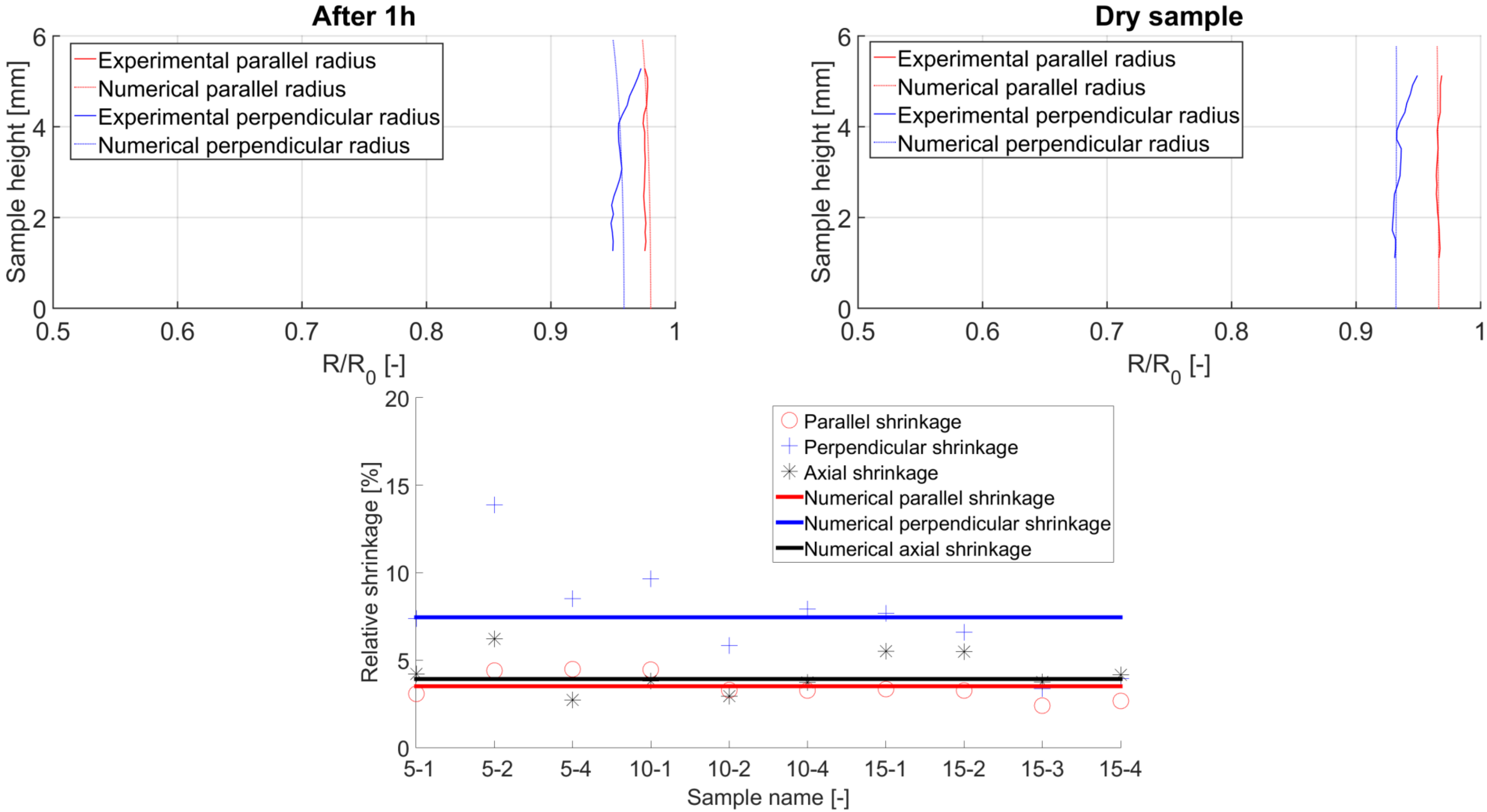
- Shrinkage



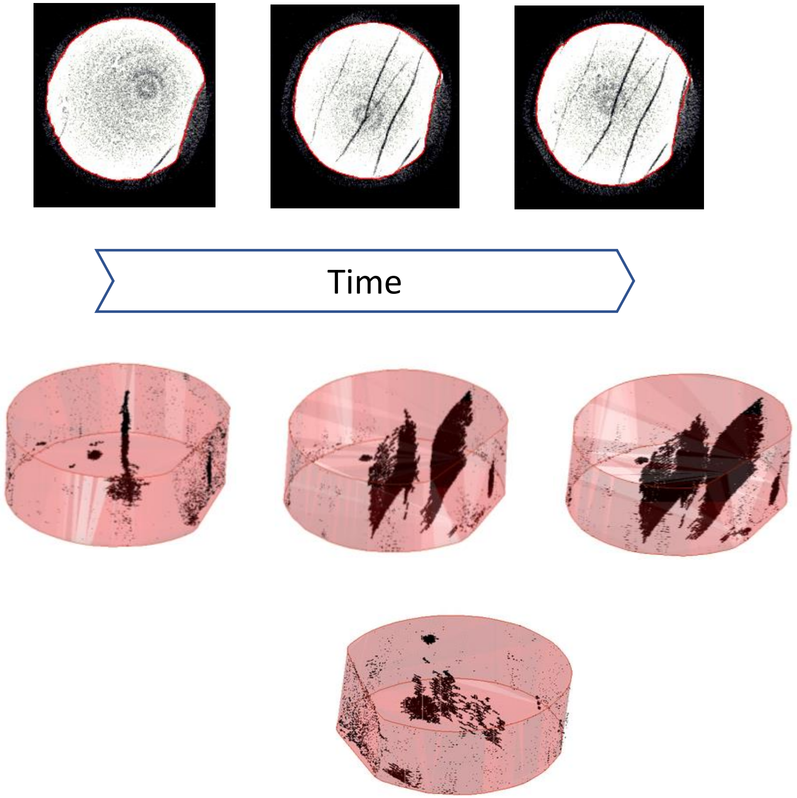
# Numerical results

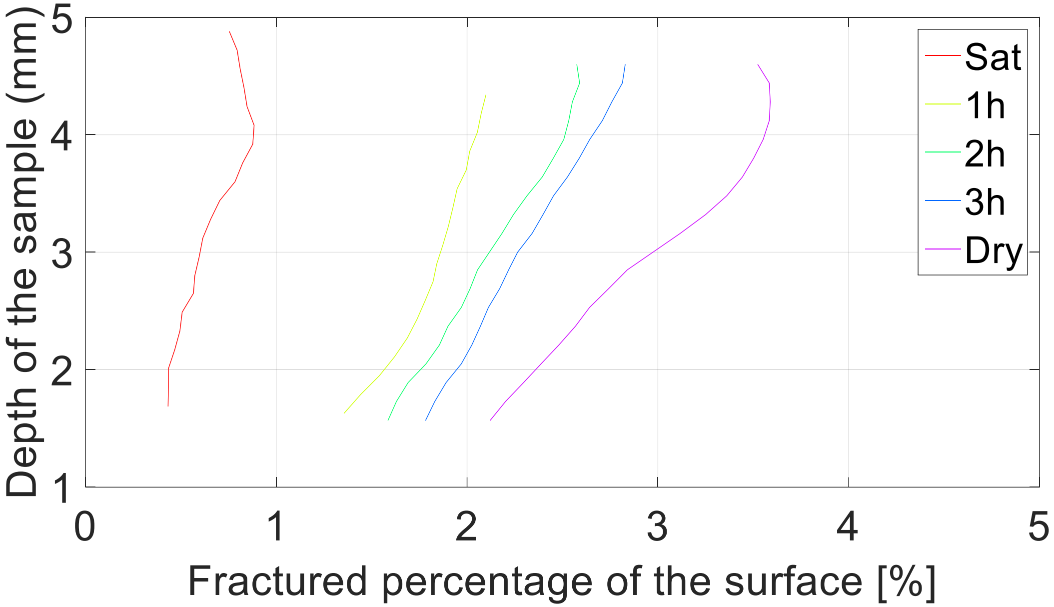
- Shrinkage



# CONCLUSION

- Dessication cracking



# References

Andra (2005a). Dossier 2005 Argile. Synthesis: Evaluation of the feasibility of a geological repository in an argillaceous formation, Meuse/Haute Marne site. Technical report, Paris, France.

Bastiens W., Demarche M., 2003. The extension of the URF HADES: realization and observation. Proceedings of the WN'03 Conference, Tucson, USA.

Craeye B., De Schutter G., Van Humbeeck H., Van Cotthem, 2009. *Early age behaviour of concrete supercontainers for radioactive waste disposal.* Nuclear Engineering and Design, 239, 23-35.

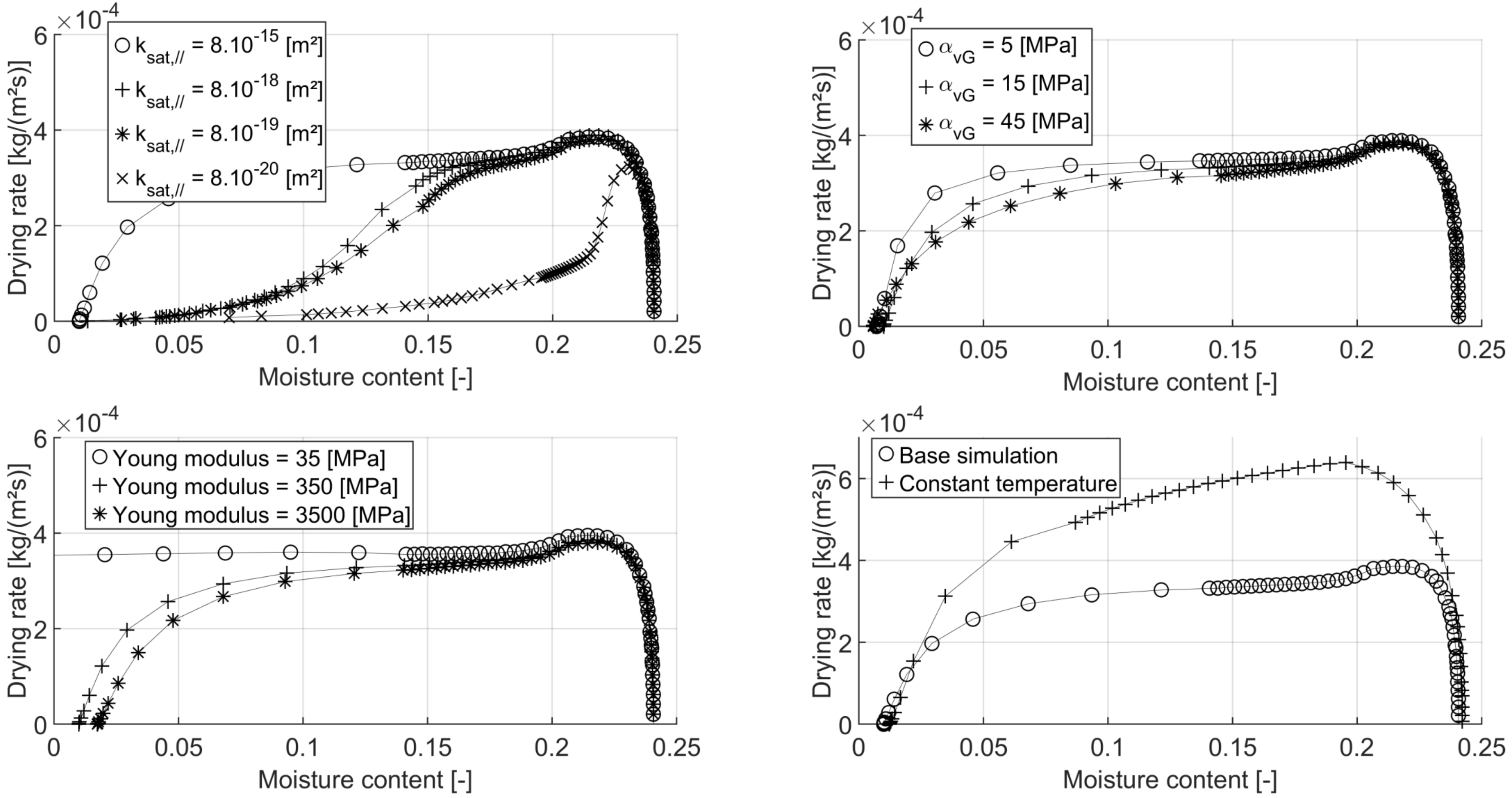
Gerard P., Charlier, R, Chambon, R, & Collin, F. 2008. Influence of evaporation and seepage on the convergence of a ventilated cavity. Water resources research, 44(5), W00C02.

Léonard A., Étude du séchage convectif de boues de station d'épuration. Suivi de la texture par microtomographie à rayons X. Thèse de doctorat, Université de Liège, Faculté des Sciences appliquées, 2003.

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

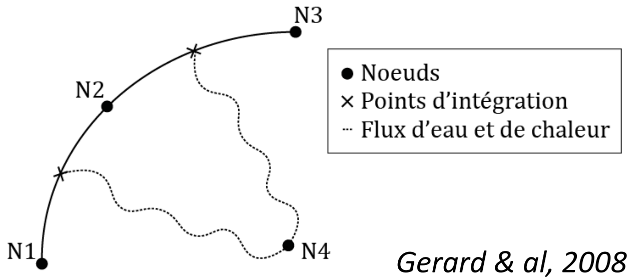
Lehmann, P., Assouline, S., & Or, D. (2008). Characteristic lengths affecting evaporative drying of porous media. *Physical Review E*, *77*(5), 056309.

# Sensitivity study



# NUMERICAL MODELING

- Boundary layer model in FEM code:



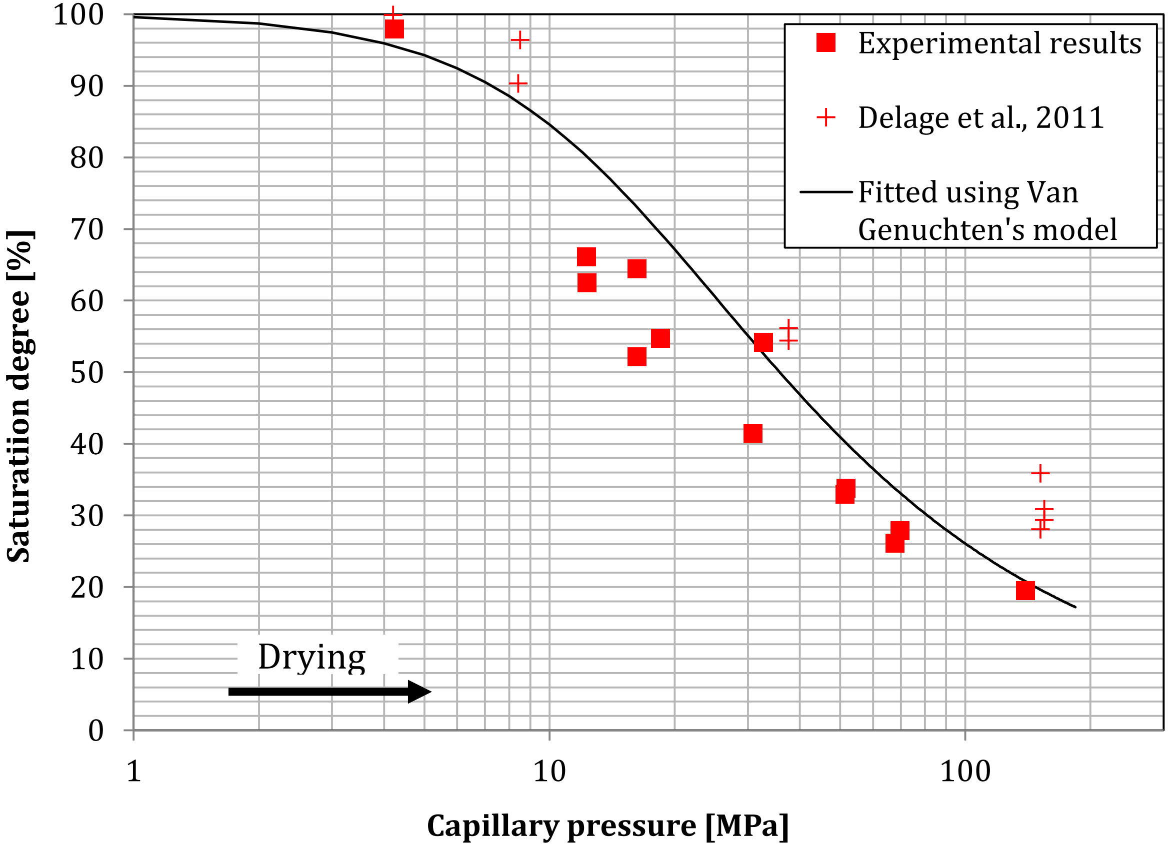

*Gerard & al, 2008*

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

| $\alpha$ [$m/s$] | $\beta$ [$W/m^2/K$] |
| --- | --- |
| 0.048 | 53 |

# 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 | | |
|---|---|---|
| $S_{res}$ | 0 | [-] |
| $S_{sat}$ | 1 | [-] |
| $\alpha_{vg}$ | 15 | $[MPa]$ |
| $m_{vg}$ | 0.449 | [-] |
| $n_{vg}$ | 1.70 | [-] |

# Boom clay composition

| *Composition minéralogique en [%]* | *Al-Mukhtar et al., 1996* | *Wouters et Vandenberghe, 1994* | *Decleer et al., 1983* | *Horseman et al., 1986* |
|---|---|---|---|---|
| *Quartz* | 20-25 | 20 | 23.8-58.3 | 30 |
| *Interstratifié illite-smectite* | 33 | 40-50 | | |
| *Illite* | 16 | 25-35 | 3-23 | 19 |
| *Smectite* | | | 19-42 | 22 |
| *Kaolinite* | 13 | 15-25 | 1-9 | 29 |
| *Feldspaths:* | | 5-10 | | |
| *Microcline* | 4-5 | | 6.5-11.3 | |
| *Plagioclase* | 4-5 | | 3.2-6.2 | |
| *Chlorite* | | 5-10 | | |
| *Pyrite* | 4-5 | 1-5 | 0.7-2.5 | |
| *Carbonates* | traces | 1-5 | 0.0-4.3 | |
| *Matières organiques* | | 1-5 | | |

**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

*Skyscan 1172*

| | | |
|---|---|---|
| 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