Comportement hygrothermique des bâtiments : des matériaux aux ambiances

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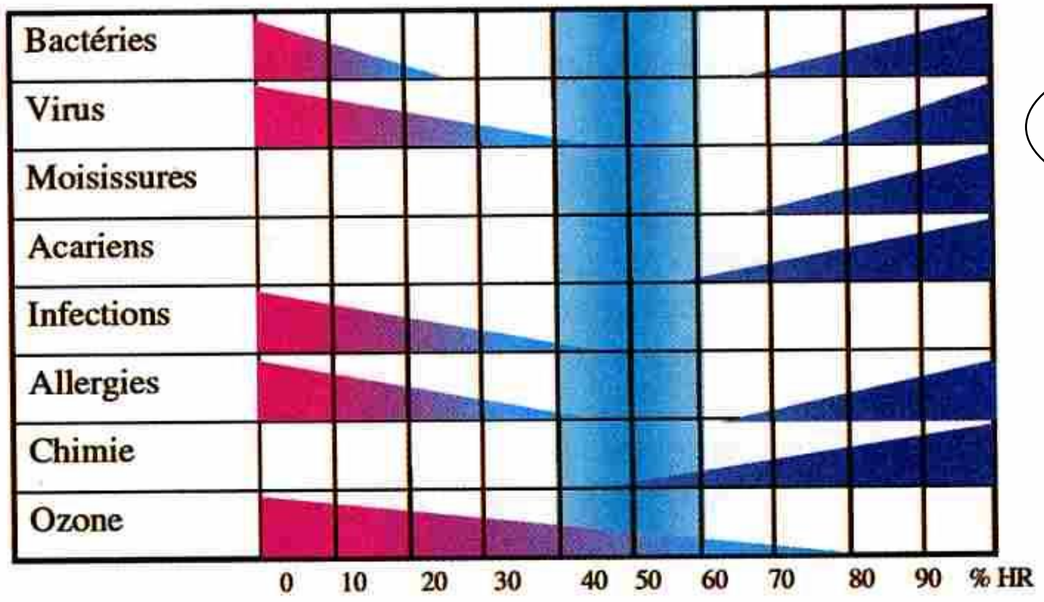
My thanks go to collegues and students: Clémence Legros, Alessia Losini, Marine Fouquet, Jeanne Goffart, Lucile Soudani, Yannick Kedowidé, Anne-Cécile Grillet, Jean-Jacques Roux, Matthieu Labat, Simon Rouchier, Mickael Pailha, Etienne Wutz …..

Comportement hygrothermique des bâtiments – Pourquoi est-ce important ?



Santé des occupants

Durabilité des matériaux

Gestion efficace de l'énergie

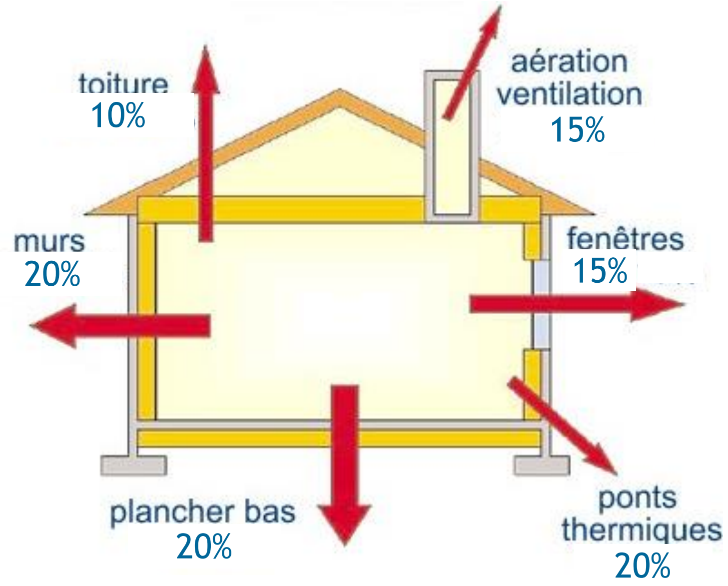
Confort thermique

Comportement hygrothermique des bâtiments – Pourquoi est-ce important ?

General context

ENERGY - COMFORT

« BBC » house (heating: 15 kWh/m²/an)



Energy transferts through the envelope:
(~80% of heating)

HEALTH

DURABILITY

Hi-Tech industry

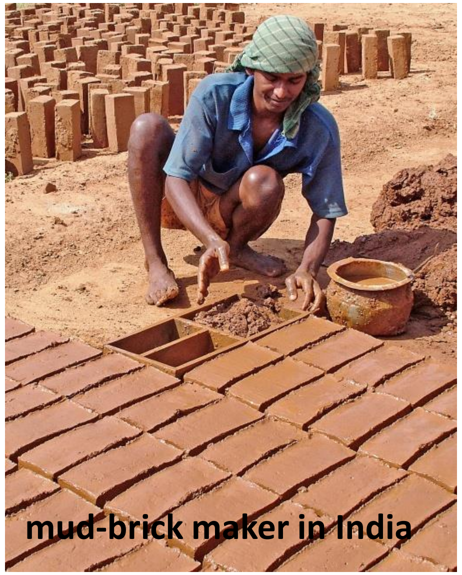
http://auto-online24.info/

Low-Tech industry

http://stratmastorisphotography.com/industrial/

Matériaux « Low Tech »
Ou **Matériaux bas carbone ?**

No-Tech Building Sector



mud-brick maker in India

Charrue, 2014

Innovative vs. Traditional

Rammed Earth

Wales Institute Sustainable Education, 2010

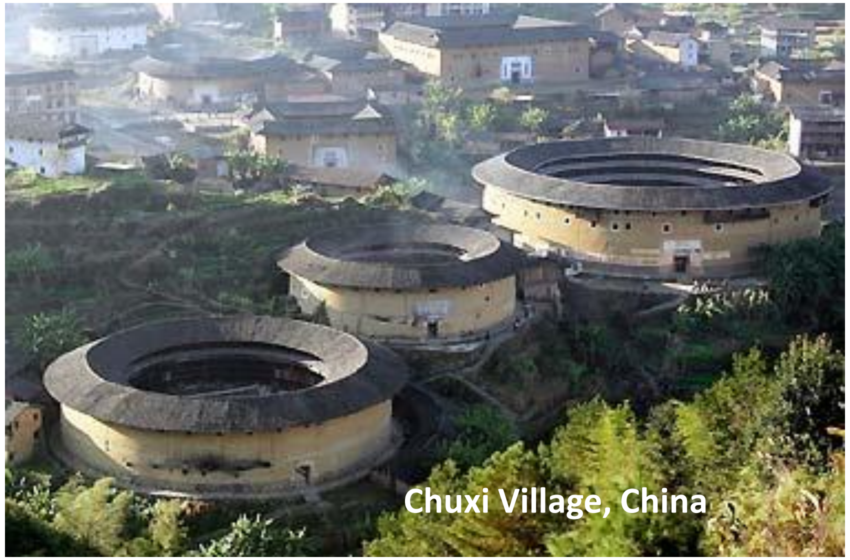
Timbuktu, XIV c

Modern ?

Traditional ?

An old architectural heritage in Europe, Africa, Asia


Timbuktu, Mali, Africa


Chuxi Village, China


Rhône Alpes, France

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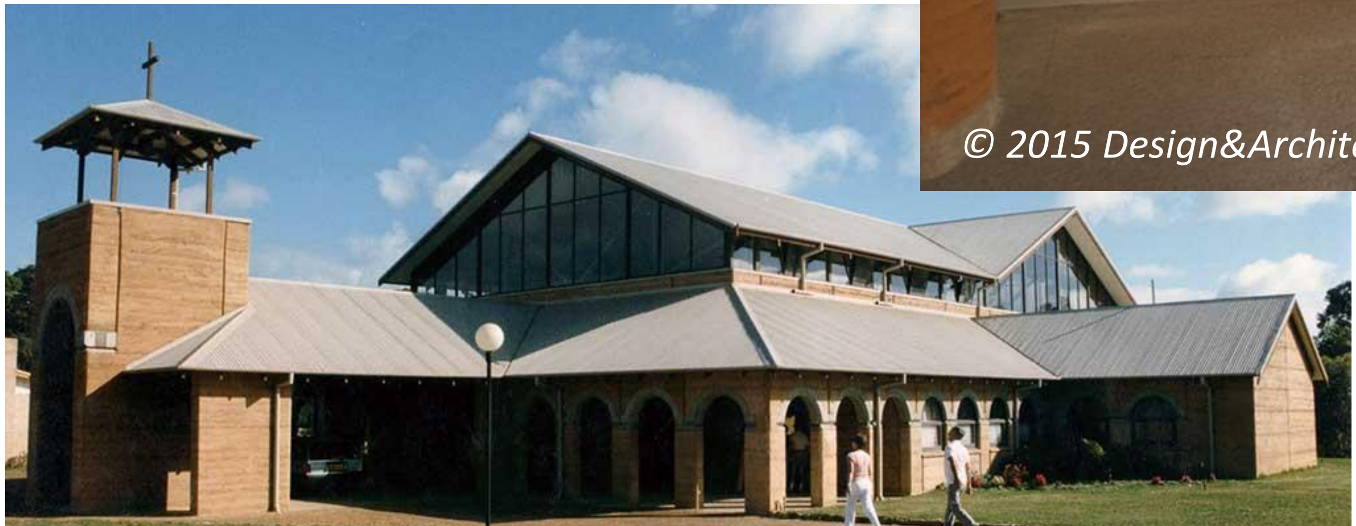
Rammed earth : a ‘modern’ material

Local material

Low process energy

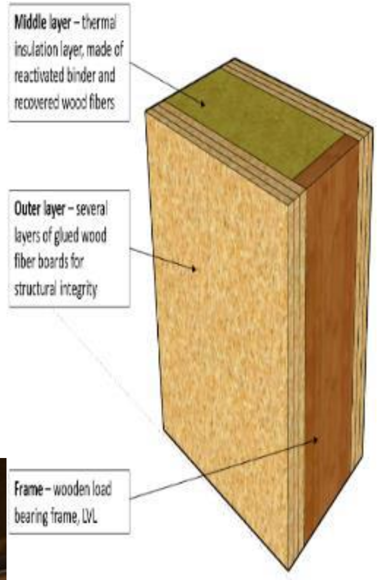
Wales Institute Sustainable Education, 2010

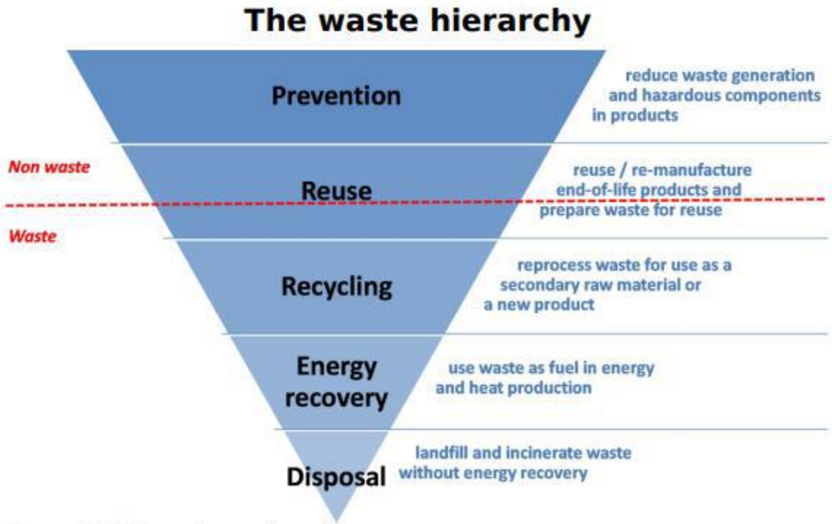
Margaret River, Australia



Matériaux bio-sourcés

Wood waste containing composites for high performance nearly zero energy building panels





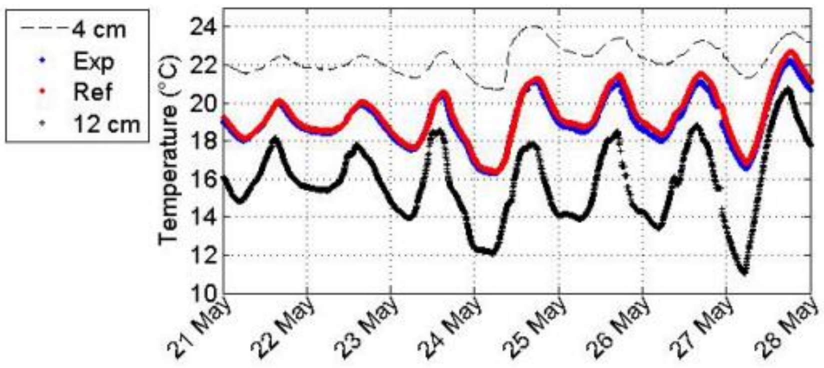
Source: OECD based on various other sources.

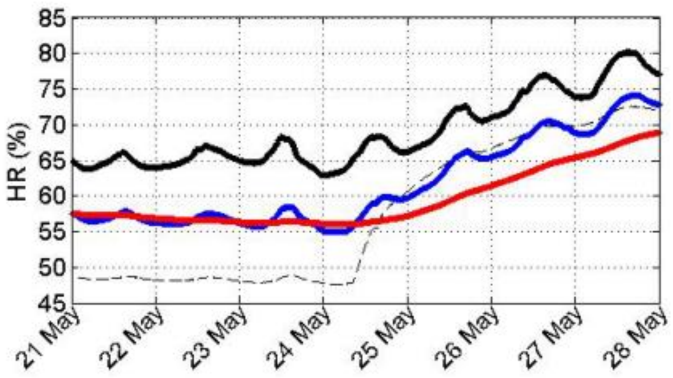
Comportement hygrothermique des bâtiments –

Pourquoi est-ce important pour les modélisateurs ?

IBPSA
International Building
Performance Simulation Association

Comportement hygrothermique des bâtiments – Pourquoi est-ce important ?

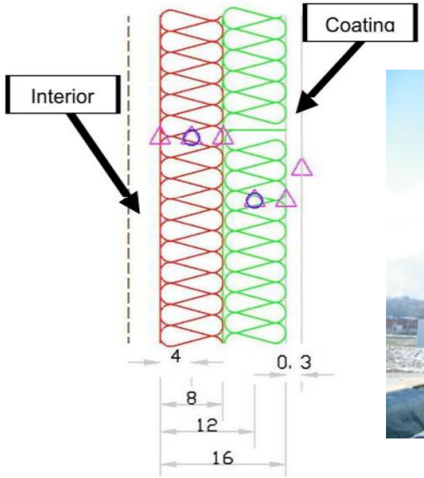




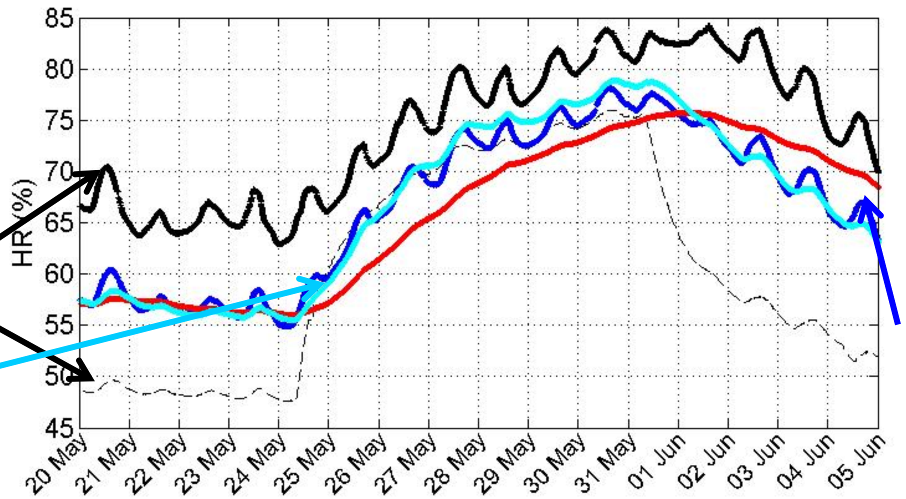
Modélisation échelle paroi

Temperature : **correct**

Humidity : dynamic behavior should be improved



Boundary conditions :
@ 4 cm
@ 12 cm



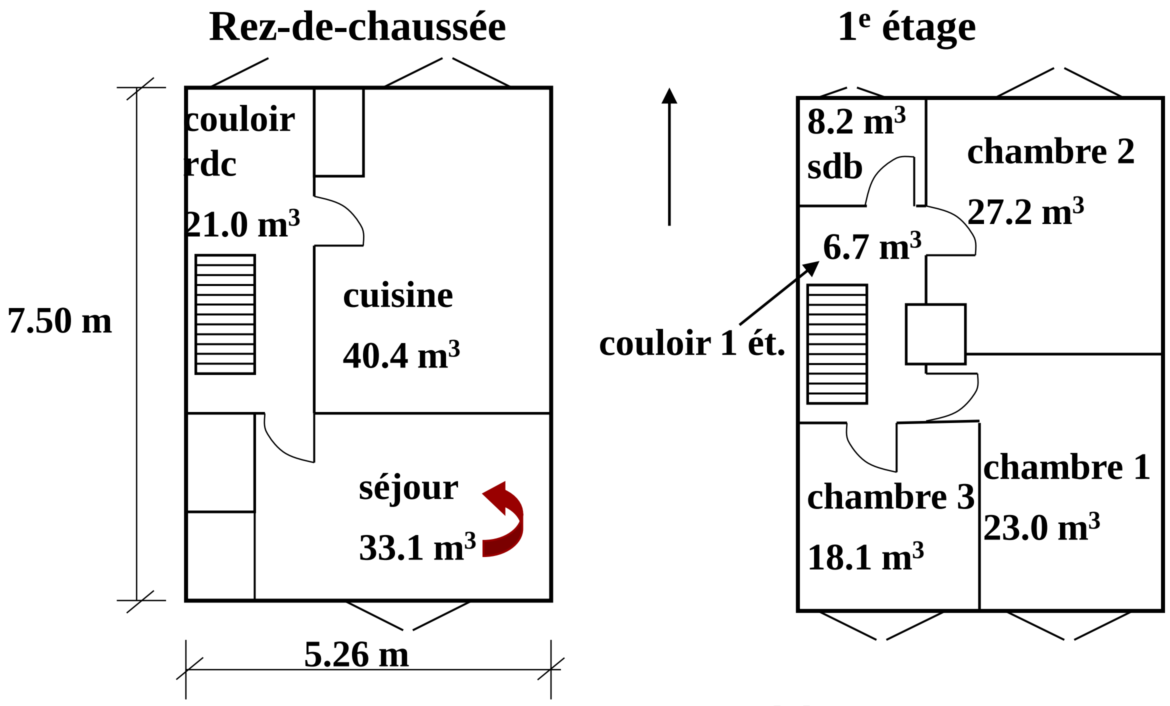
Model at 8 cm
Measured properties

Measurements at 8 cm

Model with adapted properties:
- vapour permeability x 2
- sorption isotherm smoothed

Comportement hygrothermique des bâtiments – Pourquoi est-ce important ?

Modélisation échelle bâtiment



BRE, UK, (Plathner & Woloszyn, 2002)

Vapour source

- **1.7 kg/h**
- **1 h**

Measurements :

- tracer gaz (SF_6)
- Vapour

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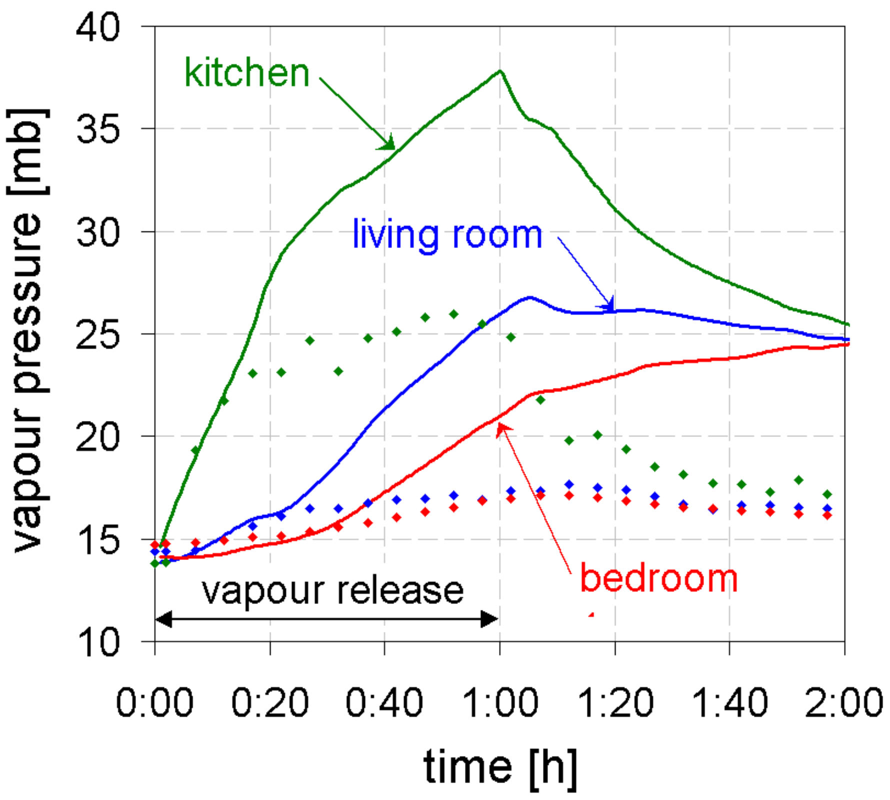
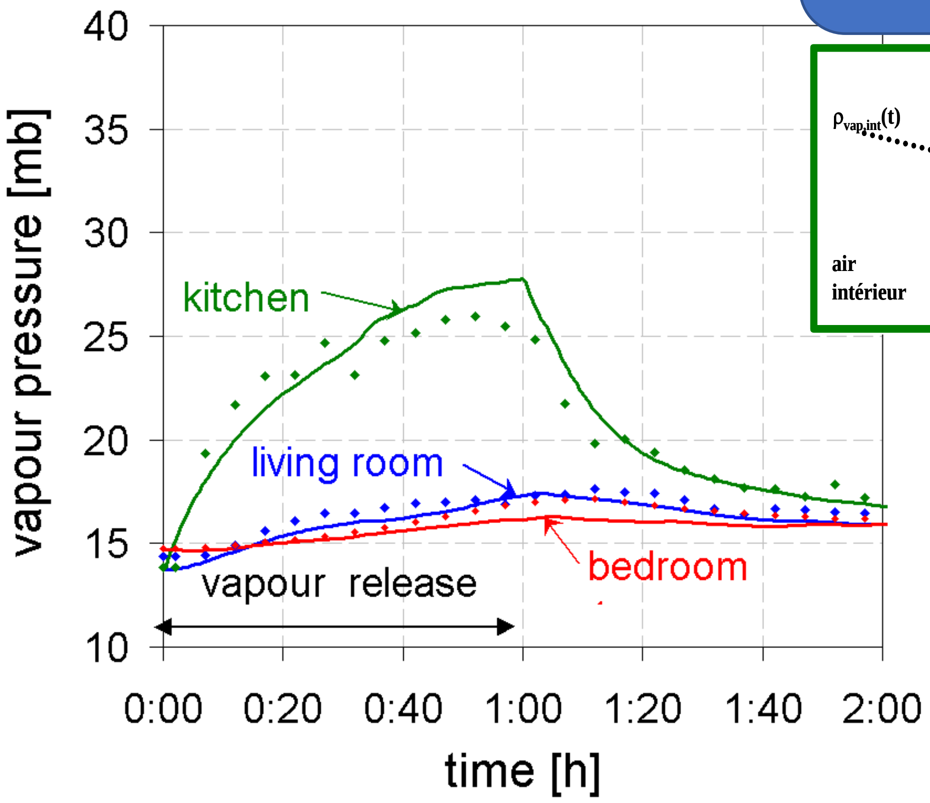
Comportement hygrothermique des bâtiments – Pourquoi est-ce important ?

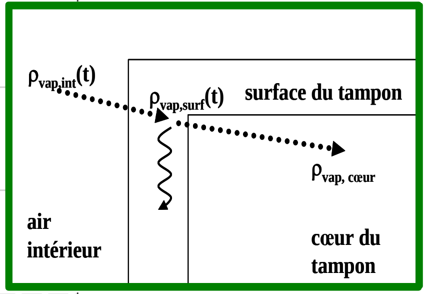
Modélisation échelle bâtiment

STD classique



Modèle HAM (ici “moisture buffer”)





Moisture buffering : ~45% of vapour source

Mesured effet of <u>mass flow</u> of sorption

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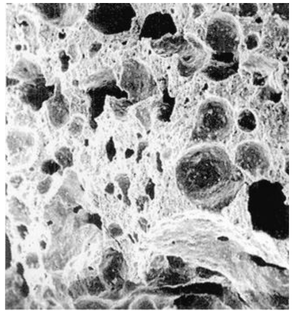
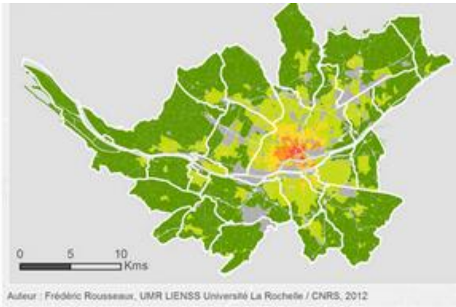
Comportement hygrothermique des bâtiments –

Modélisation

Différentes échelles sont importantes





Material

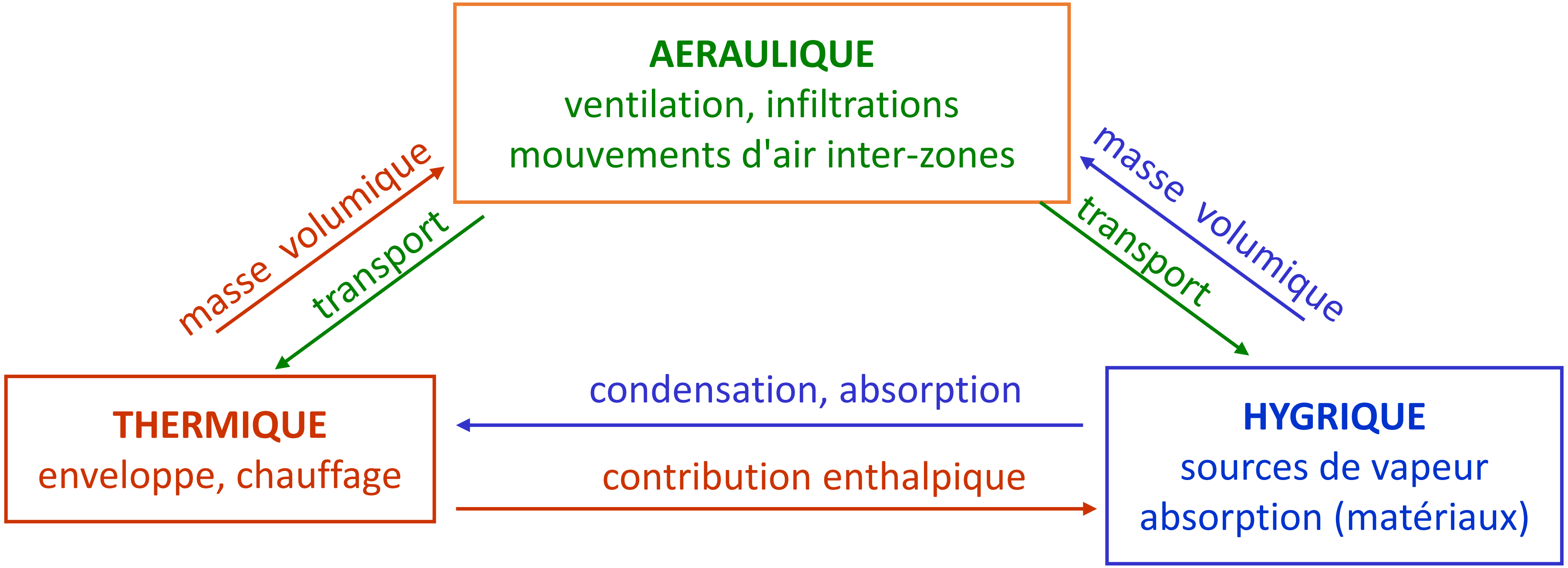
Wall

Building

Urban

Couplages à l'Échelle Bâtiment

Hygro – Thermo - Aéraulique



Équations de bilan

Chaque **zone d'air**

Conservation **d'énergie**

$$\frac{dH_i}{dt} = \sum_j \left[\dot{H}_{j\to i}\right] - \sum_j \left[\dot{H}_{i\to j}\right] + \Phi_{\text{charge int}} + \Phi_{\text{chauffage}} - \Phi_{\text{transfert vers l'enveloppe}}$$

Conservation de la **masse d'air sec**

$$\frac{dm_{as,i}}{dt} = \sum_j \left[\dot{m}_{as,j\to i}\right] - \sum_j \left[\dot{m}_{as,i\to j}\right]$$

Conservation de la **masse de la vapeur d'eau**

$$\frac{dm_{vap,i}}{dt} = \sum_j \left[\dot{m}_{vap,j\to i}\right] - \sum_j \left[\dot{m}_{vap,i\to j}\right] + D_{\text{production int}} - D_{\text{sorption/desorption}} + D_{\text{humidication}}$$

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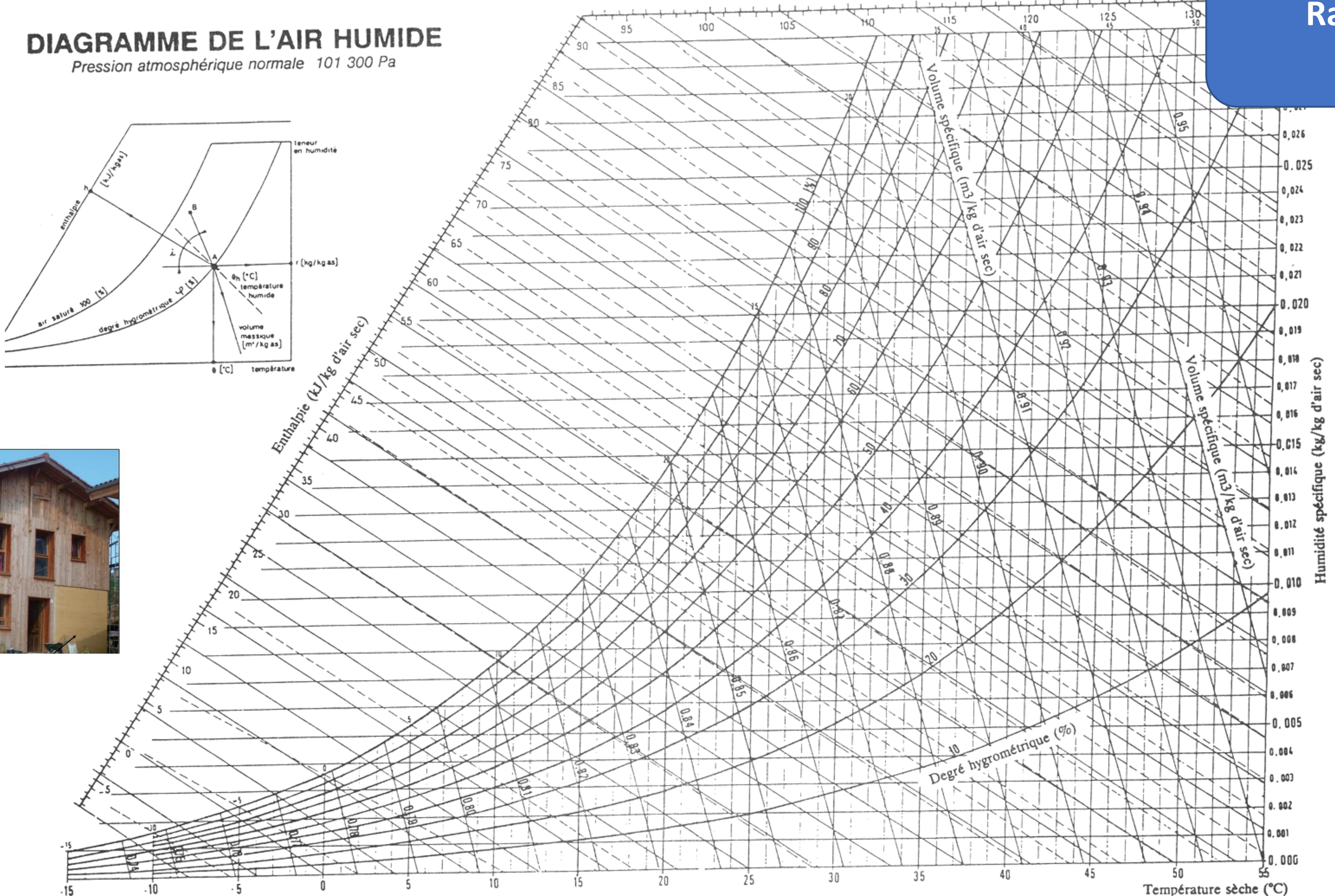
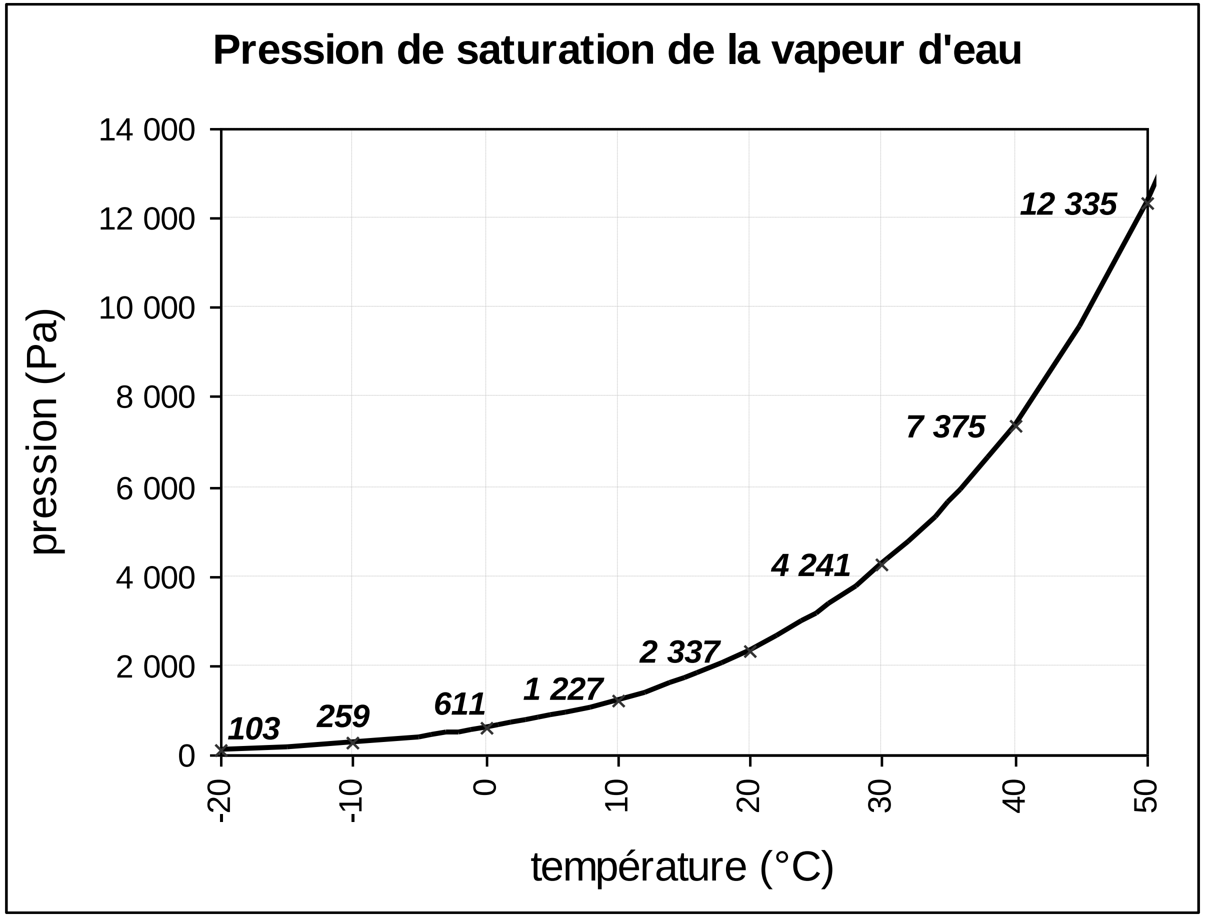
Bilans globaux (macroscopiques)

Psychrométrie

Rappels



Pression de saturation de la vapeur d'eau



Grandeurs caractéristiques de l'air humide

l'humidité relative :

HR = P_{vap} / P_{sat} *(degré hygrométrique)*

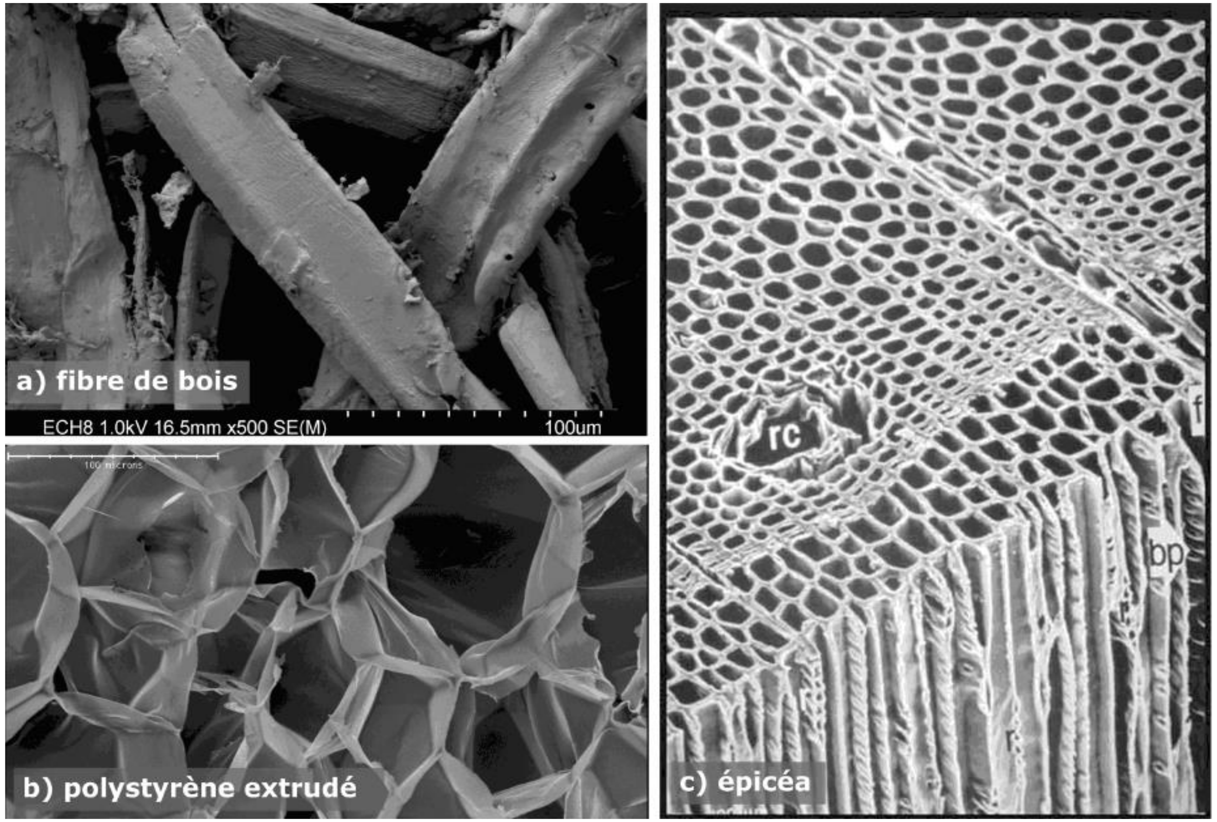
l'humidité spécifique :

w = m_{vap} / m_{as}

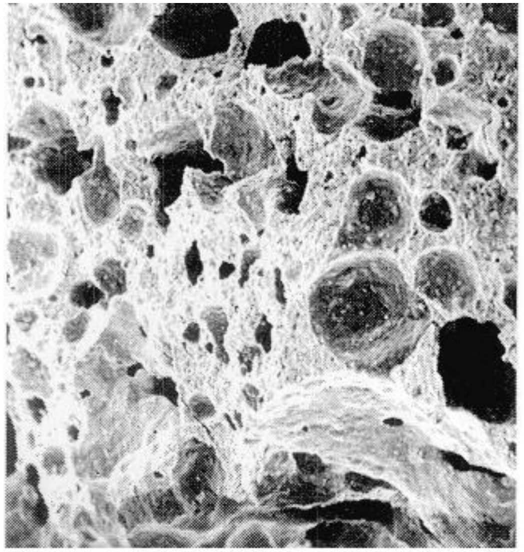
Rappels

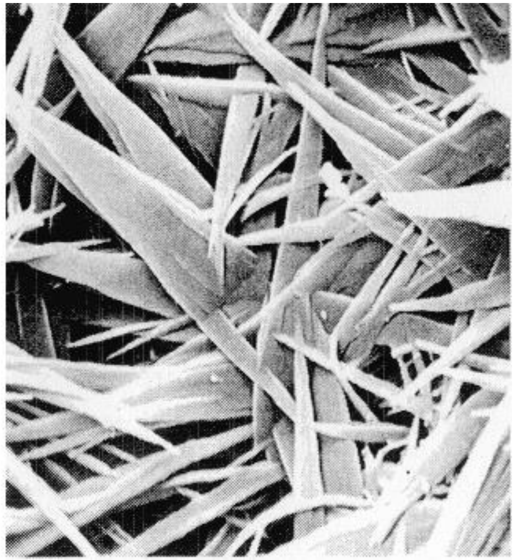
vapeur d'eau :
condense à
températures ambiantes

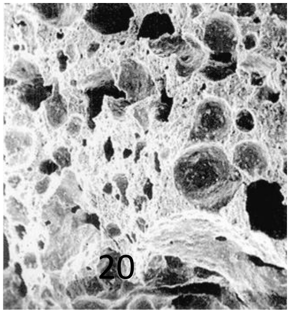
Matériaux de construction
=
matériaux poreux



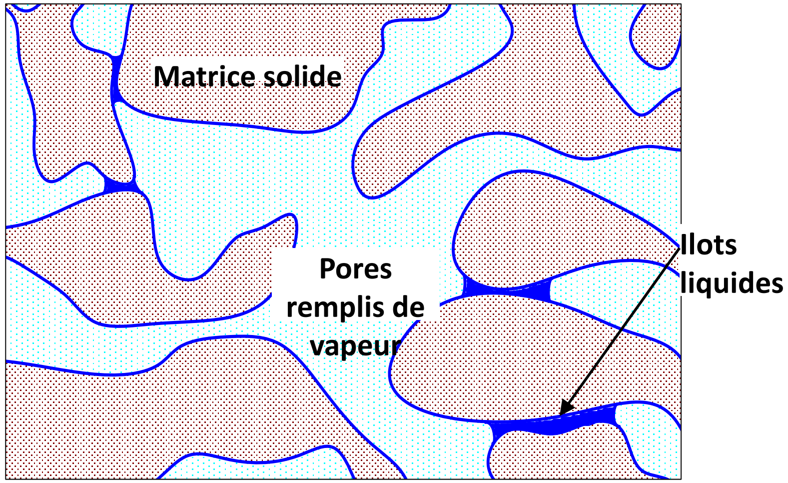
Béton cellulaire agrandi
22 fois et
11000 fois

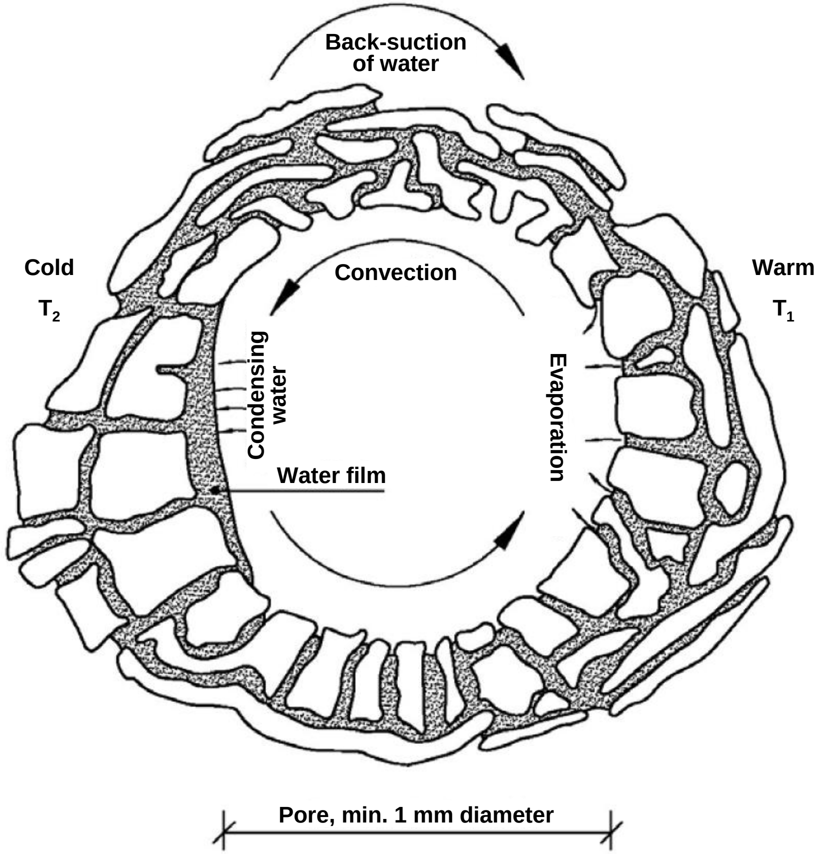




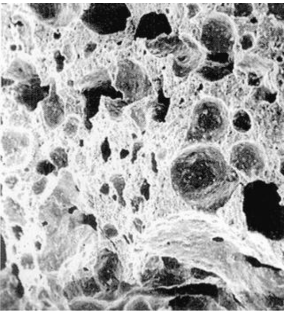


L'humidité dans les matériaux





L'eau est sous forme liquide
Pour HR < 100%



Métrologie : gravimétrie, conductivité électrique, vapeur dans les grands pores

Équations de bilan

Bilans sur un petit volume (différentielles)

Chaque **« maille » du matériau ou du système ...**

Conservation **d'énergie**

$$\rho c V \frac{\partial T}{\partial t} = -div(\varphi) + p$$

$$\varphi = -\lambda\, grad(T) \qquad \rho c V \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2}$$

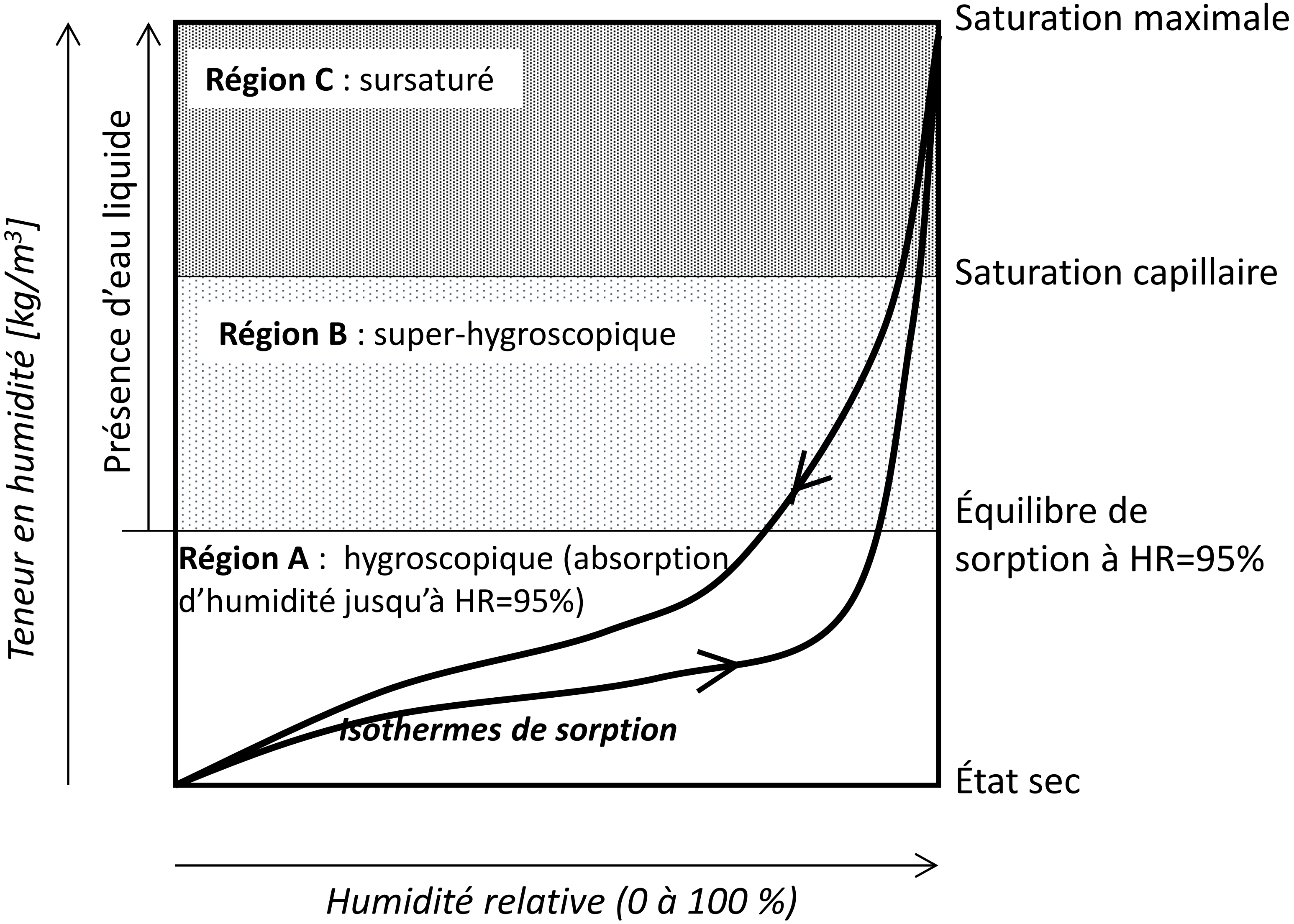
Forme discrétisé

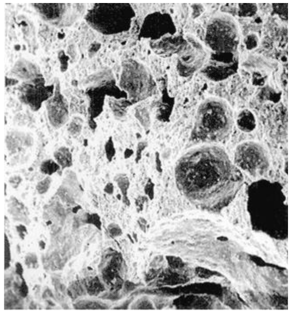
$$\phi_{n-1,n} = \lambda \frac{T_{n-1} - T_n}{e} S \qquad \rho c e S \frac{dT}{dt} = \frac{T_{n-1} - T_n}{\frac{e}{\lambda S}} - \frac{T_n - T_{n+1}}{\frac{e}{\lambda S}}$$

Conservation de la **masse de la vapeur d'eau**

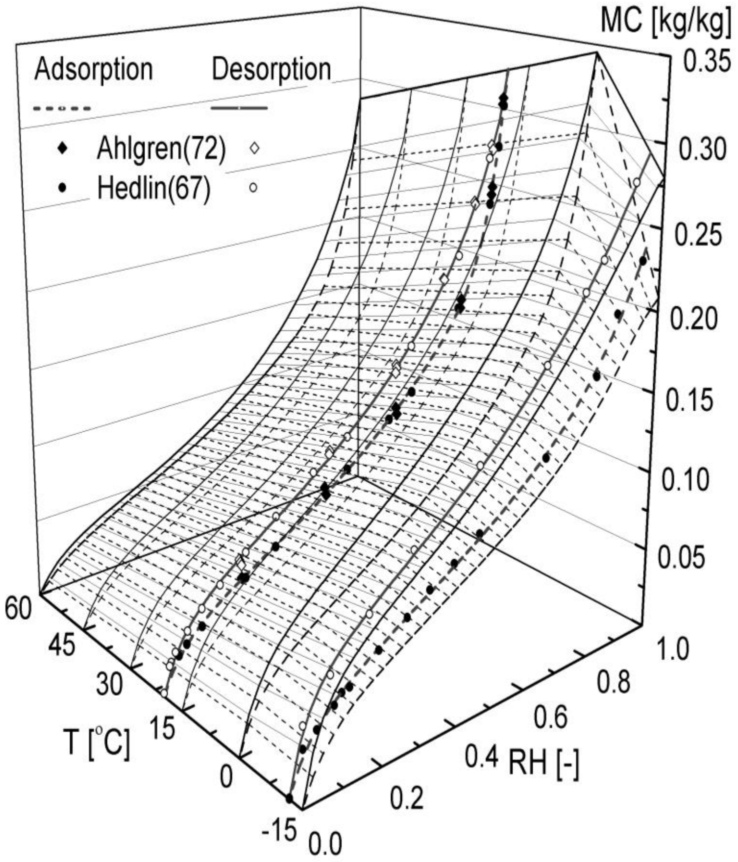
$$\frac{\partial w}{\partial t} = -div\left(g_{vap} + g_{liq}\right) + S_h$$

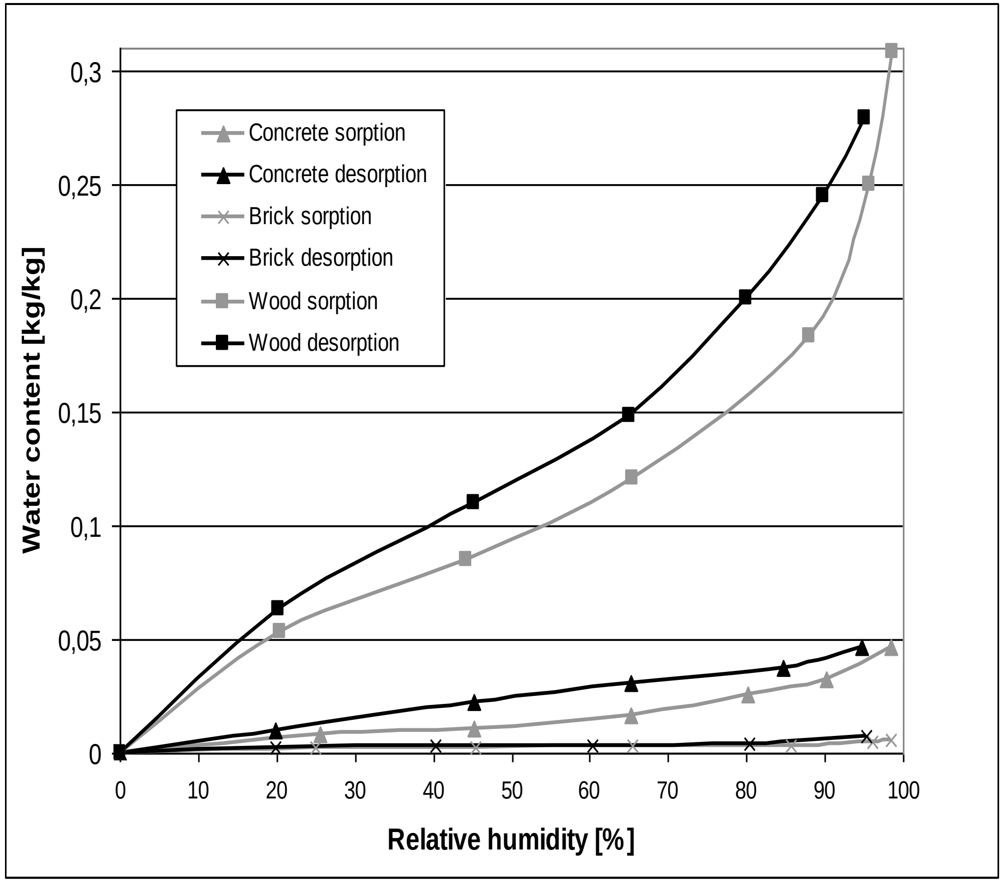
Absorption d'humidité par les matériaux

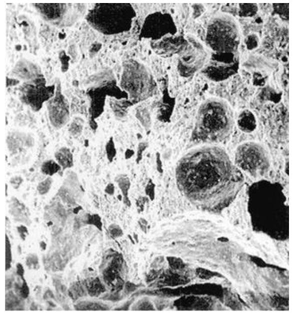




Exemples des isothermes de sorption







bois

Transferts d'humidité dans les murs

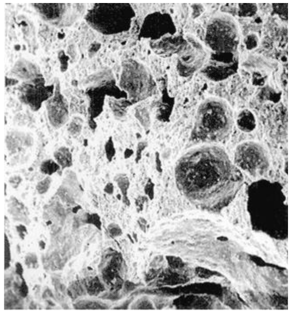
Dans les matériaux l'eau se déplace sous forme :
- liquide
- gaz

Les **mécanismes** principaux
- ***Diffusion de vapeur*** *(grands pores)*
- ***Transport du liquide*** *(micropores et surface des grands pores)*

D'autres mécanismes existent : advection, gravité, électrocinétique, osmose…

Dans les **cas courants** :

- on s'intéresse à la masse totale de l'eau
- région hygroscopique
- on peut négliger l'hystérésis dans les isothermes de sorption



Diffusion de vapeur (loi de Fick)

dans des grands pores

↕

diffusion dans l'air

Densité de flux massique de vapeur [kg/s/m²]

$$g_{vap} = -D_{vap,P}\ \overrightarrow{gradP}_{vap}$$

P_{vap} : pression partielle de la vapeur [Pa]

$D_{vap,P}$: perméabilité du matériau à la vapeur d'eau [kg/(m s Pa)]

On introduit un facteur de résistance à la diffusion de vapeur :

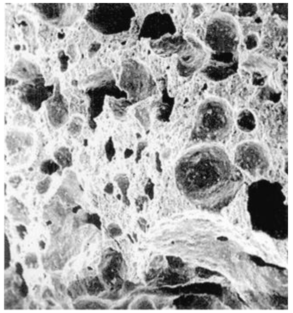
$$\mu = \frac{D_{vap,P}}{\delta}$$

avec δ : perméabilité de l'air à la vapeur

$$\delta = 1.97 \cdot 10^{-10}\, kg/(m.s.Pa) = 2,0 \cdot 10^{-7} \frac{T^{0.81}}{P_{tot}}$$

P_{tot} : pression totale d'air ambiant [Pa]

T : température ambiante [K]



D'où :

$$g_{vap} = -\delta\ \mu\ \overrightarrow{gradP}_{vap}$$

Conditions aux limites et Lien Paroi – Volume d'air

À l'interface entre deux couches de matériau :

- pression (vapeur et/ou liquide) continue
- flux massique continu

Attention : la teneur en eau n'est pas continue entre deux matériaux !

À l'interface matériau / air :

- flux massique proportionnel au gradient

$$g_{vap} = \beta\,(P_{vap,int} - P_{vap,surf})$$

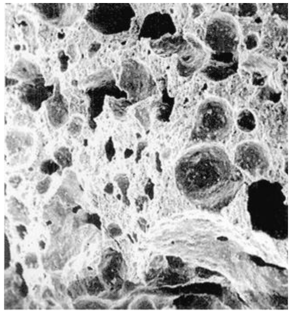
Valeurs habituelles

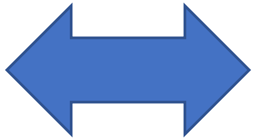
$\beta = 1.9 \times 10^{-8}\, s/m$ Intérieur

$\beta = 14 \times 10^{-8}\, s/m$ Extérieur

ou $\beta = 7.4 \times 10^{-9} h_c$

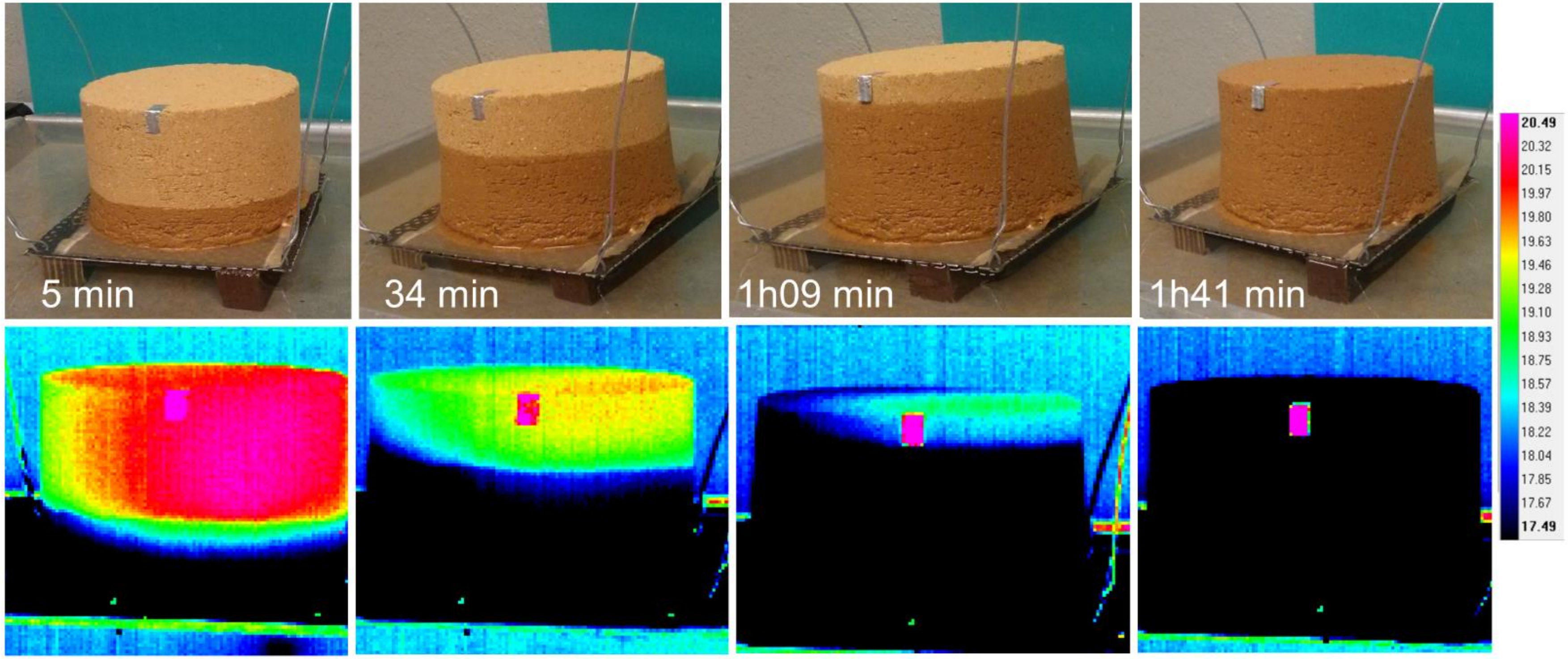
P_{vap} : pression partielle de la vapeur [Pa]
h_c : coefficient d'échange convectif [W/m²K]





Nos mesures (pièce peu ventilée)
$\beta = 1 \times 10^{-8} s/m$

Transferts liquides – souvent négligées à l'échelle d'un bâtiment



Couplages à l'Échelle Bâtiment

Hygro – Thermo - Aéraulique

AERAULIQUE
ventilation, infiltrations
mouvements d'air inter-zones

masse volumique
transport

masse volumique
transport

THERMIQUE
enveloppe, chauffage

condensation, absorption

contribution enthalpique

HYGRIQUE
sources de vapeur
absorption (matériaux)

Ordres de grandeur

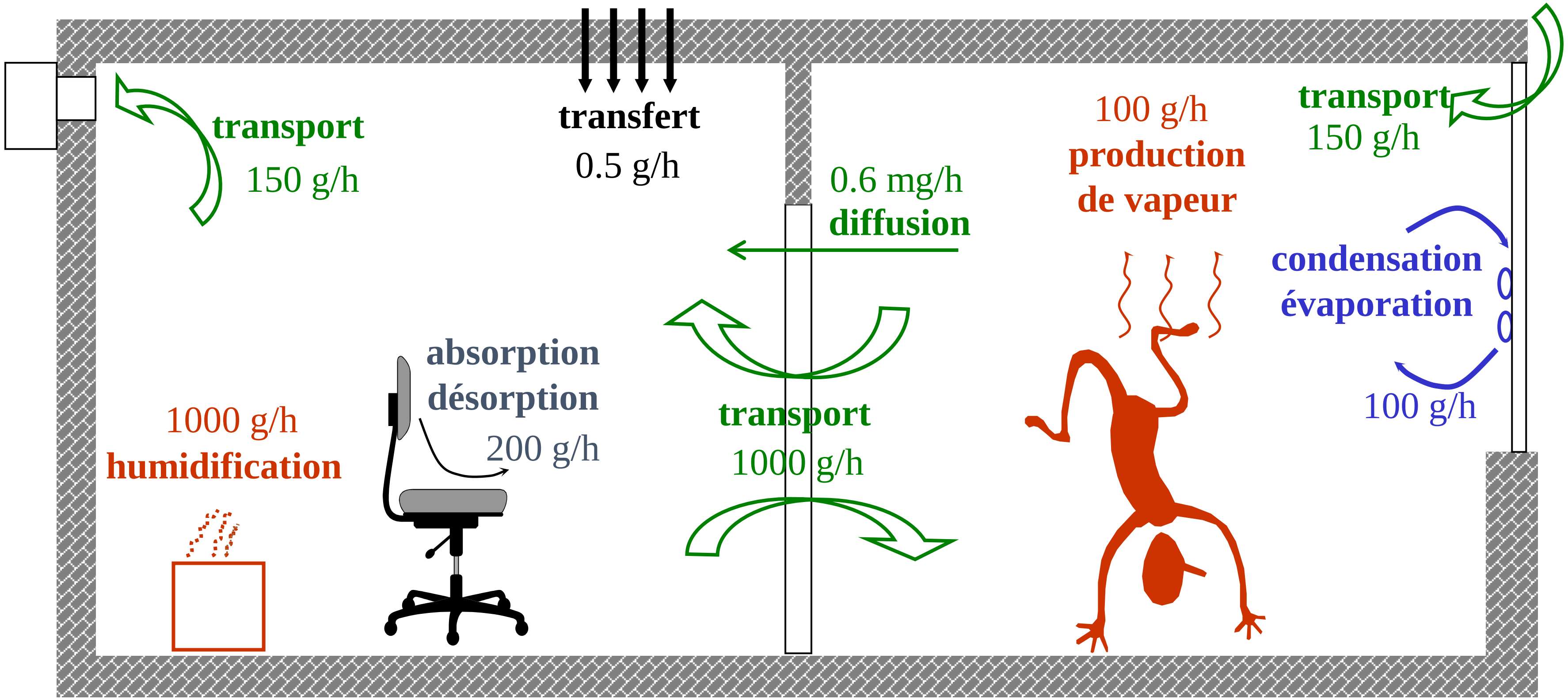
transferts dans l'air

transferts dans les matériaux

sources de vapeur

changements de phase

Bilan massique vapeur d'eau air intérieur



$$\frac{dm_{vap,i}}{dt} = \sum_j \left[\dot{m}_{vap,j\rightarrow i}\right] - \sum_j \left[\dot{m}_{vap,i\rightarrow j}\right] + D_{production\ int} - D_{sorption/desorption} + D_{humidication}$$

Comportement hygrothermique des bâtiments –

Couplages Energie – Humidité

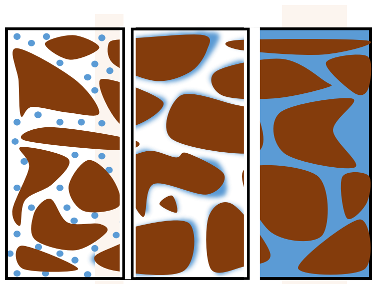
Energy Balance

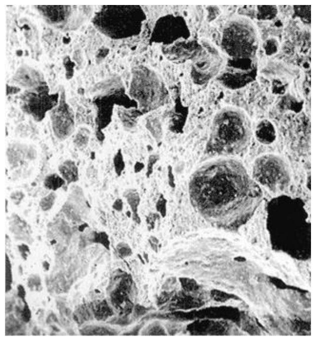
Energy balance at **material scale**

thermal conductivity

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) - \mathring{m}_{\to V} L(T,\varphi)$$

Latent heat of sorption





H [J]: total enthalpy

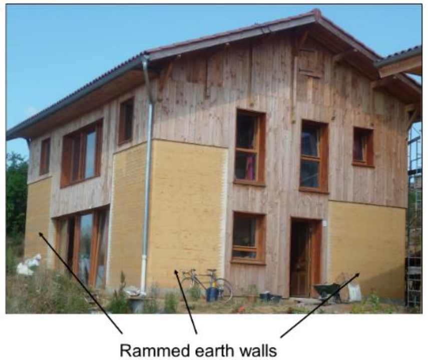
Energy balance at **room scale**

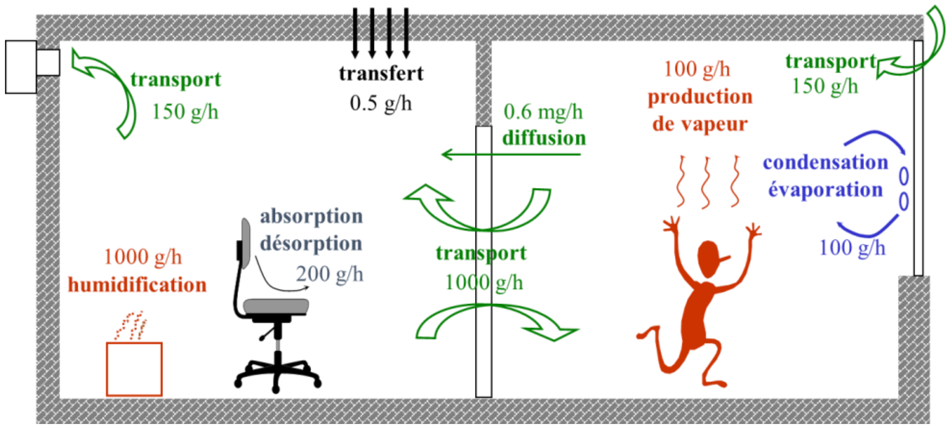
$$\frac{dH_i}{dt} = \sum_j [\dot{H}_{j\to i}] - \sum_j [\dot{H}_{i\to j}] + \Phi_{internal\ load} + \Phi_{heating} - \Phi_{envelope}$$

Air transfer

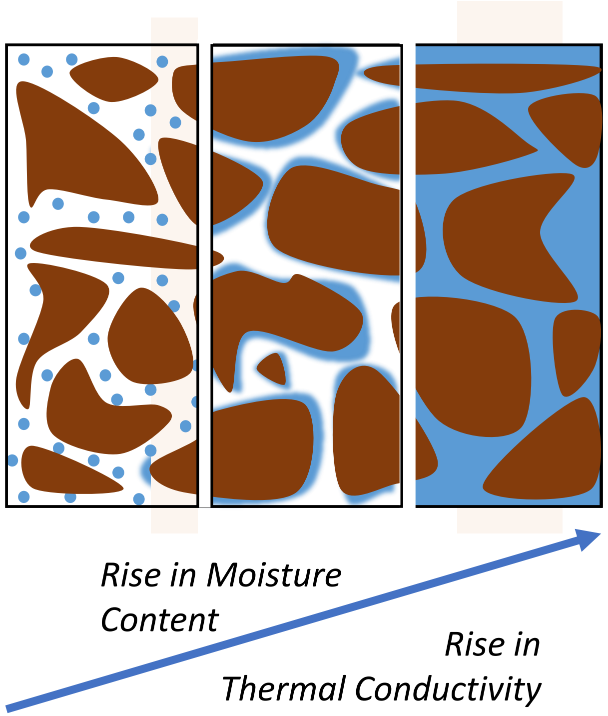
Impact on **HVAC load**

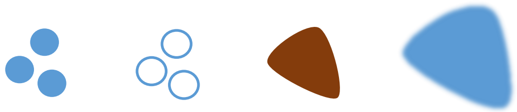
Impact on
Room Temperature
(free floating)



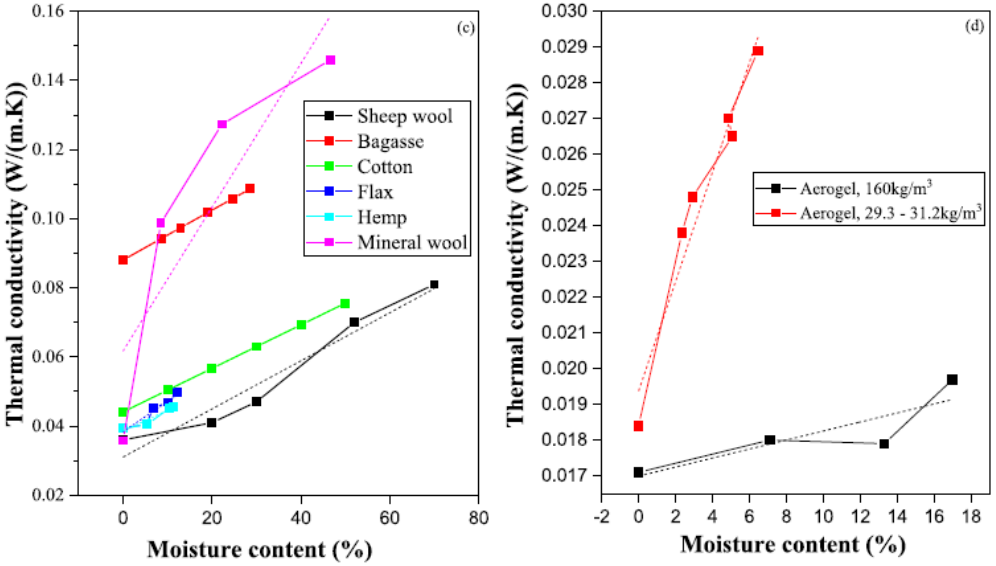


Impact on Material Properties





Rise of thermal conductivity



Le Duong Hung Anh, Zoltán Pásztory, An overview of factors influencing thermal conductivity of building insulation materials, JoBE, vol 44, 2021,

Polystyrene insulation

At 80% moisture content at 24 °C (as compared with dry material)

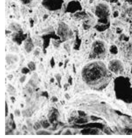
+ 12%, cooling load the wall transmission

+ 25%, cooling load roof transmission

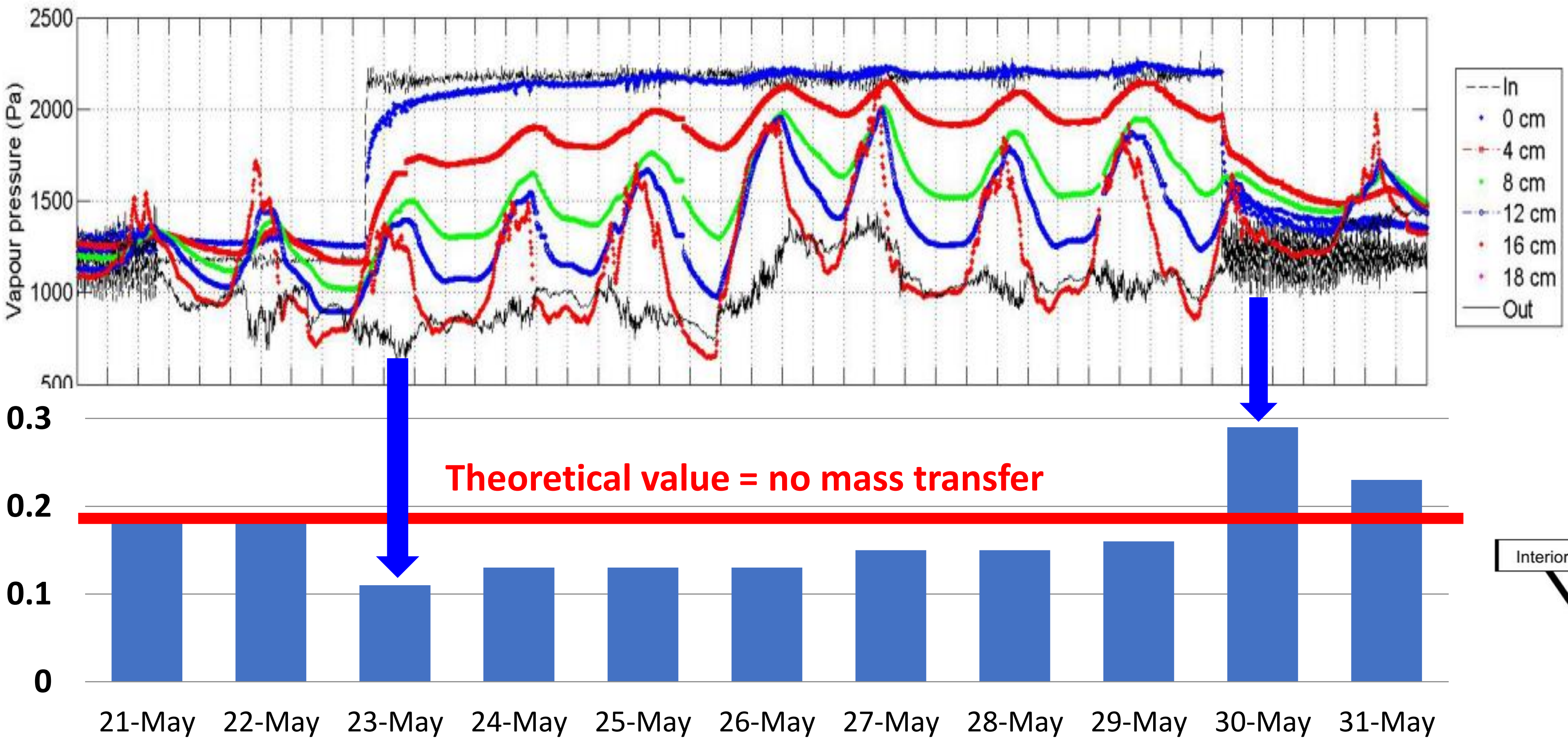
+ 13% cooling load, and the total zone load,

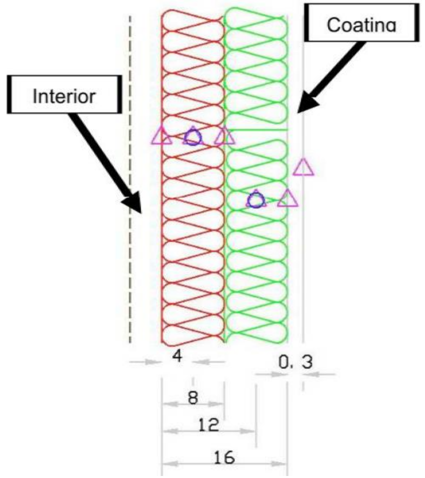
=> Large impact on cooling loads in hot-humid climate

Maatouk Khoukhi, The combined effect of heat and moisture transfer dependent thermal conductivity of polystyrene insulation material: Impact on building energy performance, Energy and Buildings, Vol 169, 2018



Experimental results – impact of mass on heat transfer





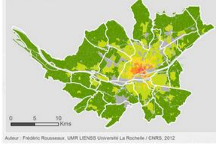
Normalised temperature difference at 4 cm depth

(in the insulation)

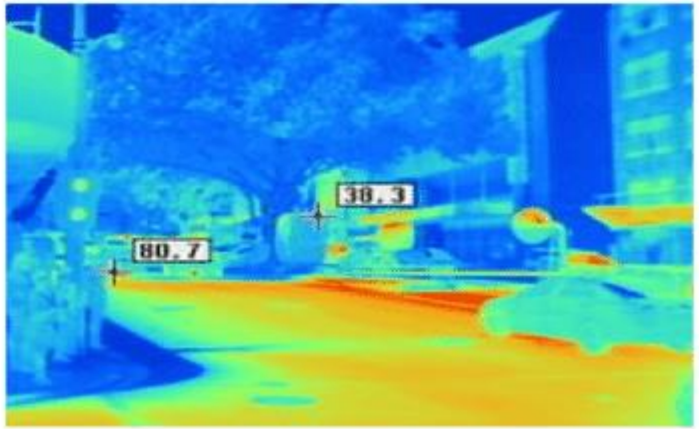
Mesured effect of latent heat of sorption

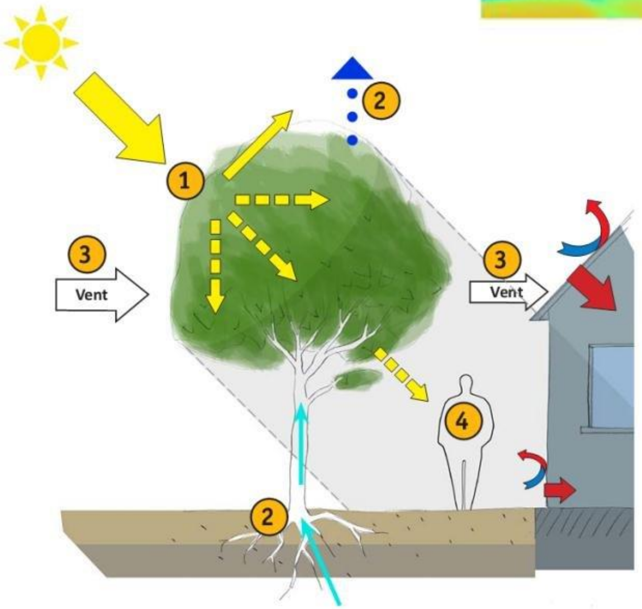
$$\Delta T_n = \frac{T_{0cm} - T_{4cm}}{T_{0cm} - T_{16cm}}$$

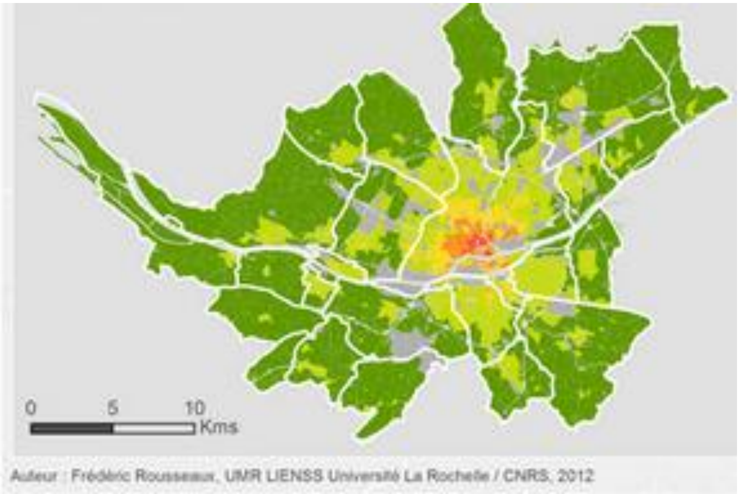
Impact of moisture on urban scale ?



Excellent capabilities to **mitigate heat island** efect due to moisture: plants, lakes, watering….







Different sources from internet

Impact on HVAC Loads

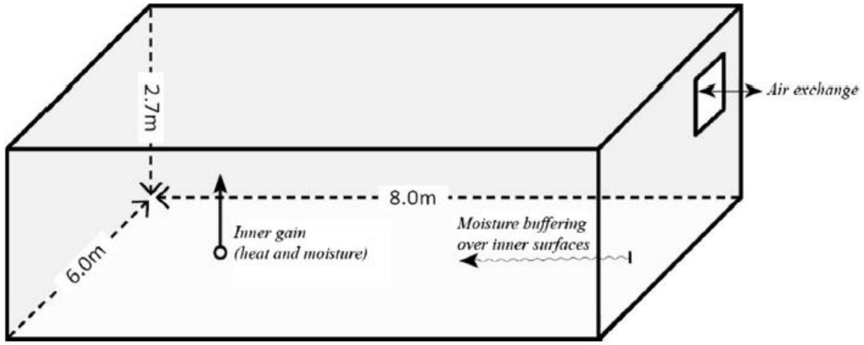
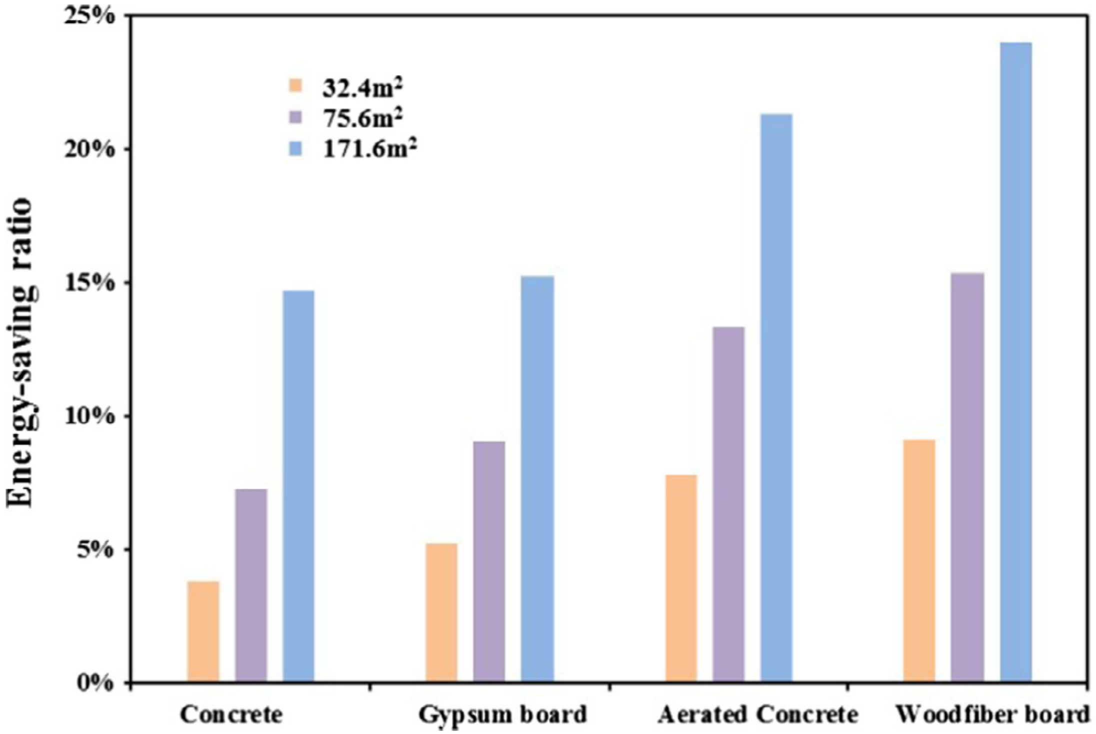


Fig. 3. IEA BESTEST base case building.

Office building:
- occupation 09:00 - 17:00
- HVAC: T between 20°C and 26°C, RH < 65%
- different moisture buffering materials

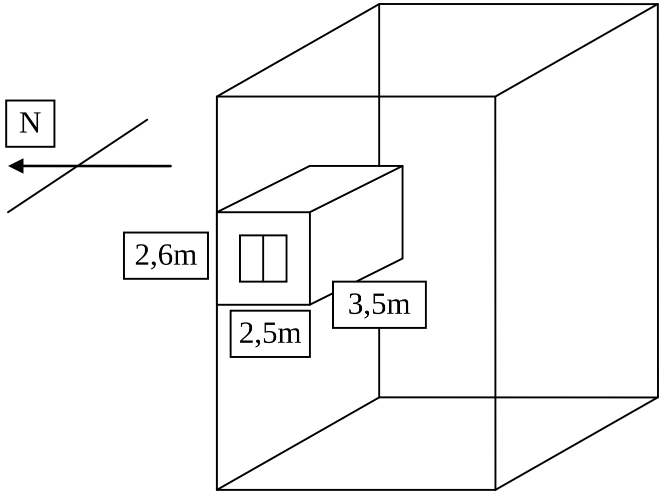


Energy-saving rates in Paris case

=> **energy savings up to 25–30%** when using proper hygroscopic materials temperate climates and semi-arid climates

Mingjie Zhang, Menghao Qin, Carsten Rode, Zhi Chen, Moisture buffering phenomenon and its impact on building energy consumption, Appl. Therm. Eng. Vol 124, 2017

Impact on HVAC Loads

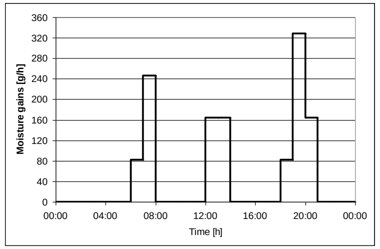


Test cases:

- “**reference**”: **neglecting** moisture **buffering** of the materials
- “**gypsum**”: **including** moisture **buffer** effect, but neglecting hysteresis in sorption isotherm
- “**gypsum hys**.”: **including** moisture **buffering** effect and **hysteresis** in sorption isotherm

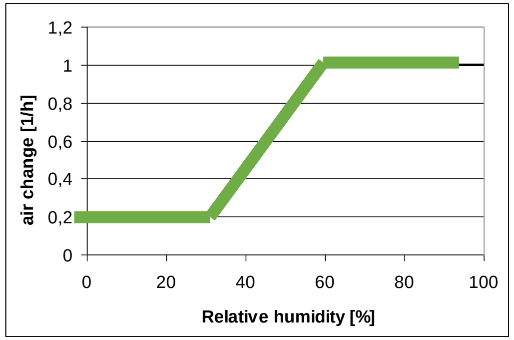
Parameters of calculation:

- Room in block of apartments
- Heating season for Warsaw (Poland)
- Buffering material: 30 m^2 of gypsum board
- Standard occupancy



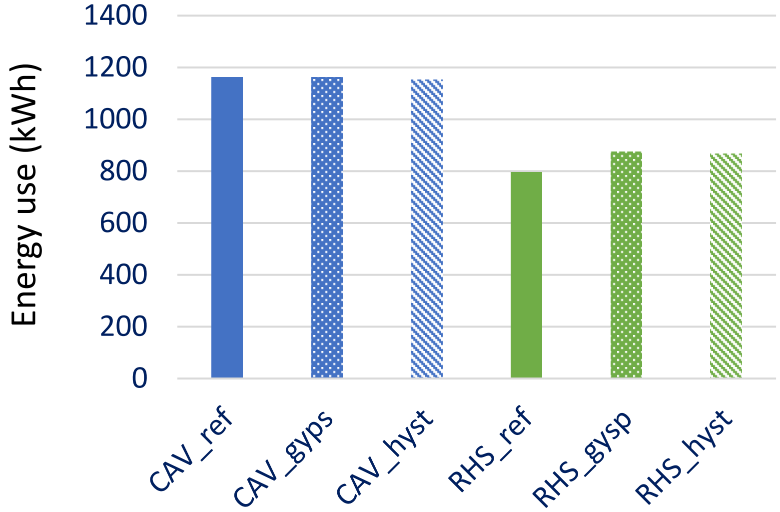
Two ventilation strategies:

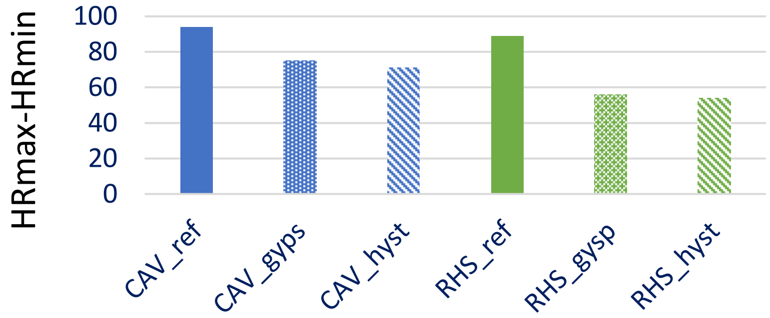
- **CAV** (constant air volume), ach=1 [h^{-1}]
- **RHS** (relative humidity sensitive ventilation), ach depending on RH



Kwiatkowski, J., Woloszyn, M., & Roux, J. J. (2011). Influence of sorption isotherm hysteresis effect on indoor climate and energy demand for heating. Applied thermal engineering, 31(6-7),

Impact on HVAC Loads





- **Moisture buffering materials**
  - significantly improve the indoor conditions (regardless ventilation)
- **RHS ventilation strategy**
  - decrease the energy demand of the zone
- **RHS ventilation strategy + Moisture buffering materials**
  - significantly improve the indoor conditions
  - but also to slightly **higher energy demand**
- **hysteresis of the sorption isotherm**
  - Very small effect on indoor condition

⇒ energy savings are very much depending on indoor / outdoor scenarios!

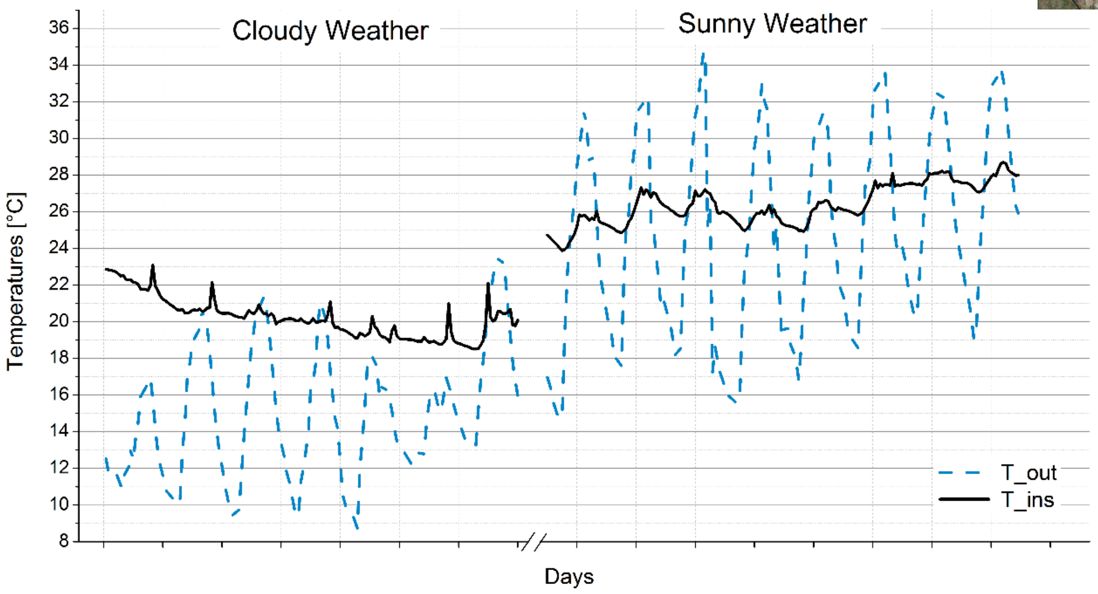
Kwiatkowski, J., Woloszyn, M., & Roux, J. J. (2011). Influence of sorption isotherm hysteresis effect on indoor climate and energy demand for heating. Applied thermal engineering, 31(6-7)

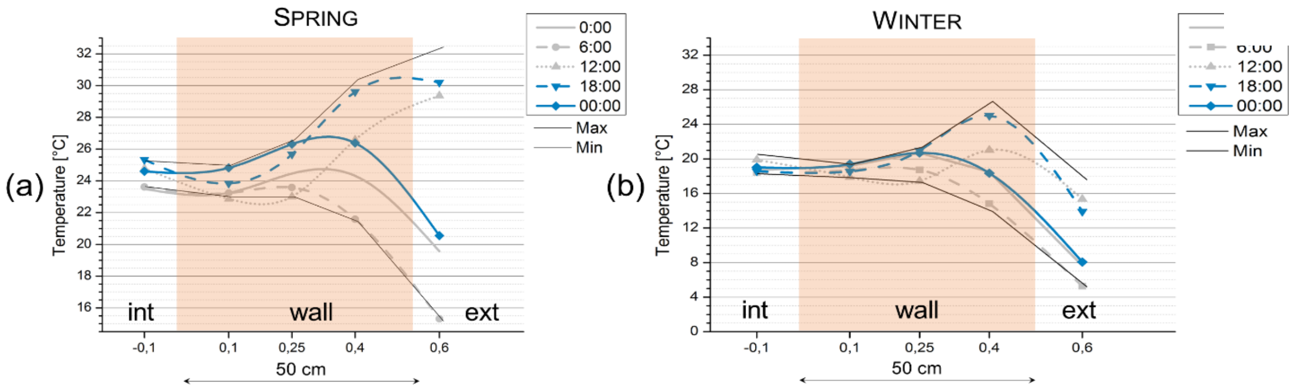
Impact on free floating temperature (‘passive cooling’)

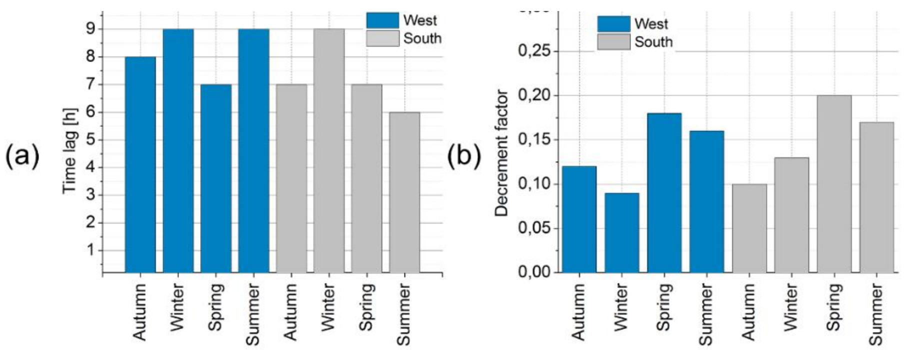
Rammed earth walls

Rammed earth walls

Highly hygroscopic



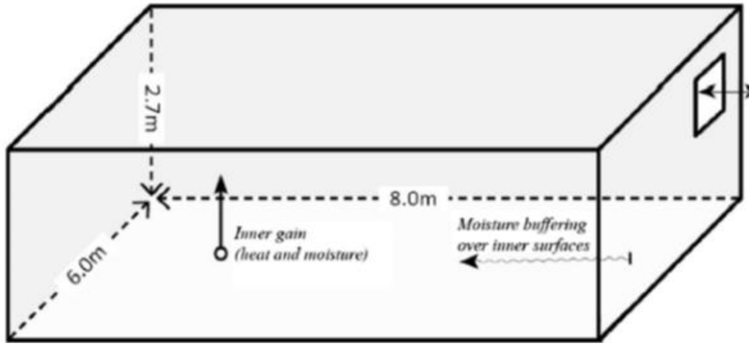




Very high **thermal mass** => stabilizing indoor climate (excellent in summer)

Impact of moisture difficult to assess

Impact of hygroscopic materials

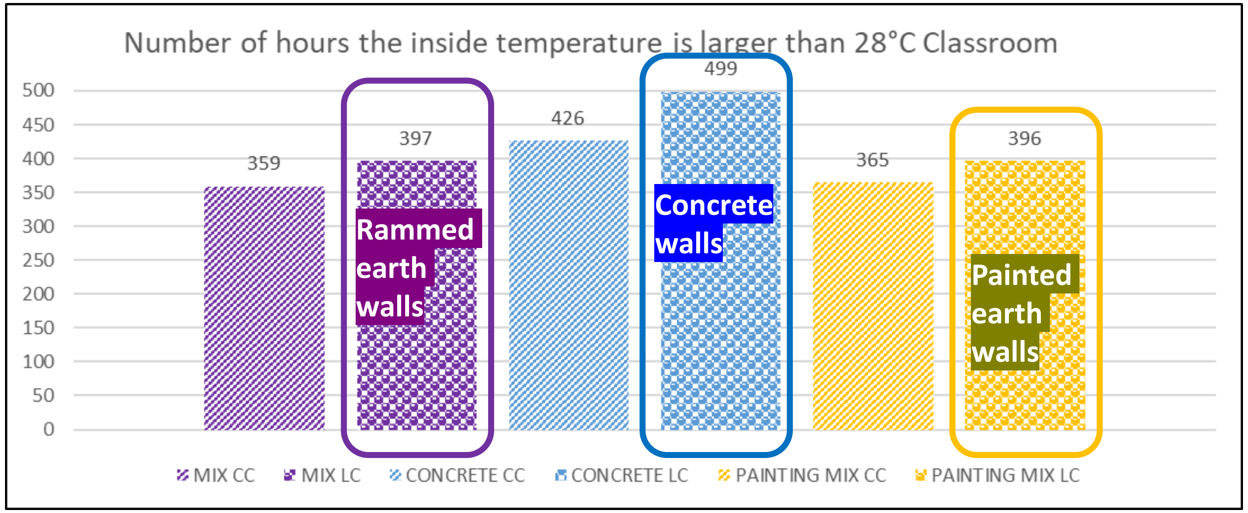


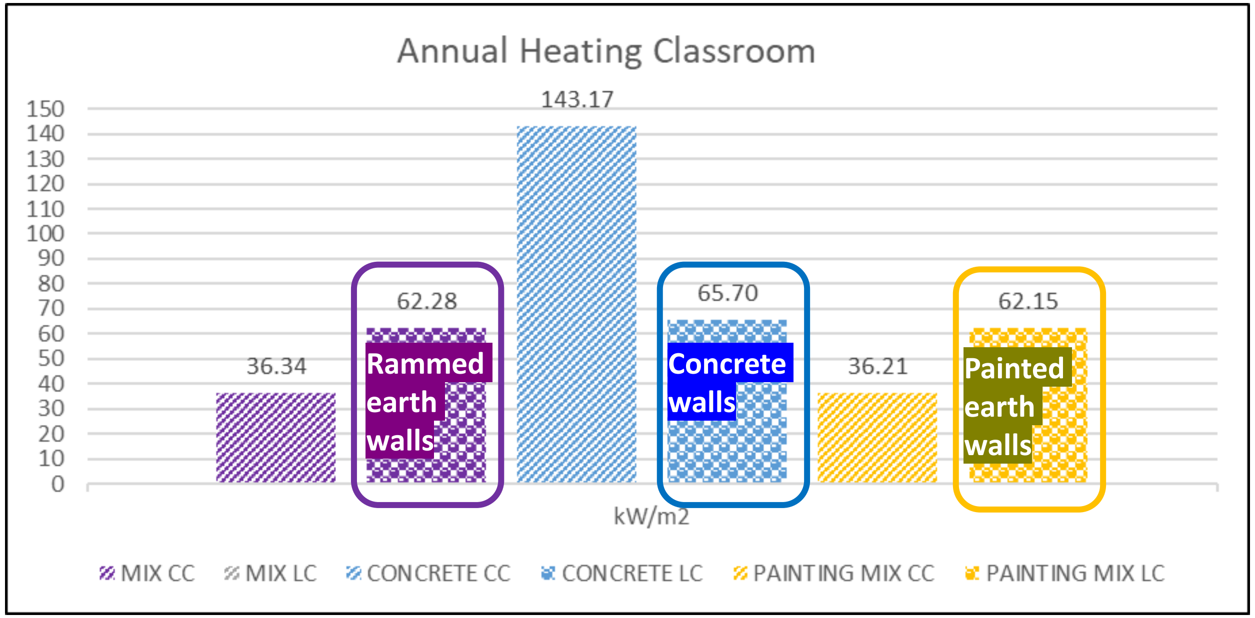
- Classroom with rammed earth walls
- EnergyPlus simulations
- **Lyon** (France) and Casablanca (Marocco) climates

Very **high thermal mass** => stabilizing indoor climate (excellent in summer)

Impact of moisture on energy difficult to assess

High **hygric mass** => stabilizing relative humidity (not shown)





PhD work by Alessia Losini, USMB

So, what do we know?

- Impact of **moisture** content on **thermal conductivity** — ESTABLISHED
- High **moisture buffering** capacity **stabilize indoor RH** — ESTABLISHED
- High **thermal mass stabilize indoor Temperature** — ESTABLISHED
- High **moisture buffering** contributes to Energy Savings ? — COMPLEX RELATIONSHIP

and open research question

Comportement hygrothermique des bâtiments –

Hygrothermique et confort ?

Wood and bio-based materials

Carbon storage ?

Warm ambience ?

Impact of wood on (hygro)thermal-comfort ?

Experimental setup :

Experimental house
(Chambéry, France)

raw spruce panelling

painted plasterboards
(reference room)

LABORATOIRE PERSONNALITÉ INTER-UNIVERSITAIRE COGNITION DE PSYCHOLOGIE CHANGEMENT SOCIAL

Experiment
- 78 participants + questionnaire
- Measurement during the tests
- Very similar conditions in both rooms
- Clothing recorded

Impact of wood on (hygro)thermal-comfort ?

Subjective perception:

Confined
Pleasant
Calm
Dark
Warm
Wooden
Comfortable

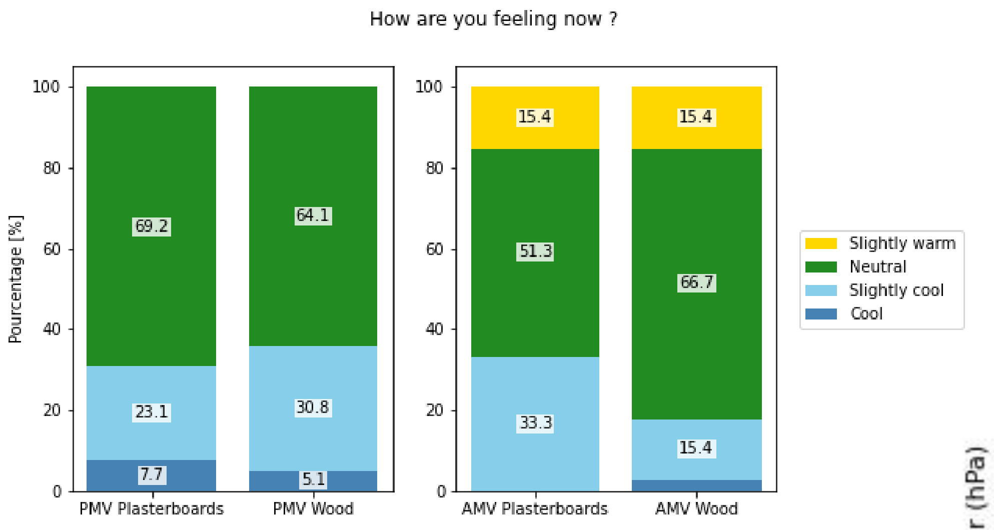
Wood

Gypsum plaster

Confined
Pleasant
Calm
Cool
Cold
Dark
Empty

Clémence Legros, PhD, USMB

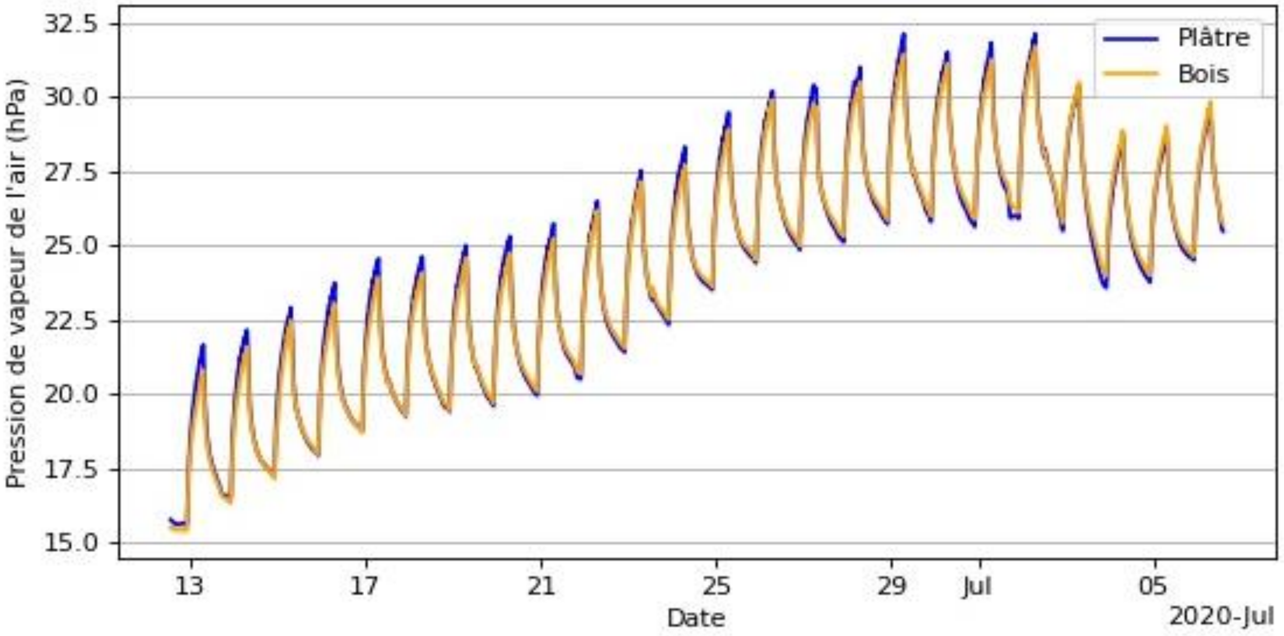
Impact of wood on (hygro)thermal-comfort ?



Results

- Similar reported temperature
- Similar measured temperature
- But **more confortable thermal sensation in wooden room**

physical measurements



COURS 2

Clémence Legros, USMB

Pour finir….

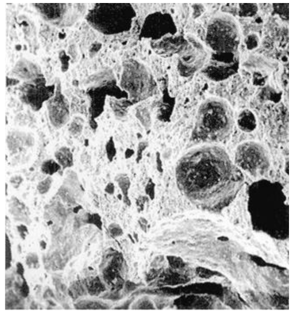
WUFI®

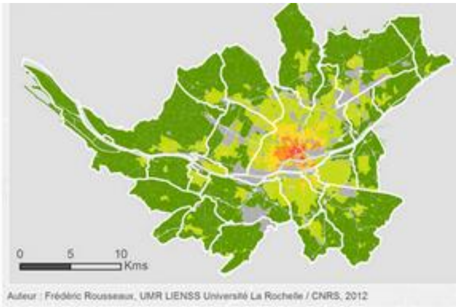
PLEIADES

EnergyPlus

DELPHIN

Pour finir….





Material

Wall

Building

Urban

48

Pour finir….

Comportement hygrothermique des bâtiments –

Importance des données d’entrée - Atelier

MERCI !