Sorrento SAPEM'23 常熟

A discussion about the acoustical properties of bio- and geo-based materials

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Outline

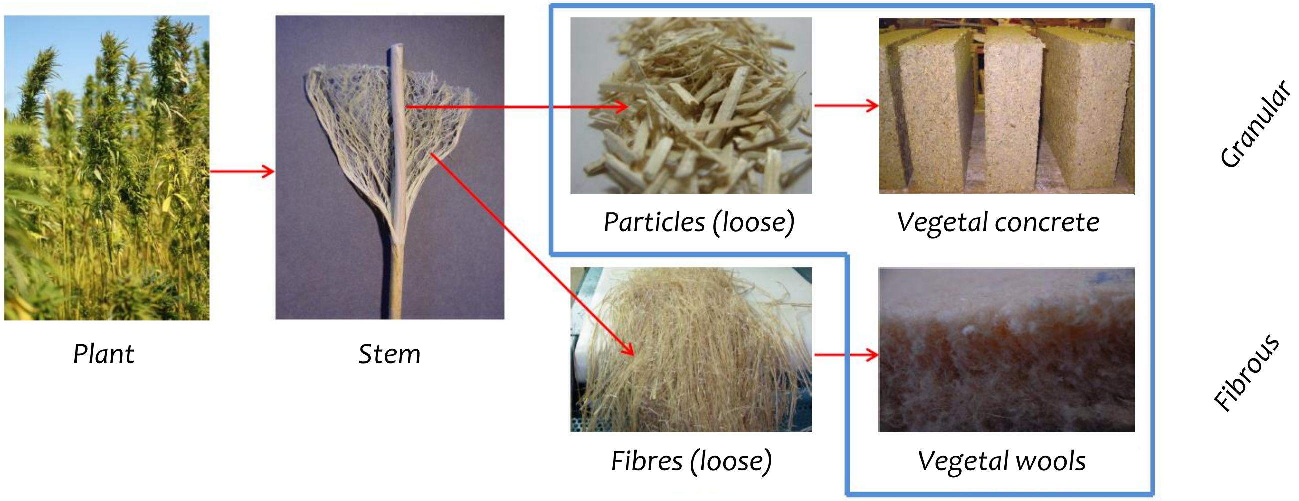
On the acoustic behaviour of bio/geobased poro-elastic materials

- A review of the materials under investigation
- Characterization approach: Specific issues & how to deal with it?
- Modelling approaches & applications
- Some optimization attempts and other outlooks

A review of the materials under investigation

Bio & geobased materials?

- Definitions:
  - Biobased materials: Materials partially or totally derived from plant or animal biomass, with two families of by-products.



  - Geobased materials: Materials derived from mineral resources, such as raw earth or dry stone.

Some granular materials

- A wide range of resources :

Wood

Hemp shiv

Flax shiv

Rapeseed

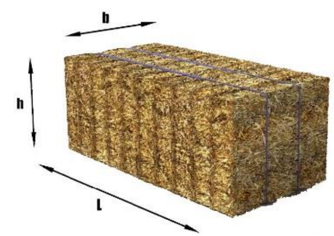
Sunflower pith

- Several options for implementation :

Lime/cement

Clay

Polymerisation



Webbing

Loose

Some fibrous one

- Resources:

Wood

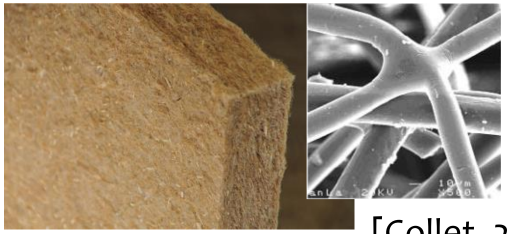
Hemp

Flax

Jute

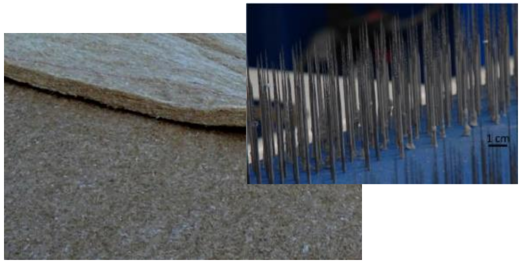
Sheep

- Implementation:



[Collet, 2004]

Thermobinding



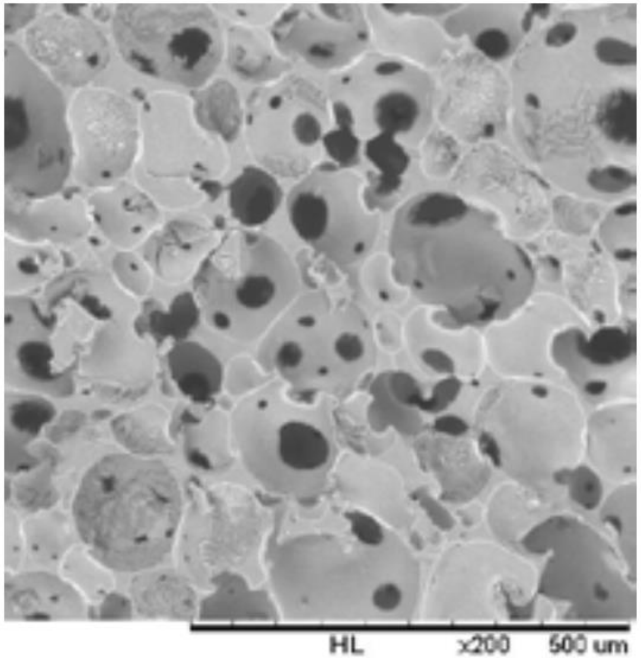
Needling

Loose

And others…

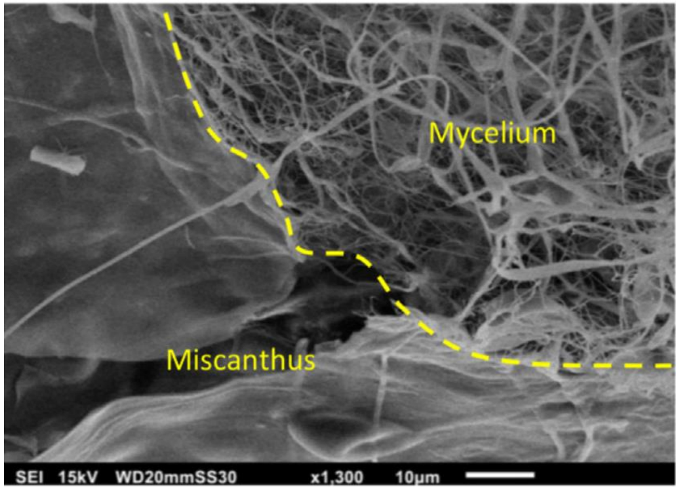
- Foam-like materials:

[Lacoste, 2014]

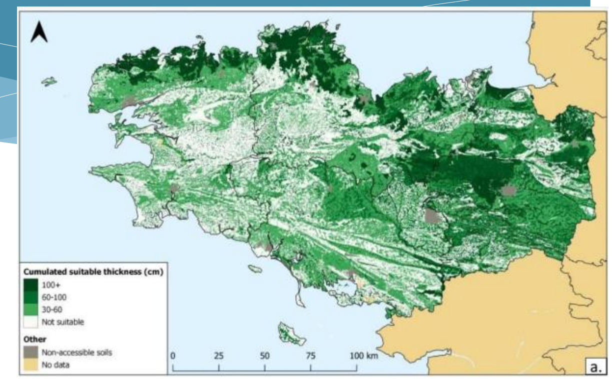


- Mixes:

[Pereira Dias et al., 2021]

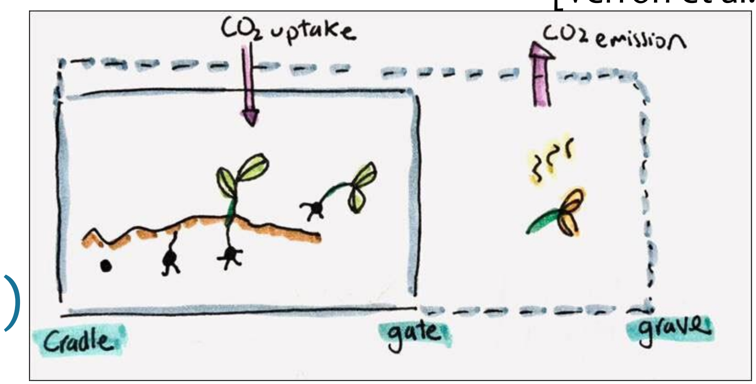


Why is it interesting?



[Verron et al., 2022]

- Locally produced materials
  - Use of local materials can divide the embodied energy of buildings by 2

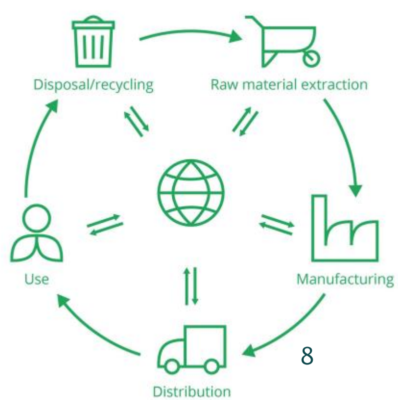


[Ayer & Taylor 2023]

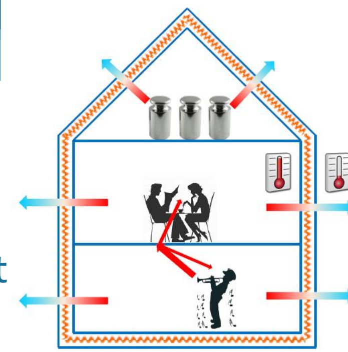
- CO2 storage (biogenic carbon)
  - CO2 stored during the growth
  - Fast carbon storage (year rotation)

- Low grey energy

  [Asdrubali 2011]



What applications?



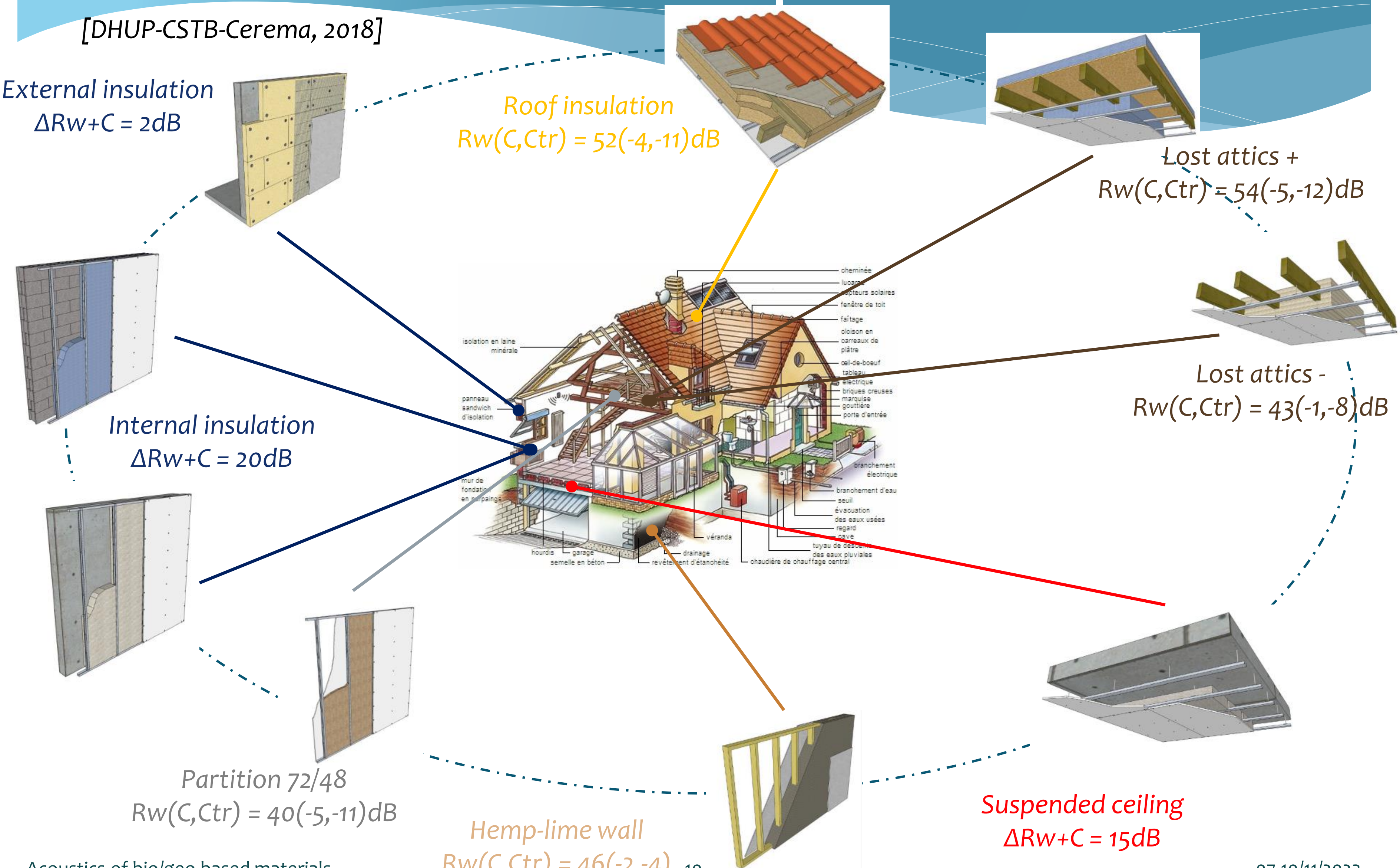
- Multiple applications
  - Automotive, textiles, plastic, paper, …
  - Buildings (with thermal, acoustical and mechanical functions)
    -> ~30% of the world's population lives in raw earth housing
- Some products already industrialised, some others in development

biofib isolation | pavatex SOPREMA | BUITEX | KANABAT
Métisse L'isolation durable | STEICO Le système constructif par nature | Isonat | BIOSYS

- Volume & surface on the market
  - Biobased insulation = 3.35 million m^3 (33 million m^2) in 2021 [TBC Innovation 2021, Karibati 2021]
  - ~ 10-11% of the market with an increase of around 30% over the last 6 years

- Economic growth
  - High potential for adding value to the surface areas and volumes of co-products available (e.g. for vegetal fibres, only 2 to 3% of resources are used) [FRD, 2020].
- **A need of knowledge regarding their acoustical performance to help the building sector**

What level of performances?



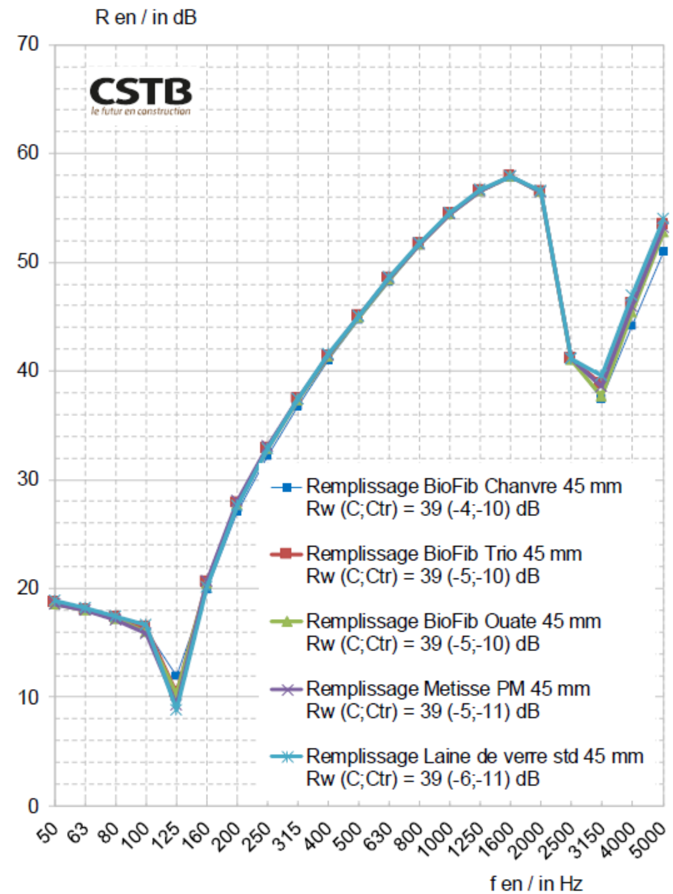
What level of performances?

- [Conclusion of the project *[DHUP-CSTB-Cerema, 2018]:*]

Equivalent acoustic performance between systems using standard mineral wool and systems using bio-sourced materials (⚠: implementation!)

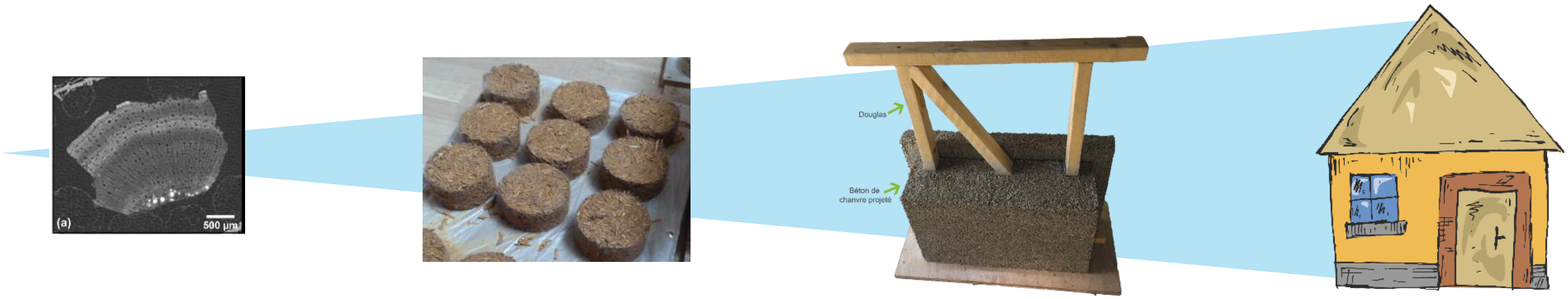
  - Partitions
  - Insulation lining on framework (without contact with supporting wall)
  - Suspended ceilings on framework under 140mm concrete floor (without contact with floor)
  - Lost attics and roofs (excluding loose materials)

- But many questions remain unanswered.

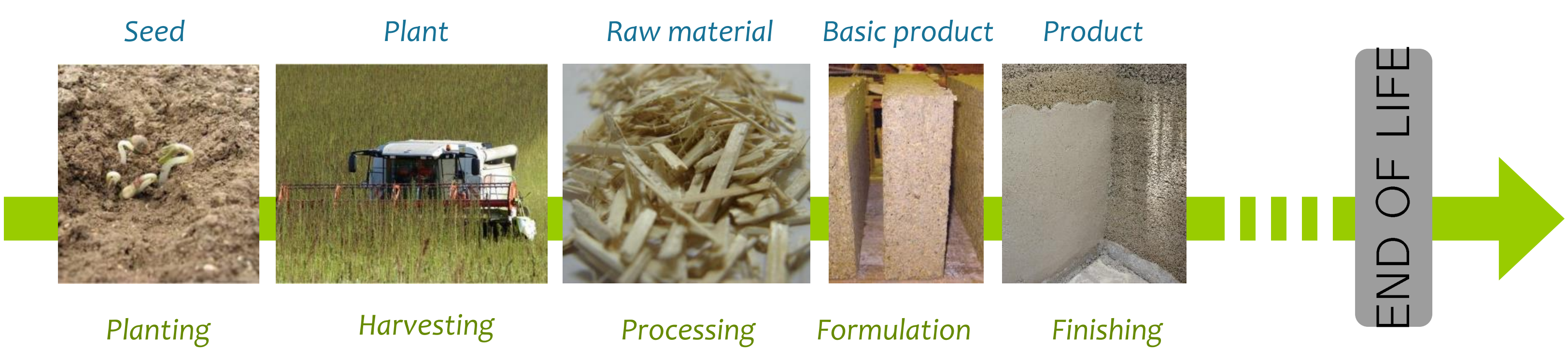


Some questions?

- Related to space scales…



- Related to time scales…

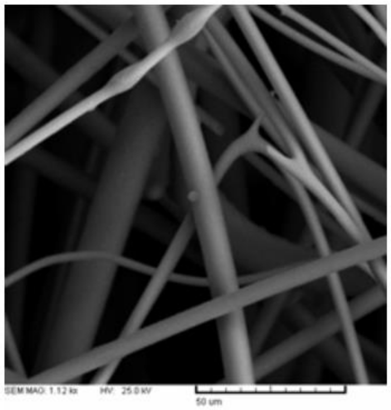


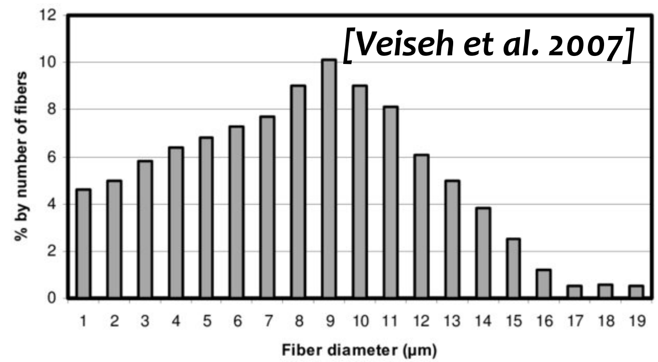
Characterization approach: Specific issues & how to deal with it?

Intrinsic variability of the materials

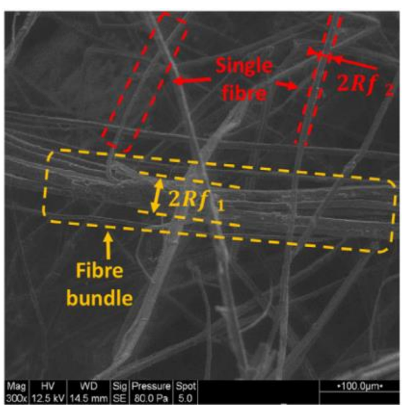
- Polydisperse size distribution

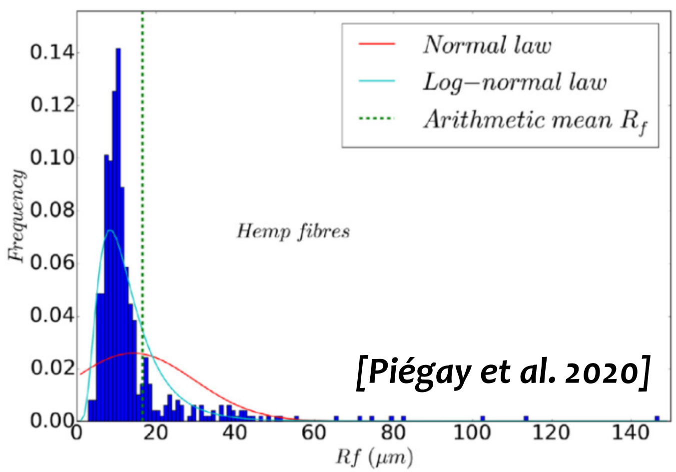
Glass fibers





Hemp fibers

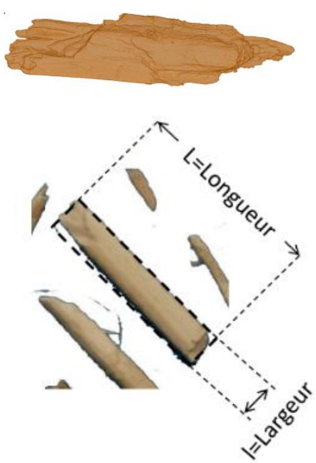


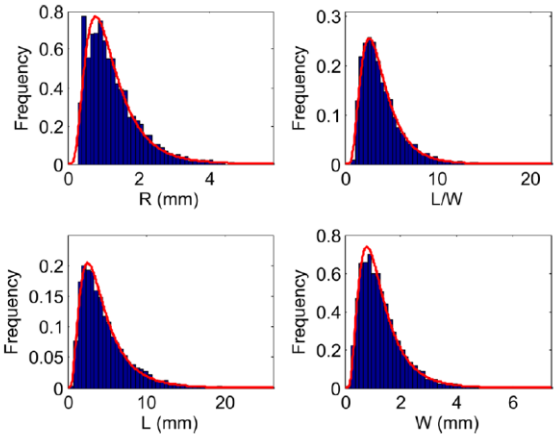


- Questions…
  - Homogeneity / REV
  - Equivalent size of a monodisperse distribution / polydisperse modelling?

Intrinsic variability of the materials

- Shapes

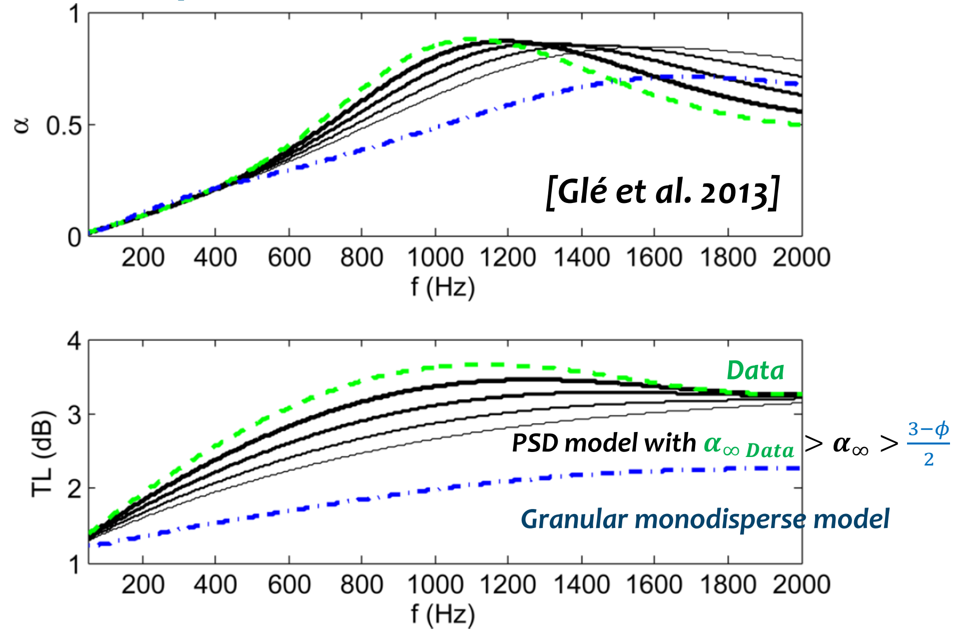




- Anisotropy

-> Variations by factors 2 to 3 of resistivities following orientation of particles [Glé 2013, Ledure 2018]

- Impact on acoustics

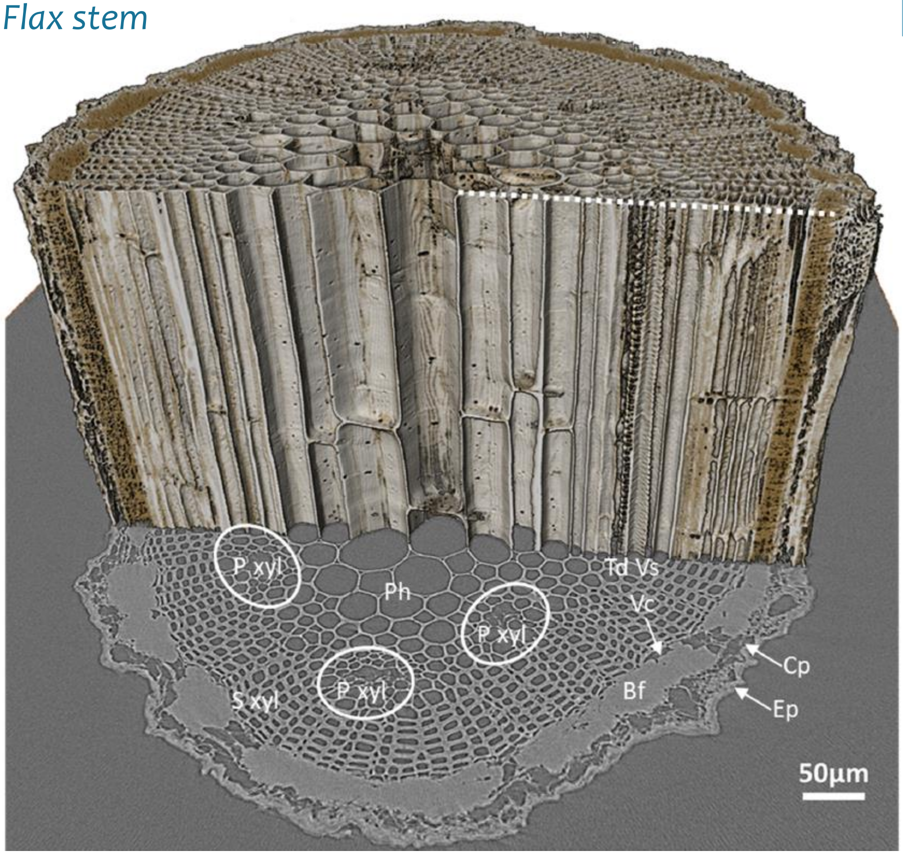


-> Illustration of the effect of hemp particles shape on acoustical properties

- An effect of tortuosity
- An effect of the pore/particle size distribution

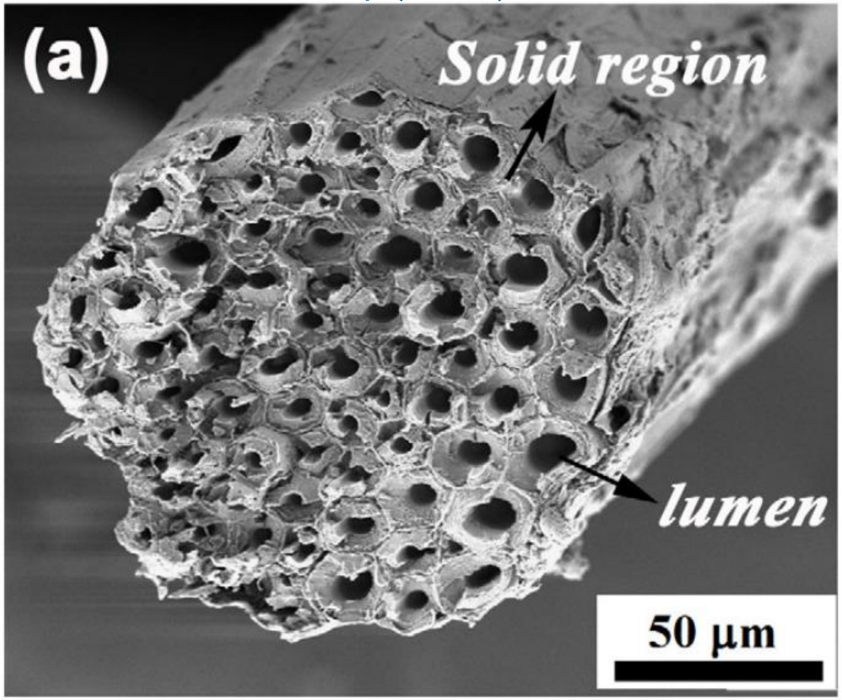
What about microstructure?

Flax stem



[*Nuez et al. 2022*]

Manila hemp (Abaca) bundle



[*Liu et al. 2011*]

-> A possibly large porosity within aggregates or fibers

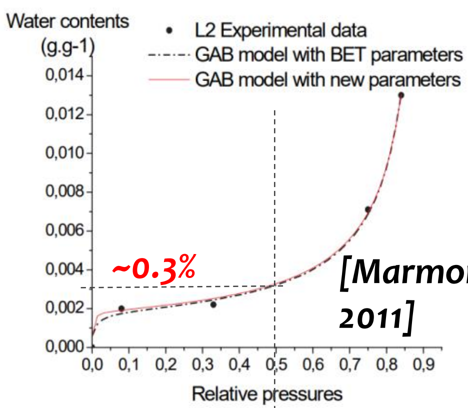
-> Size distribution suitable for acoustical dissipation

-> Porosity partially open/connected

Hygroscopic nature of the materials

- Sorption / Desorption in materials

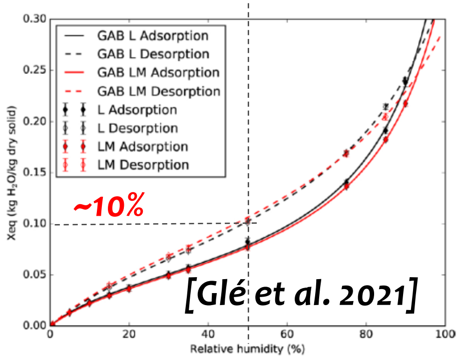
Glass wool



~0.3%

[Marmoret et al. 2011]

Hemp shiv

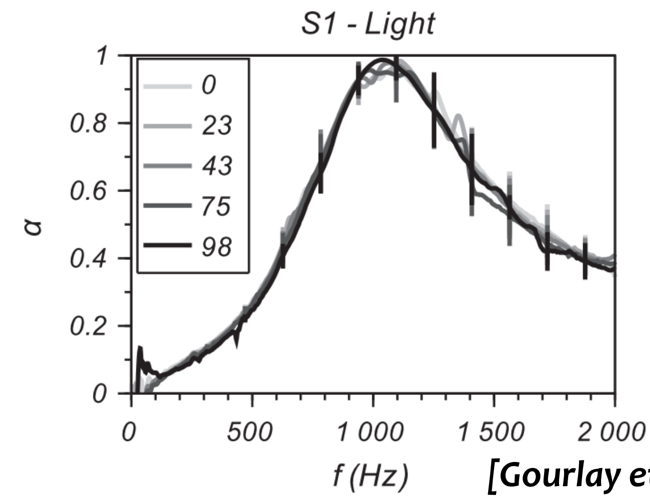


~10%

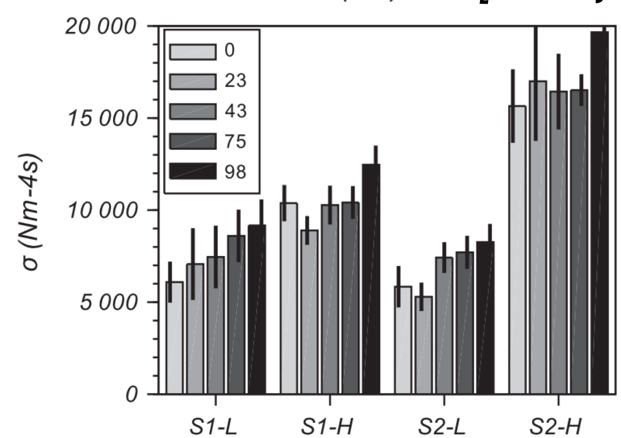
[Glé et al. 2021]

50% RH

- Impact on acoustics?



[Gourlay et al. 2017]

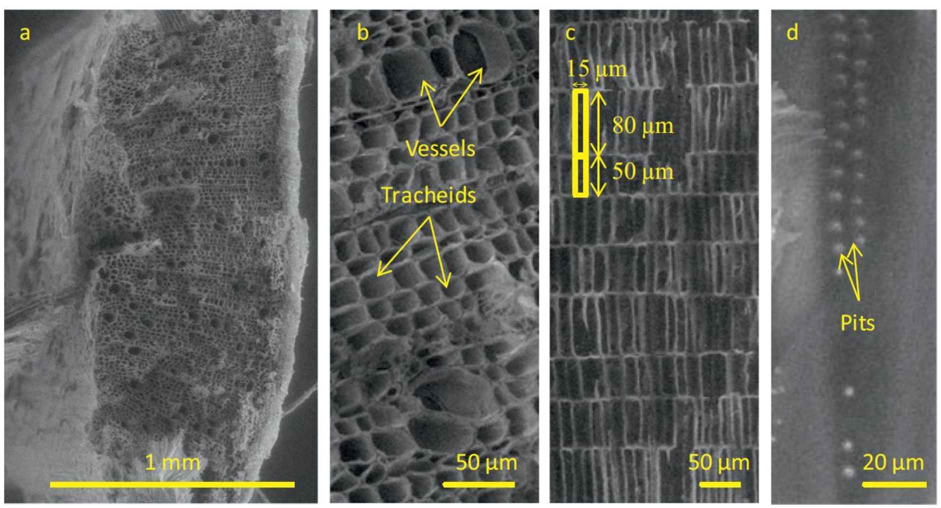


A ‘dynamic’ microstructure?

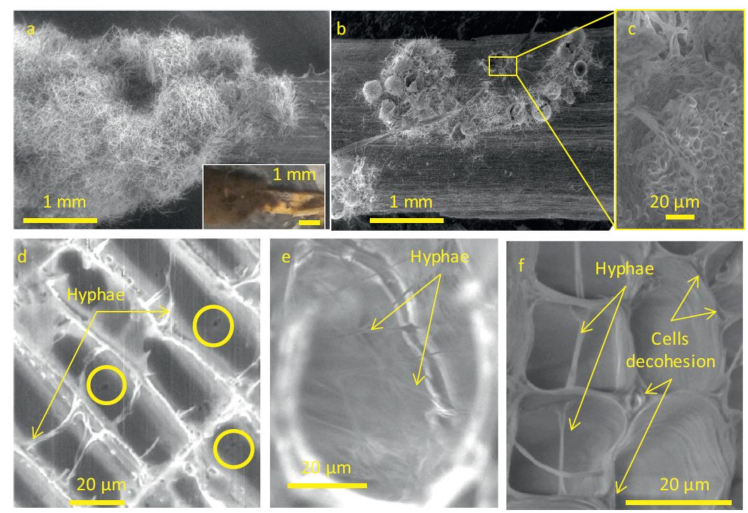
- Sensitivity to micro-organisms
  - ‘Suitable’ conditions: RH, T, pH, Water activity, Nutrients (C, N, P, S, O)
  - Effect of the manufacturing process (wet or dry process, pH of binder…)
  - Effect of the environment

- Consequences
  - Mass loss
  - Swelling
  - Cracks, porosity opening

Reference hemp particles



Hemp particles after 15 months of exterior aging



[Delannoy et al. 2020]

Modelling approaches & applications

Modelling steps…

Microstructure

$R, L, l, e, \ldots$

Homogeneisation, numerical, hybrid approach …

Acoustical parameters

$\phi, \sigma, \alpha_\infty, \Lambda, \Lambda', k_0' \ldots$

Analytical, ½ phenomenological, empirical models, …

Material acoustical properties

$(\Pi, \Theta), (\rho, K), (k, Zc)$

Transfer matrix method, numeric computation, … + Spatial windowing

System acoustical properties

Zs, α, T, TL

From microstructure to acoustical parameters

○ Fibrous materials

[Mechel 1976] $R_f \in [3;5]\ \mu m$ $\qquad \sigma = 10,56\mu\frac{(1-\phi)^{1,531}}{R_f^2\phi^3}$

[Mechel 1976] $R_f \in [10;15]\ \mu m$ $\qquad \sigma = 6,8\mu\frac{(1-\phi)^{1,296}}{R_f^2\phi^3}$

[Bies & Hansen 1980] $\qquad \sigma = 7,25\mu\frac{(1-\phi)^{1,53}}{R_f^2}$

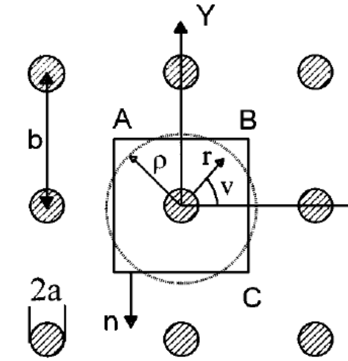
[Garai & Pompoli 2005] $R_f \in$ 10-25 μm $\qquad \sigma = 9,55\mu\frac{(1-\phi)^{1,404}}{R_f^2}$

[Tarnow 1996a] // (idéal) $\qquad \sigma = 4\mu\frac{1-\phi}{R_f^2[\ln(1/(1-\phi))-1,500+2(1-\phi)]}$

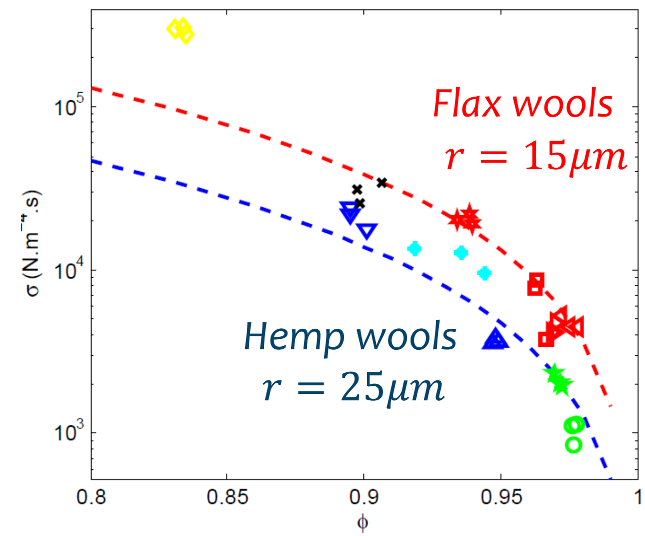
[Tarnow 1996a] // (aléatoire) $\qquad \sigma = 4\mu\frac{1-\phi}{R_f^2[1,280\ln(1/(1-\phi))-1,474+2(1-\phi)]}$

[Tarnow 1996a] $\perp$ (idéal) $\qquad \sigma = 4\mu\frac{1-\phi}{R_f^2[\ln((1-\phi)^{-1/2})-0,750+(1-\phi)-0,250(1-\phi)^2]}$

[Tarnow 1996a] $\perp$ (aléatoire) $\qquad \sigma = 4\mu\frac{1-\phi}{R_f^2[0,640\ln(1/(1-\phi))-0,737+(1-\phi)]}$



[Tarnow 1996]



[Glé 2013]

From microstructure to acoustical parameters

- Granular materials

[Attenborough 1993] $$\sigma = \frac{27\mu}{R_p^2}\frac{(1-\phi)^2}{\phi^{3.5}}$$

[Prieur du Plessis & Woudberg 2008] $$\sigma = \frac{A\mu(1-\phi)^2}{(\frac{4}{3}\pi)^{2/3}R_p^2\phi^3}$$

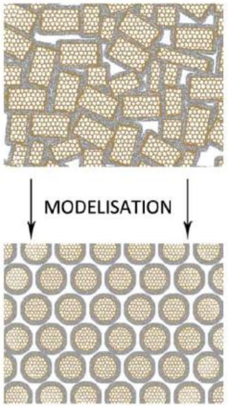
$$A = \frac{25.4\phi^3}{(1-\phi)^{2/3}(1-(1-\phi)^{1/3})(1-(1-\phi)^{2/3})^2}$$

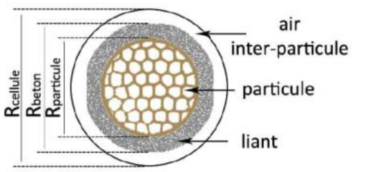
[Voronina & Horoshenkov 2003] $$\sigma = \frac{100\mu(1-\phi)^2(1+\phi)^5}{\phi R_p^2}$$

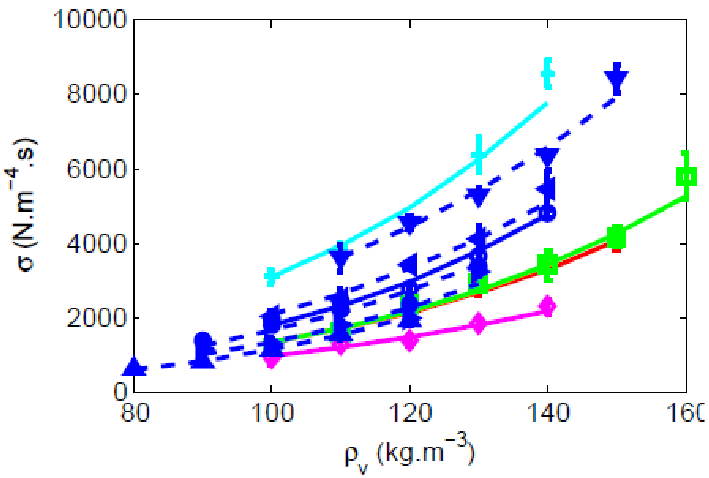
[Umnova *et al.* 2000] $$\sigma = \frac{9\mu}{2\frac{\phi^2}{(1-\phi)(1-\Phi)\Omega}R_p^2}$$

$$\Omega = \frac{5}{5-9\Theta^{1/3}+5\Theta-\Theta^2} \quad \Phi = \frac{3}{\sqrt{2\pi}}(1-\phi)$$

[Boutin & Geindreau 2010] $_p$ $$\sigma = \frac{3\beta^2\mu}{(-1+\frac{2+3\beta^5}{\beta(3+2\beta^5)})R_p^2} \quad \beta = (1-\phi)^{1/3}$$



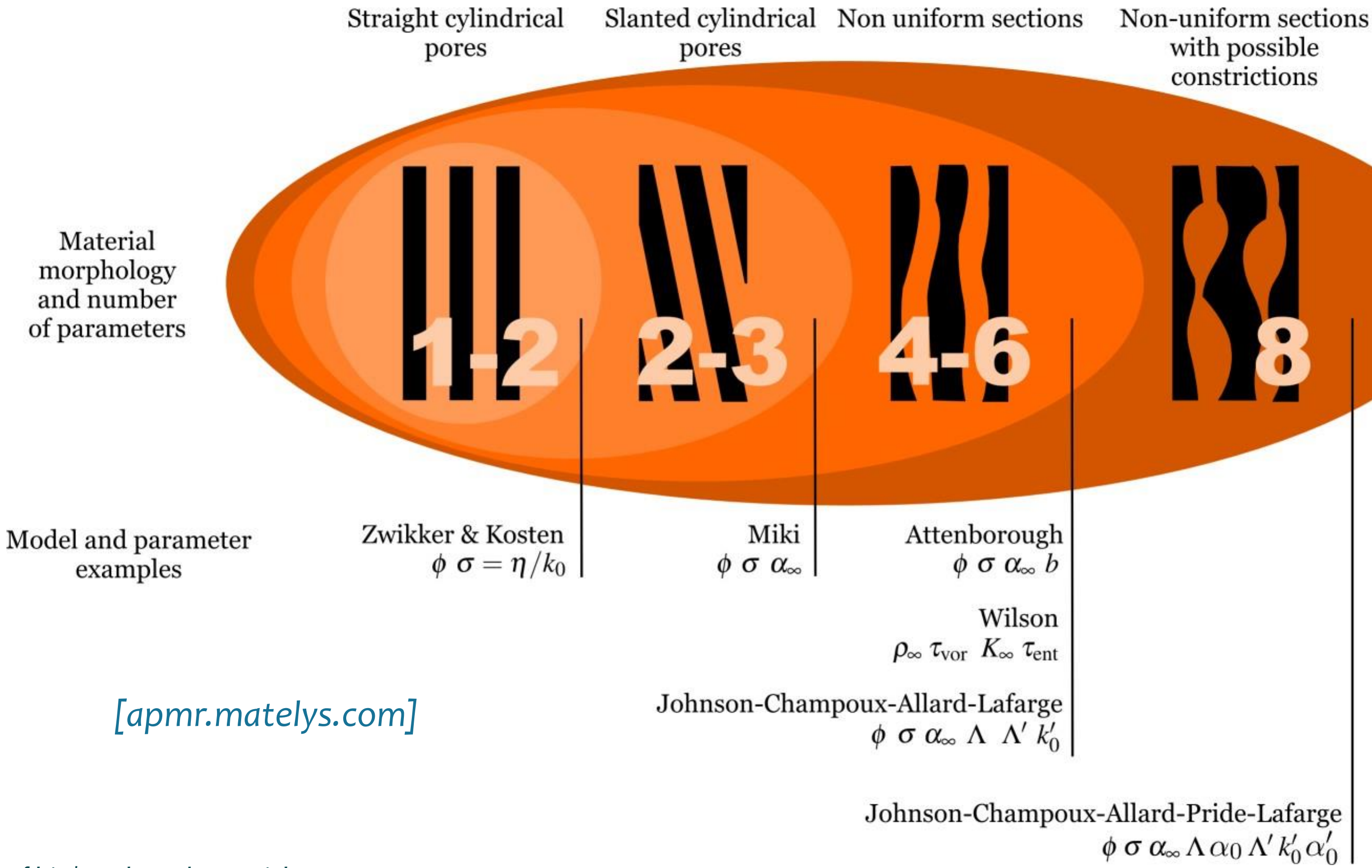




[Glé et al. 2013]

From acoustical parameters to acoustical properties

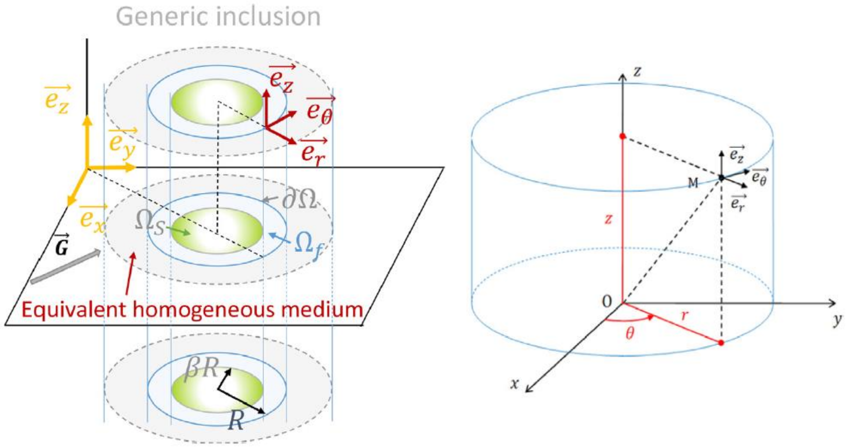
- Porous geometry based models



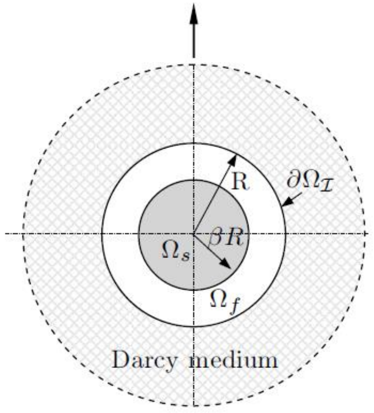
[apmr.matelys.com]

From acoustical parameters to acoustical properties

- Microstructural (Frame based) models
  - Fibrous materials *[Tarnow 1996, Piégay 2019]*
    - Monodisperse cylindrical fibers
    - Random or regular arrangments
    - Anisotropy: Parallel and perpendicular sollicitations
  - Granular materials *[Umnova 2000, Boutin & Geindreau 2010]*
    - Monodisperse spherical aggregates



[Piégay et al. 2021]

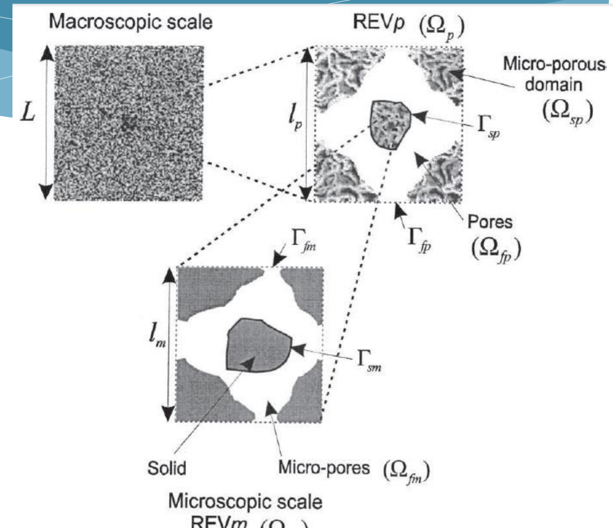


[Boutin & Geindreau 2010]

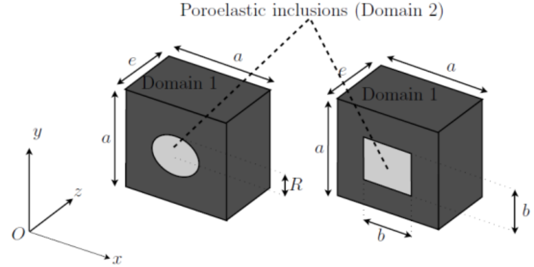
Some particular cases

- Multiscale porosity *[Olny et Boutin, 2003]*
  - General application

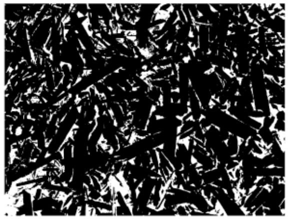
$$\left\{\begin{aligned} \rho_{eq}(\omega) &= \left(\frac{1}{\rho_p(\omega)} + \frac{1-\phi_p}{\rho_m(\omega)}\right)^{-1} \\ K_{eq}(\omega) &= \left(\frac{1}{K_p(\omega)} + \frac{(1-\phi_p)F_d(\omega,\omega_d)}{K_m(\omega)}\right)^{-1} \end{aligned}\right. \qquad \left\{\begin{aligned} \omega \ll \omega_d &\Rightarrow F_d \approx 1 \\ \omega \approx \omega_d &\Rightarrow F_d \in [0;1] \\ \omega \gg \omega_d &\Rightarrow F_d \approx 0 \end{aligned}\right.$$

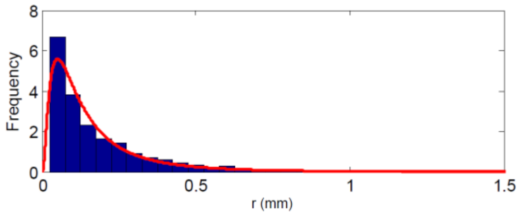


  - Perforated materials case *[Sgard et al, 2005]*
  - Composite materials case *[Gourdon et Seppi, 2010]*
  - Porous aggregates *[Venegas et al, 2012]*



- Pore size distribution *[Horoshenkov et al., 2001]*





-> Random distrib. :

$$F(\omega) = -\frac{j\omega\rho_0\alpha_\infty I(\omega)}{\sigma\phi(1-I(\omega))}$$

$$I(\omega) = 1 - \frac{j\omega\rho_0}{\mu}\int_0^{+\infty} s^2 e(s)\bar{\xi}\left(\sqrt{-j}\sqrt{\frac{\rho_0\omega}{\mu}}s\right) ds$$

-> Lognormal distrib. :

$$\tilde{F}(\omega) = \frac{1+\theta_3\epsilon(\omega)+\theta_1\epsilon(\omega)^2}{1+\theta_3\epsilon(\omega)}$$

$$\epsilon(\omega) = \sqrt{\frac{j\omega\rho_0\alpha_\infty}{\sigma\phi}}$$

Modelling of vegetal wools

- Rigid frame hypothesis
- Analysis of the double porosity behaviour [Olny and Boutin, 2003]
  - Viscous and isothermal behaviours in intra-fiber pores:

ϕ_{intra} (≈5%) << ϕ_{inter}, σ_{intra} >> σ_{inter}

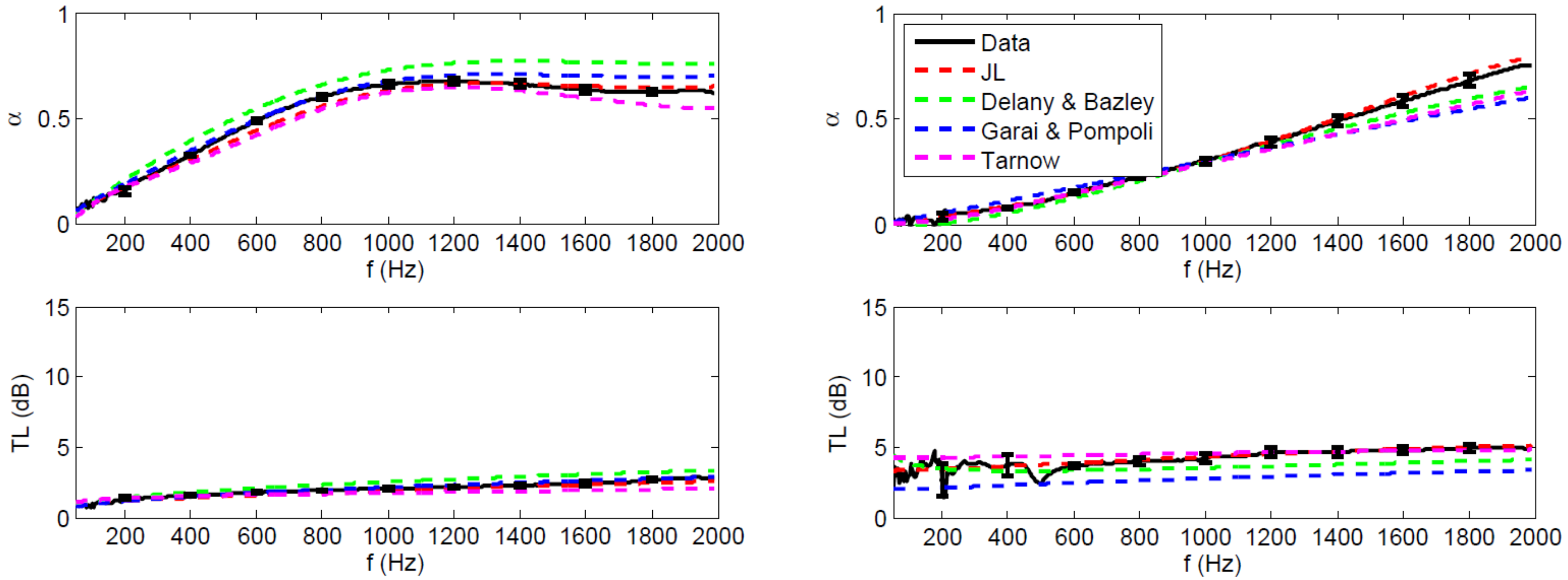
$$\rho \approx \left[\frac{1}{\rho_{inter}} + (1-\phi_{inter}) \frac{\frac{\rho_0 \alpha_{\infty intra}}{\phi_{intra}} + j\frac{\sigma_{intra}}{\omega}}{\left(\frac{\rho_0 \alpha_{\infty intra}}{\phi_{intra}}\right)^2 + \left(\frac{\sigma_{intra}}{\omega}\right)^2} \right]^{-1} \approx \rho_{inter}$$

$$K \approx \left[\frac{1}{K_{inter}} + (1-\phi_{inter}) \frac{\phi_{intra}}{P_0} \right]^{-1} \approx K_{inter}$$

- Models used and parameters
  - Fibrous models [Delany and Bazley 1970, Garai and Pompoli 2005, Tarnow 1996, Piégay 2019] : ϕ and σ measured
  - JCAL model [Johnson et al., 1987, Lafarge et al., 1997] : ϕ and σ measured, α_∞, Λ, Λ', and k_0' indirectly measured from (ρ,K) [Panneton and Olny, 2006, Olny and Panneton, 2008]

Modelling of vegetal wools

- Green hemp
- Hemp wool / shiv



- Accuracy of ±10% on α and ±2dB on TL for all models (except for resistive samples)
- Use of JCAL (6 parameters) model not absolutely necessary for such materials

Modelling of vegetal concrete

- Hyp. rigid frame
- Double porosity approach [Olny & Boutin, 2003]

→ Viscous domain for intraparticles pores

→ Case of double porosity with high contrast of permeability

$$\rho = \left[\frac{1}{\rho_{inter}} + (1 - \phi_{inter}) \frac{1}{\rho_{intra}} \right]^{-1} \overset{?}{\approx} \rho_{inter}$$

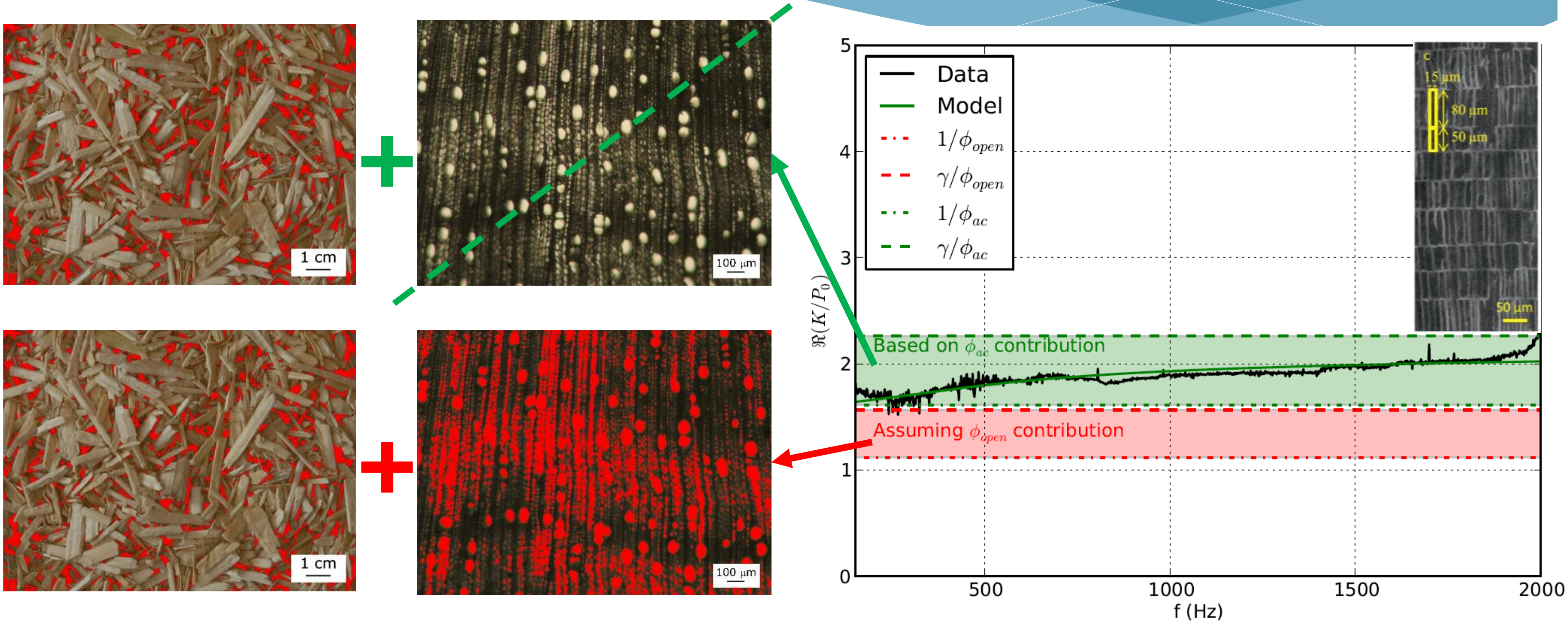
$$K = \left[\frac{1}{K_{inter}} + (1 - \phi_{inter}) \frac{F_d(\omega)}{K_{intra}} \right]^{-1} \overset{?}{\approx} K_{inter}$$

$$\longrightarrow \quad k = \omega \sqrt{\frac{\rho}{K}}, \quad Zc = \omega \sqrt{\rho K} \quad \longrightarrow \quad \alpha$$

- Models and associated parameters
  - Viscoinertial effects: [Johnson *et al.*, 1987]
  - Thermal effects: [Zwikker & Kosten, 1949]

  } $\phi_{inter}, \sigma, \alpha_\infty, \Lambda$

Modelling of vegetal concrete



[Lemeurs et al. 2017]

Illustration with hemp-clay samples, three scales of porosity:

- Earth (pores < 1 µm) + Hemp particles (pores de 10 à 100 µm) + Interparticles (~1 mm)

→ $\boldsymbol{\phi_{acou}}$ **related to the dynamic contribution of interparticles pores only?**

Modelling of vegetal concrete

Further investigation

Packing scale

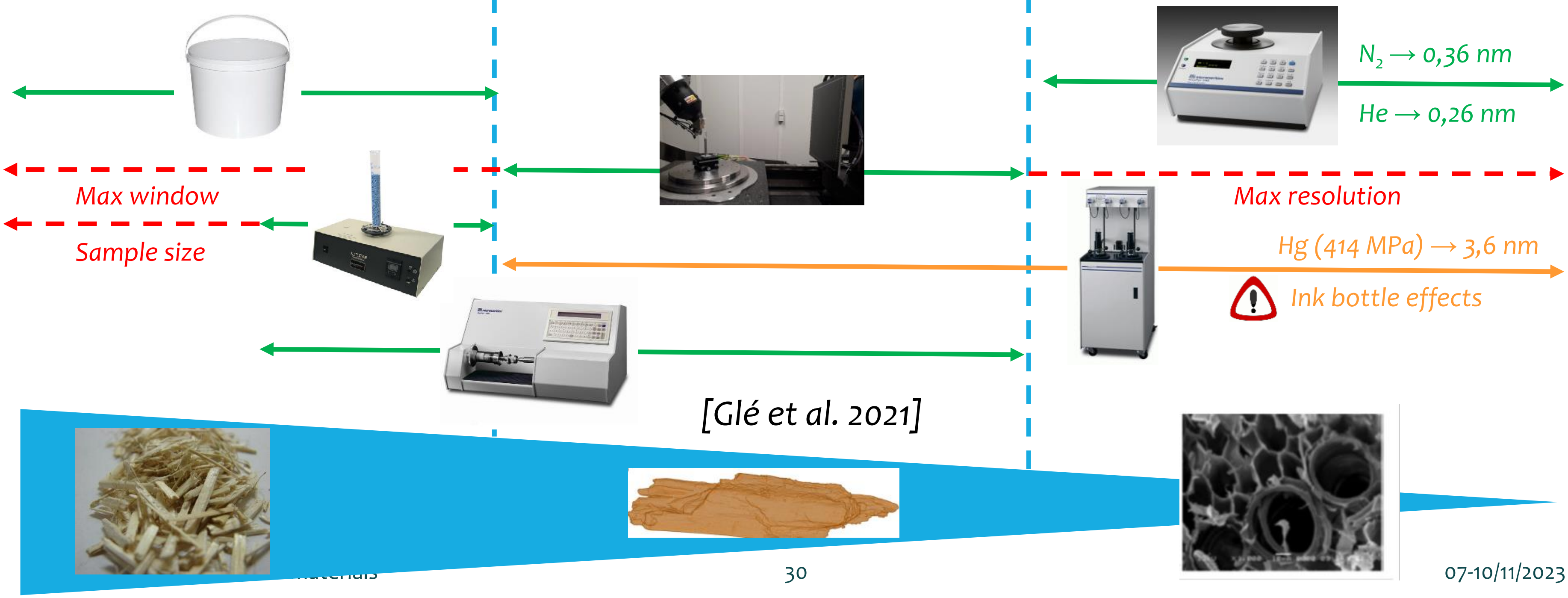
- Trimmed density
- Apparent density
- Tapped density
- Compacted density

Particle scale

- Powder pycnometry
- Mercury intrusion
- X-ray computed tomography

Cellular scale

- He pycnometry (powder)
- He pycnometry
- N_2 pycnometry
- Mercury intrusion

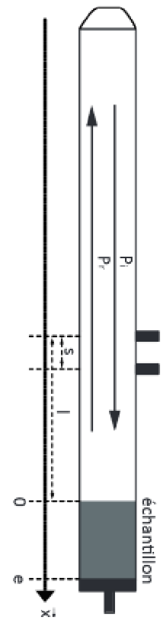


Modelling of vegetal concrete

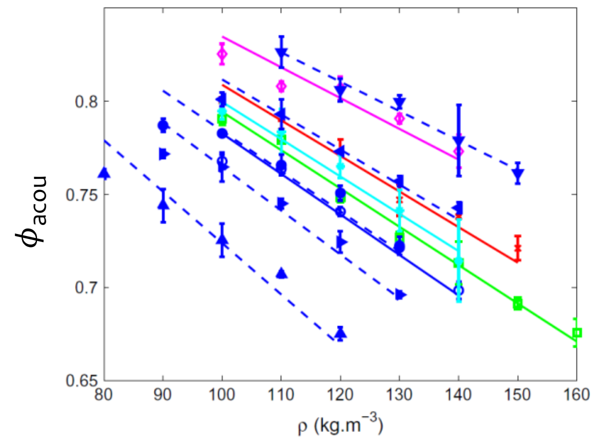
Further investigation

- **Initial 'blind' approach:**

- Particle density is not known
- Assumption of a single level of porosity
- Hypothesis H0: $\phi_{acou} = \phi_{inter}$?
- Evaluation of an acoustical density



Re(K)



Linear regression

$$\phi_{acou} = 1 - \frac{\rho}{\rho_{particle}}$$

	Particle density ρ_P (kg.m^{-3})	
	Geopyc	***Acoustic***
L	*330*	*478*
LM	*210*	*443*
L12	*326*	*515*
L12M	*254*	*469*
L24	*299*	*502*
L24M	*242*	*441*
L4+	*286*	*447*
L4+M	*274*	*396*

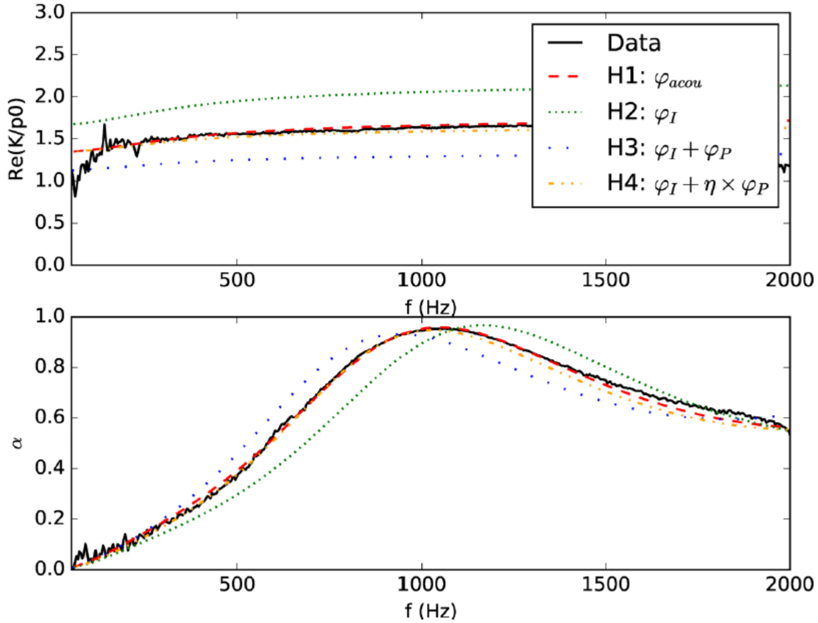
→ Acoustic densities are higher than particle densities
→ The tendencies are respected (size and immersion effects)

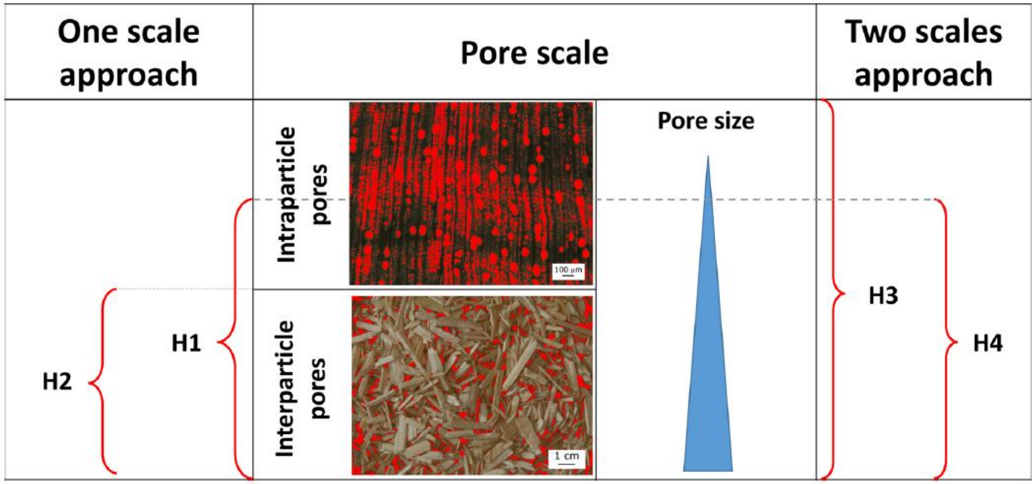
Modelling of vegetal concrete

Further investigation

- **Corrected approach:**

- Particle density from Geopyc
- 4 hypotheses / behavior
- One or two porosity scales considered [Olny & Boutin 2003]





→ All open pores do not take part to acoustic dissipation

→ Acoustic dissipation is not only due to inter particle pores

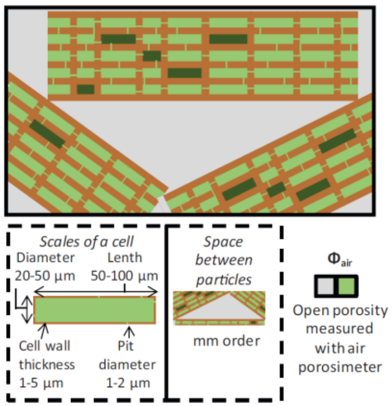
→ Interparticle pores + a fraction of the intraparticle pores are involved in sound dissipation

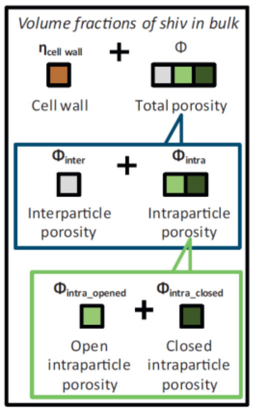
→ Two approaches are satisfying, but the (partial) double porosity is physically more accurate

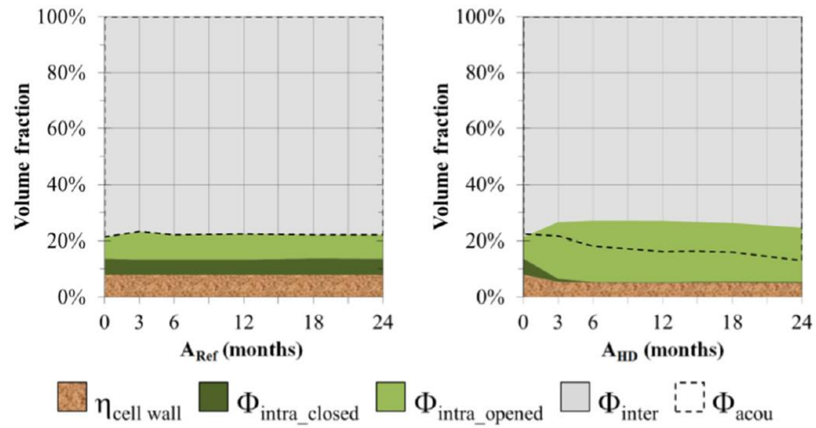
Modelling of vegetal concrete

Application

- Aging of hemp particles



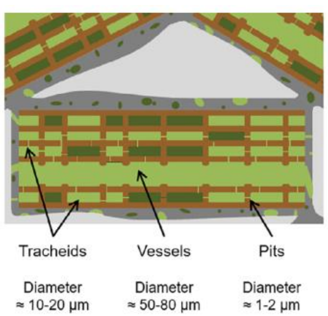


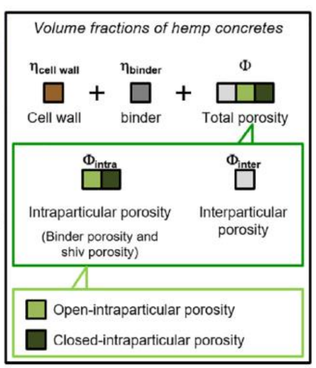


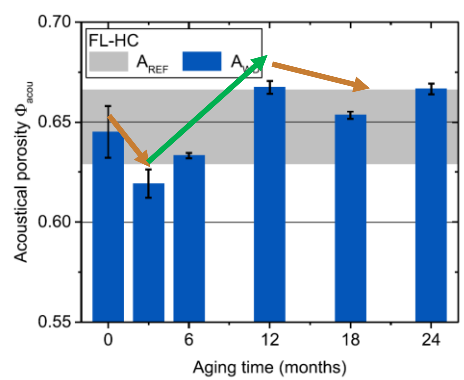
Observations:
- ✓ loss of mass
- ✓ swelling and shrinkage
- ✓ opening of the closed porosity

[Delannoy et al. 2018]

- *Aging of hemp concrete*







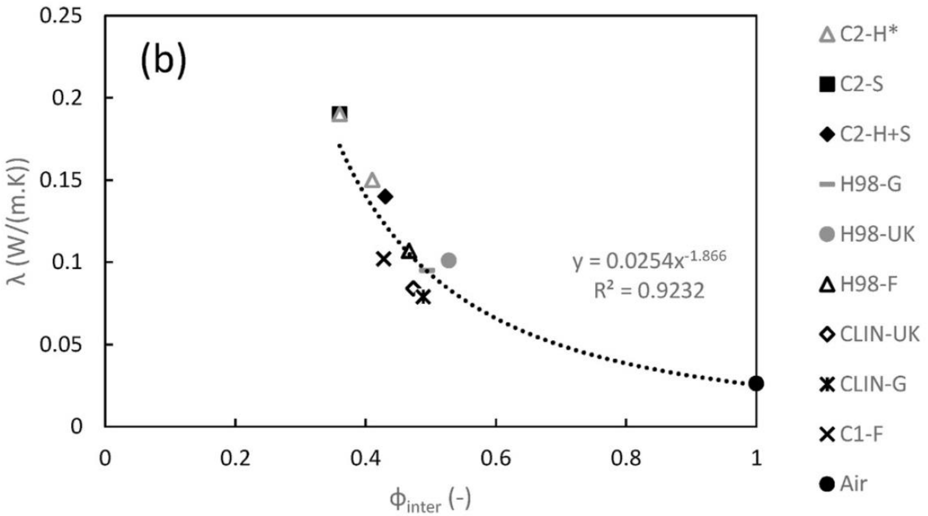
[Delannoy et al. 2020]

Observations:
- ✓ loss of mass
- ✓ swelling and shrinkage
- ✓ opening of porosity
- ✓ setting (hydratation / carbonatation) of lime
- ✓ mineralization of the vegetal particles porosity

Modelling of vegetal concrete
Application

[Abbas et al 2021]

Thermal conductivity vs 'acoustical' porisity



[Lichtenecker's formula]

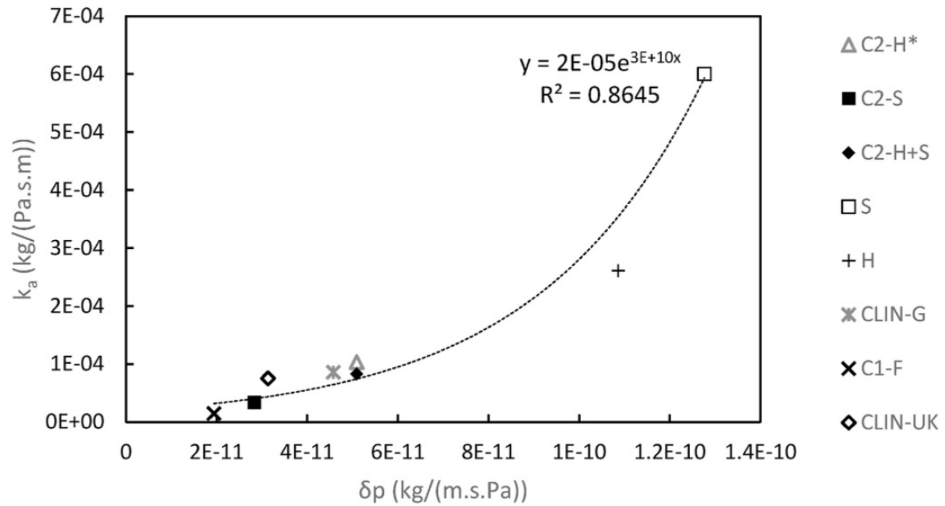
$$\lambda = \left(\Phi_{inter} \cdot \lambda_{air}{}^{\alpha} + (1 - \Phi_{inter}) \cdot \lambda_{solid}{}^{\alpha} \right)^{\frac{1}{\alpha}}$$

[Zakri et al., 1998]

$$\lambda \approx \Phi_{inter}{}^{\frac{1}{\alpha}} \lambda_{air}$$

with α = -0,54 ∈ [-1, 1]

Water vapor vs air permeabilities



Non-linear relationship: $k_a = 2 \cdot 10^{-5} \cdot e^{3 \cdot 10^{10} \cdot \delta p}$

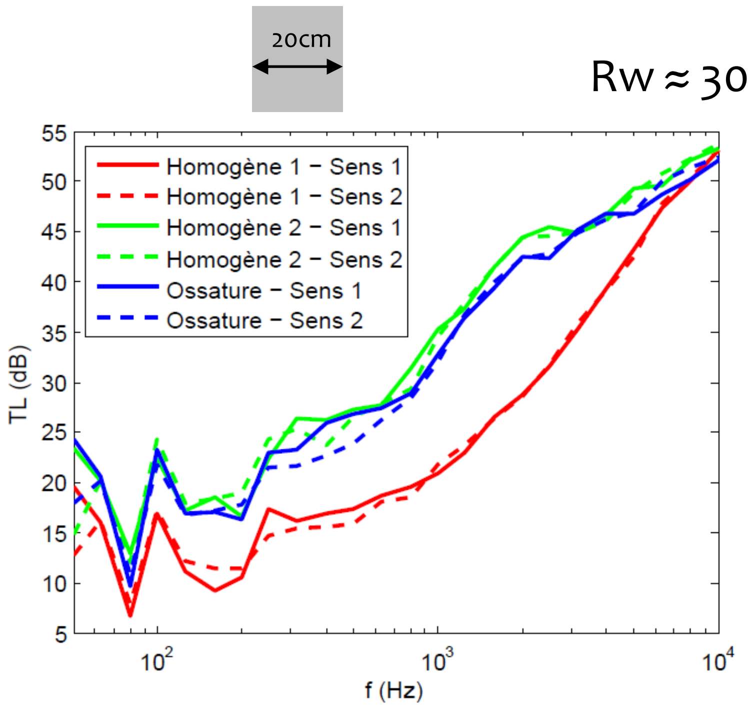
- Water vapor perm.: Fickian law (diffusion)
- Air perm.: Darcy's law (flow)

Predominance of larger pores *[Walker et al, 2014]*

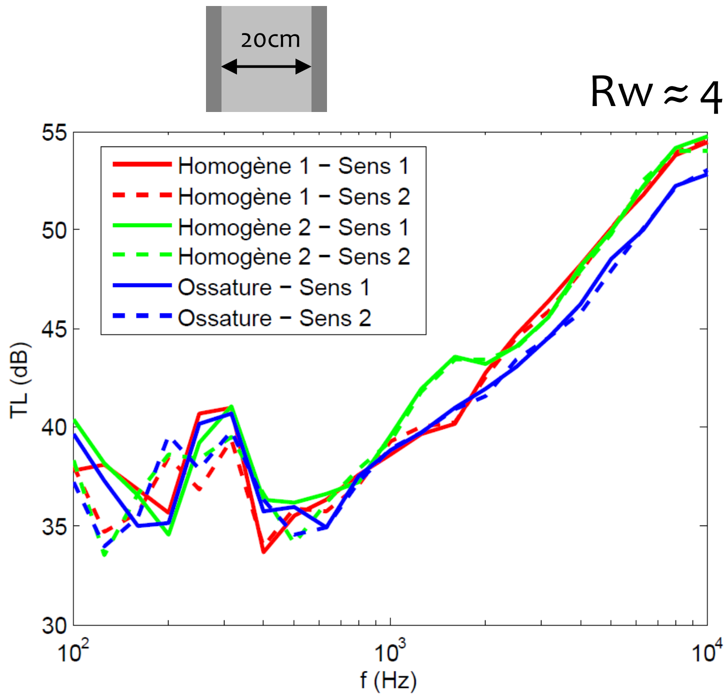
Some optimization attempts and other outlooks

Multilayer structuration, stratification

Coating concrete layers: [Bütschi et al., 2004], [Glé, 2013]



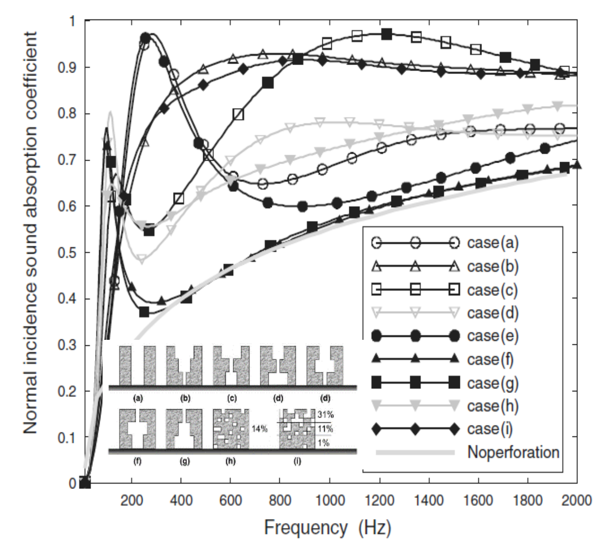
Rw ≈ 30 dB



Rw ≈ 40 dB

→ Possibility to implement stratified materials [De Ryck et al., 2008]

Surface geometry



- Perforations: [Olny & Boutin, 2003], [Sgard *et al*., 2005]

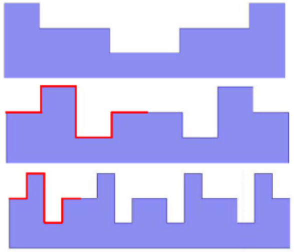
«Pressure diffusion from mesopores to micropores »

- Localisation: [Sapoval et al., 1997], [Félix et al., 2007]

« Localisation of acoustical modes at the irregularities level »

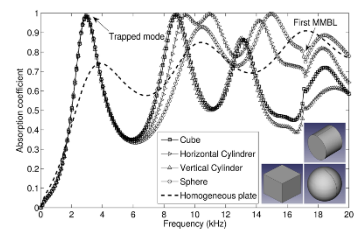
→ Application to wood concrete: [Colas, 2004]

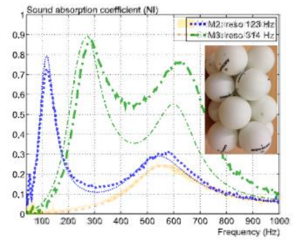
→ Application to hemp concrete: [Debrabant, 2010]



Towards biobased or bioinspired metamaterials

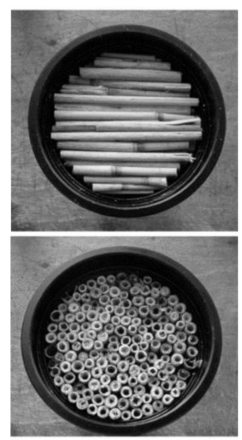
- Potentiel gain in performance (absorption, transmission loss) with solid or resonating inclusions
  - [Groby et al., 2013]
  - [Boutin et Bécot, 2014]

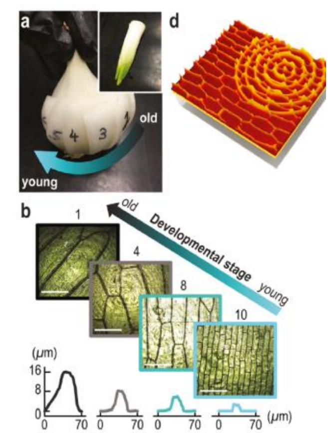




- Biobased materials (specifically vegetal concretes) are quite relevant hosts (fabrication, properties)

- Natural metamaterials / phononic cristals?
  - Typha: [Oldham et al., 2011]
  - Bamboo: [Lagarigue, 2013]
  - Onion cells: [Ghanem et al., 2021]

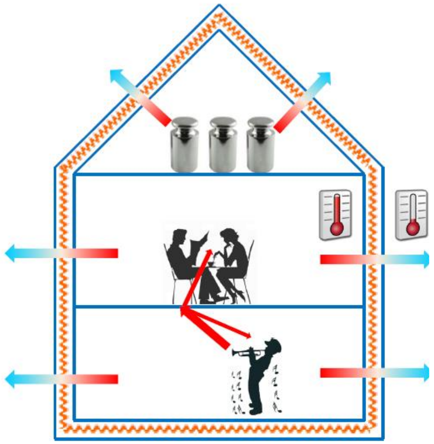




Almost the end…

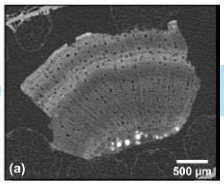
Concluding remarks

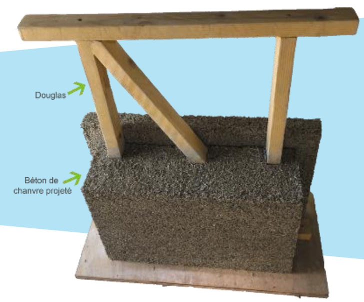
- Acoustics: a feature of bio/geobased materials
  - Such as thermic, mechanic, fire reaction…
  - A performance to be characterized
    - Quantitatively: What are the levels of needs/expectations?
    - Qualitatively: Which behaviours
- Acoustics for non destructive testings of biobased materials
  - A tool for investigating microstructure
  - Opportunities for indirect characterization
    - For hygrothermics
    - For elastic properties



[labs.openai.com]

Outlooks





- Microstructure characterisation
- Pore size vs particle size analysis
- Granulofibrous materials description
- Overview of binder effects

- Micro-macro modelling of granular packings
- Anisotropic description
- Poroelastic behaviour
- Treatments (fire reaction)

- Material/framework associations
- Qualification/extrapolation of performances (α_w, R_w, ΔR)
- Lateral transmissions (Dn,f,w)
- Optimisations

- In situ evaluations (DnT,A, L’nT,w, R’I)
- Perception / acoustic comfort analysis

- Contact :
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- Liens :
  - http://www.umrae.fr/

Scan me

L'Unité Mixte de Recherche en Acoustique Environnementale (UMRAE) est un laboratoire de recherche commun entre l'Ifsttar et le Cerema, 25·29 August 2024

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Abstract submission deadline	9 Feb 2024
Paper submission deadline	12 Apr 2024
Early registration deadline	21 Jun 2024