Acoustics of Building Materials based on Plant Fibers and Particles : Tools for Characterization, Modelling and Optimization

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ENTPE

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Towards eco-friendly buildings...

Report and measures

- Building : largest consumer of energy (≈ 44% in 2007) [cgd, 2010]

⇒ Grenelle de l'Environnement, Thermal reglementations (RT 2012)

⇒ 440 milliards €≈ 535 000 jobs [Grosselin, 2011]

New requirements for materials

- A need of thermally efficient materials
- Transition towards eco-friendly materials

Key solutions

- Eco-materials, especially bio-based materials

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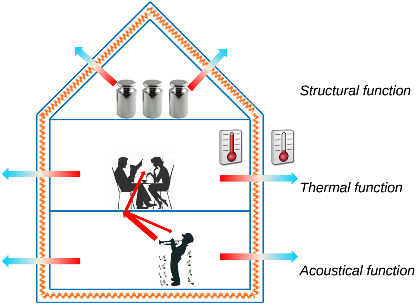
... and multifunctional materials



Example of hemp concrete

- A multifunctional material
  - ⇒ Thermics : λ = 0.06-0.15 $W.m^{-1}.K^{-1}$
  - ⇒ Mechanics : ρ_V = 200-800 $kg.m^{-3}$ and E = 1-100 MPa
  - ⇒ Acoustics : High α [Cerezo, 2005]
- An eco-friendly material
  ⇒ 1 m^2 stores 35 kg of CO_2 on a period of 100 years (LCA in [Boutin et al., 2005])

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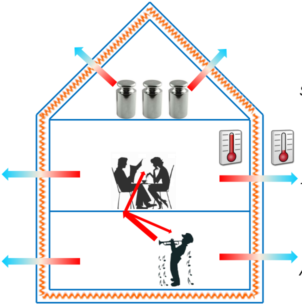

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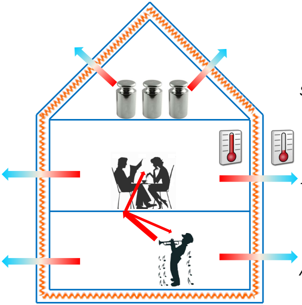

Structural function

Thermal function

Acoustical function

Hemp concrete buildings

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Hemp and products, their physical characteristics in litterature

Data of [Cerezo, 2005, Arnaud & Cerezo, 2001, Samri, 2008, Collet, 2004, Evrard, 2008, Ceyte, 2008, Placet et al., 2012] :

Plant

Particles

Parallelepipedical shape
Porosity : 57-78%
Pore size : 10-60 μm

Fibers

Cylindrical shape
Length : 5-55 mm
Diameter : 20-40 μm
Porosity : 2-16.2%
Pore size : 0.5-10 μm

⇒ Good thermal, modest mechanical, but mostly unknown acoustical properties...
⇒ Few litterature data describing the microstructure of hemp particles

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Plant

Stem

Particles

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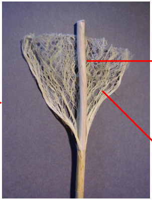

Stem

Shiv (loose particles)

Fibers

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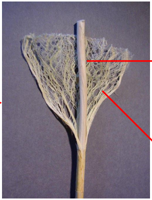

Stem

Shiv (loose particles)

Hemp concrete

Fibers

Hemp wool

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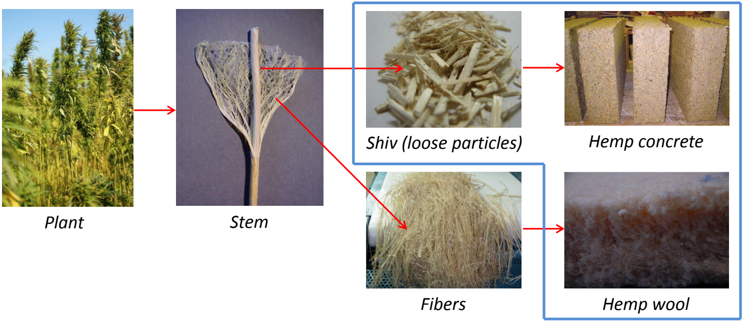

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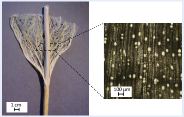
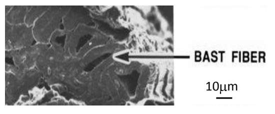
Specificities of hemp-based materials

Porous particles and fibers





[Garcia-Jaldon et al., 1998]

Anisotropy of particles

Data from [Ceyte, 2008] :

Mean length (*mm*)	4-9
Mean width (*mm*)	1-2.5
Mean thickness (*mm*)	≈0.5

Wide particle size distribution

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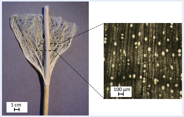

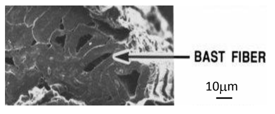

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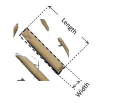

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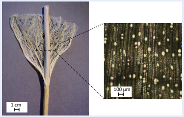

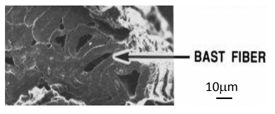

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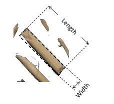

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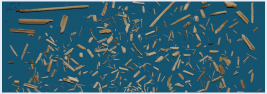
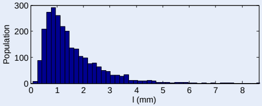
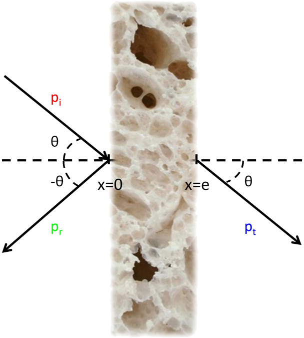




Acoustics of porous media



$$\alpha(\theta) = 1 - \left| \frac{p_r(\theta, x=0)}{p_i(\theta, x=0)} \right|^2$$

$$TL(\theta) = -10 \log \left| \frac{p_t(\theta, x=e)}{p_i(\theta, x=0)} \right|^2$$

Solid phase : Dissipation by mechanical effects

- Case of an elastic frame : Biot waves [Biot, 1956a, Biot, 1956b]
- Rigid frame hypothesis : $f > f_{dec}$ [Zwikker & Kosten, 1949]

Fluid phase : Dissipation by visco-inertial (ρ) and thermal effects (K)

$$\Delta p + \omega^2 \frac{\rho}{K} p = 0$$

- Observation level

At pore level	*At frame level*
[Johnson et al., 1987, Allard, 1993, Lafarge et al., 1997]	[Tarnow, 1996, Umnova et al., 2000, Boutin & Geindreau, 2010]

- Case of a multiscale porous network

Double porosity	*Pore size distribution*
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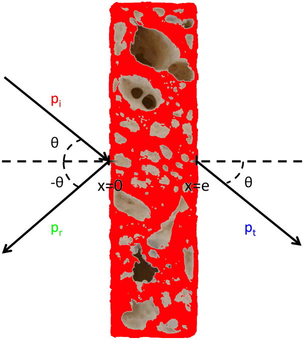

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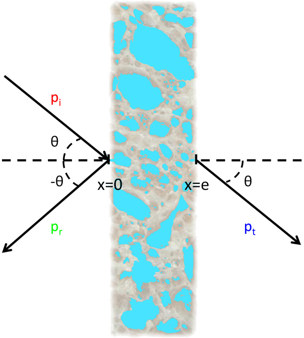

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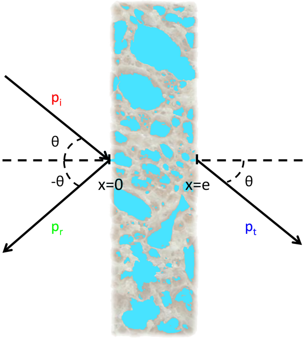

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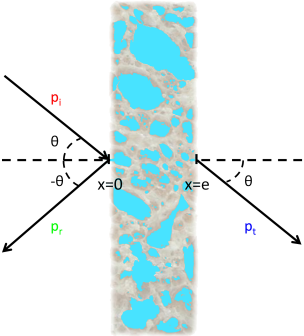

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Key Questions

- ? In what range are located the acoustical properties of hemp-based materials and how can we control them ?
- ? How can we take into account the atypical characteristics of hemp-based materials to predict and optimize their acoustical properties ?
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Approach of the thesis

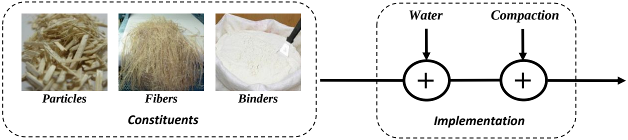
Particles

Fibers

Binders

Constituents

Approach of the thesis



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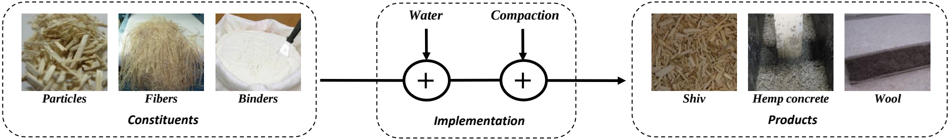


Approach of the thesis


Particles


Fibers


Binders

Constituents

Water *Compaction*

Implementation


Shiv


Hemp concrete


Wool

Products

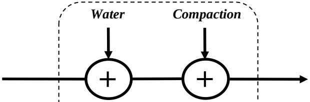
CHARACTERIZATION

Physical characteristics of constituents

- Particle size distribution
- Apparent density
- Frame density
- Porosity
- Pore size

Approach of the thesis

Constituents



Implementation

Products

CHARACTERIZATION

Physical characteristics of constituents

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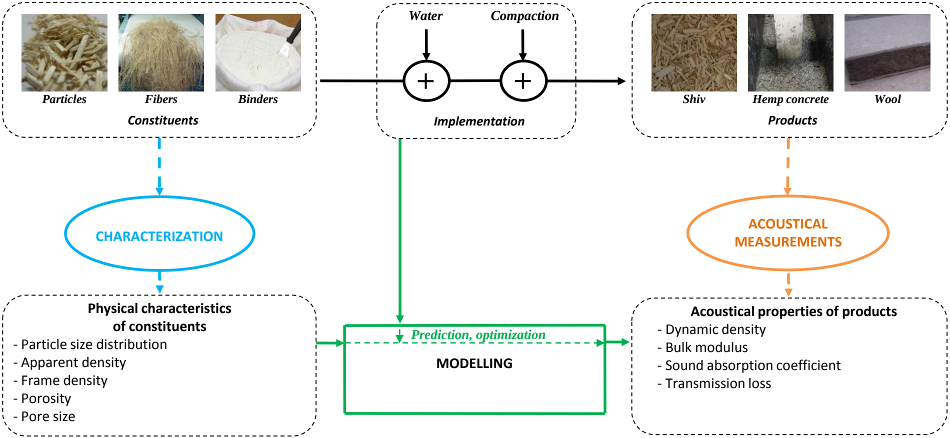
ACOUSTICAL MEASUREMENTS

Acoustical properties of products

- Dynamic density
- Bulk modulus
- Sound absorption coefficient
- Transmission loss

Approach of the thesis



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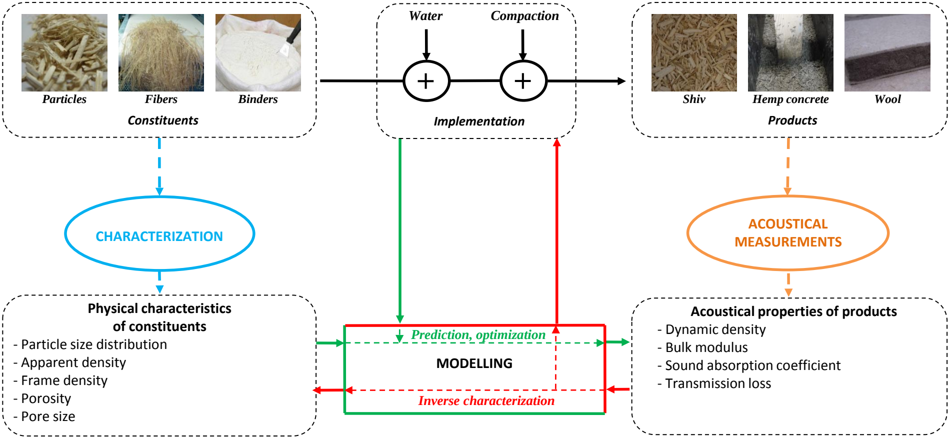

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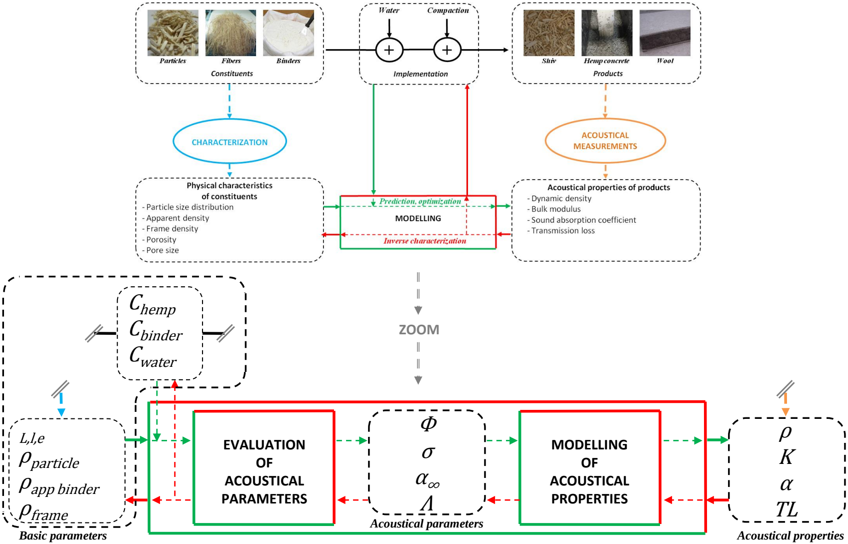


Materials tested in the thesis

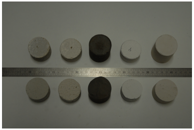
⇒ Wools

Hemp, Flax, Hemp+Flax, Jute

⇒ Shiv

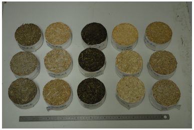
5 origins and 5 particle size distributions

⇒ Binders



5 types (lime and cement)

⇒ Hemp concretes



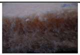
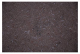
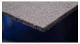
3 sets of formulations

Binders and shiv from program PREBAT/ADEME/2C2E

Content

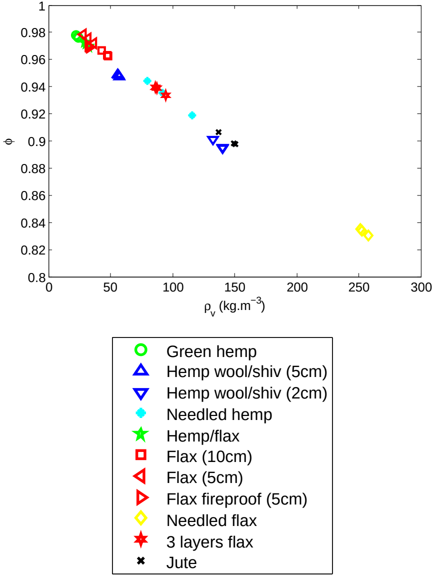
Content

Characteristics of wool samples

Material	Picture	e (mm)	ρ_v $(kg.m^{-3})$
Green hemp		100	21
Hemp wool/shiv		20 & 50	126 & 57
Needled hemp		8	95
Hemp/flax		100	32
Flax		50, 50 & 100	33, 32
Needled flax		8	252
3 layers flax		5/40/5	179/78/179
Jute		10	160

Acoustical parameters of wools

- Porosity
  - ⇒ $\rho_{frame} \in [1000\,;1500\ kg.m^{-3}]$
  - ⇒ $\phi \in [80\,;98\%]$
- Resistivity
  - ⇒ $\sigma \in [1000\,;300000\ N.m^{-4}.s]$
  - ⇒ Increase with ρ_V



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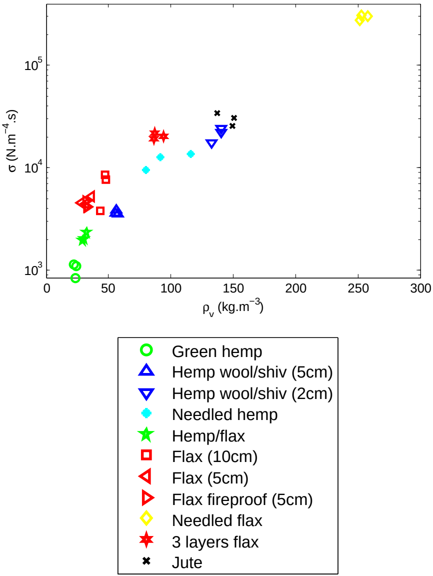
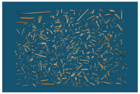
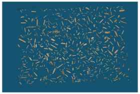
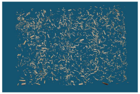
- Porosity
  - $\Rightarrow$ $\rho_{frame} \in [1000\,;1500\ kg.m^{-3}]$
  - $\Rightarrow$ $\phi \in [80\,;98\%]$
- Resistivity
  - $\Rightarrow$ $\sigma \in [1000\,;300000\ N.m^{-4}.s]$
  - $\Rightarrow$ Increase with ρ_v

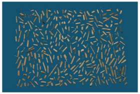
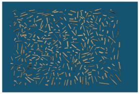
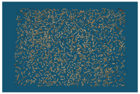
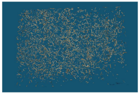


Characteristics of shiv

Material	Picture	ρ_v $(kg.m^{-3})$
CA		100-150
CB		100-140
CC		100-160
CD		100-140
CE		100-140
	⊢⊣ = 10 *cm*	

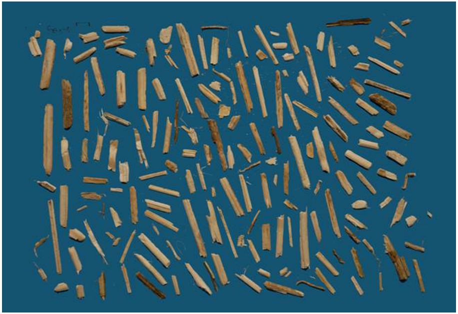
Origins : LCDA, BAFA, HEMCORE, EUROCHANVRE, FNPC

Characteristics of shiv

Material	Picture	ρ_v $(kg.m^{-3})$
CB1		80-120
CB2		90-130
CB3		90-130
CB4		100-140
CB5		110-150
	⊢⊣ = 10 cm	

Characteristics of shiv

- Analysis of PSD
  - Initial picture
  - Treatment
  - Image analysis
- Results
  - Comparison of shiv : case of L/W
  - Lognormal particle size distribution



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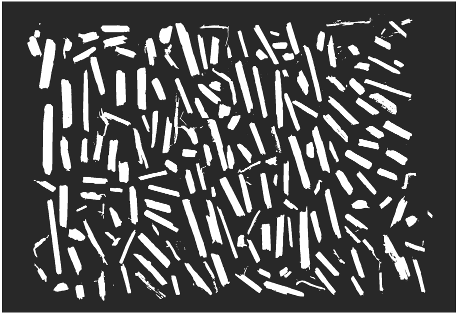

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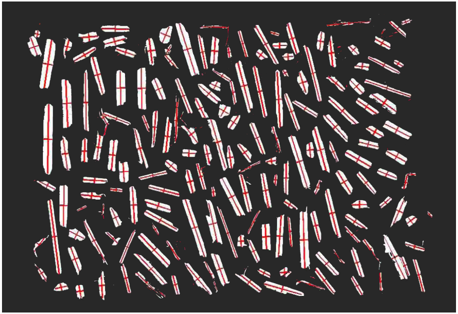

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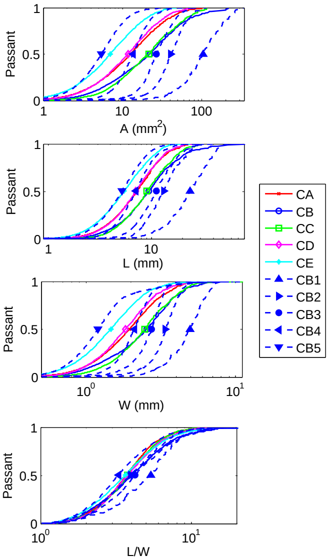

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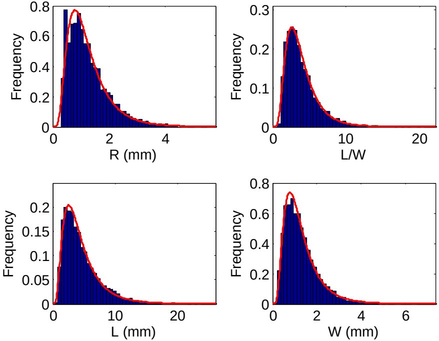

- Analysis of PSD
  - Initial picture
  - Treatment
  - Image analysis
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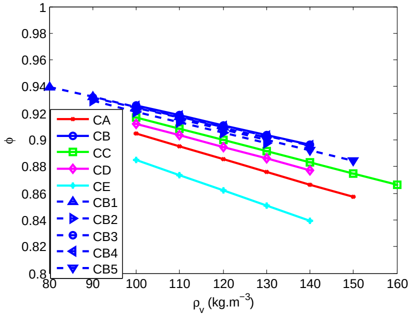
  - Comparison of shiv : case of L/W
  - Lognormal particle size distribution

Acoustical parameters of shiv

- Porosity
  - ⇒ $\phi \in$ [84% ; 94%]
  - ⇒ ϕ not function of particle size
- Resistivity
  - ⇒ σ up to 10000 $N.m^{-4}s$
  - ⇒ Very sensitive to particle size
- Tortuosity
  - ⇒ Very high values compared to classical media



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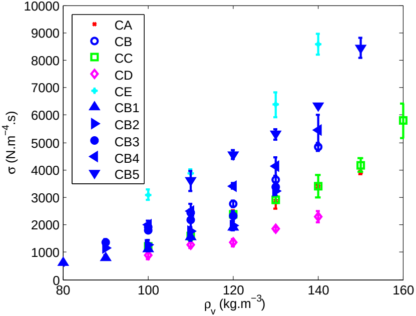

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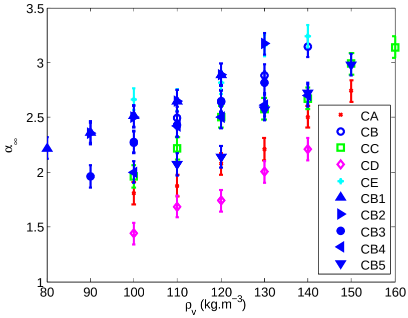
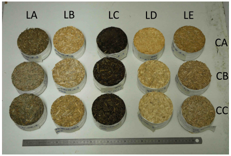
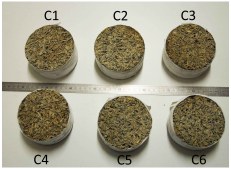


Characteristics of hemp concretes

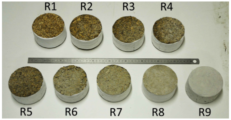
3 sets of formulations to investigate ...



⇒ Effect of constituents : 5 binders (LA-LE), 3 shiv (CA-CC) (C_{shiv} = $110 kg.m^{-3}$, C_{binder} = $220 kg.m^{-3}$)



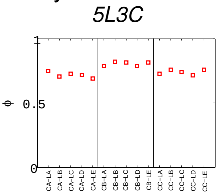
⇒ Effect of density : Formulation CA-LA, $C_{shiv} \in [90; 140 kg.m^{-3}]$ (Ratio binder-to-shiv $B/S = 2$)

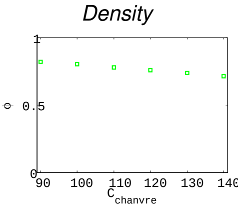


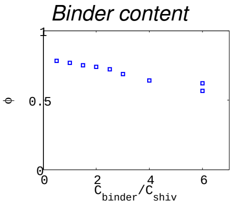
⇒ Effect of ratio binder-to-shiv : Formulation CA-LA, $B/S \in [0.5; 9]$ ($C_{shiv} = 110 kg.m^{-3}$)

Acoustical parameters of hemp concretes

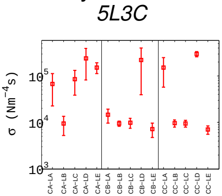
- Porosity

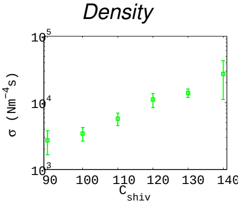


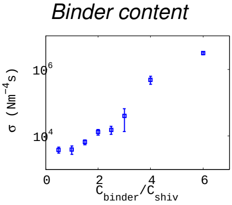




- Resistivity





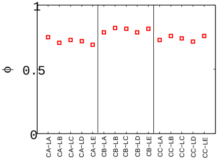


⇒ Hemp concretes behavior essentially controlled by binder content, material density and binder type

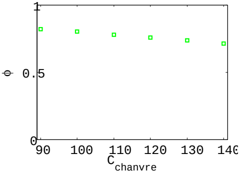
Acoustical parameters of hemp concretes

- Porosity

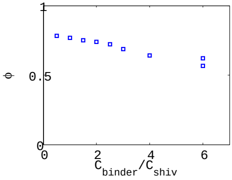
5L3C



Density

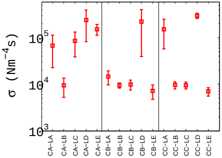


Binder content

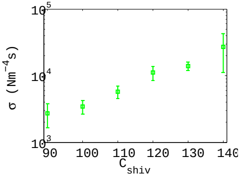


- Resistivity

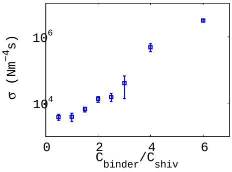
5L3C



Density



Binder content

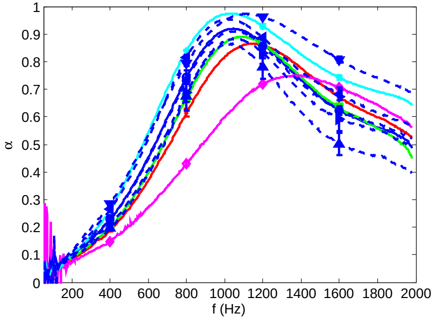


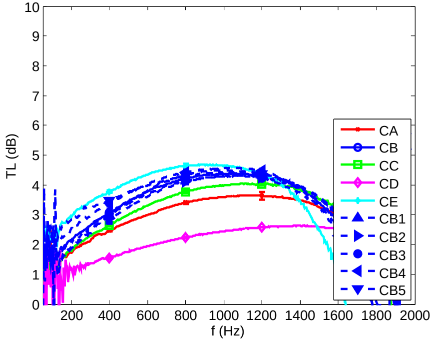
⇒ Hemp concretes behavior essentially controlled by binder content, material density and binder type

Content

Effect of constituents : Origin and granulometry of shiv

On shiv



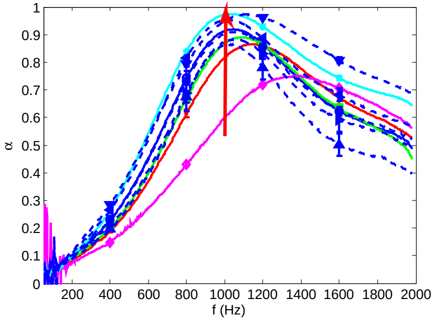


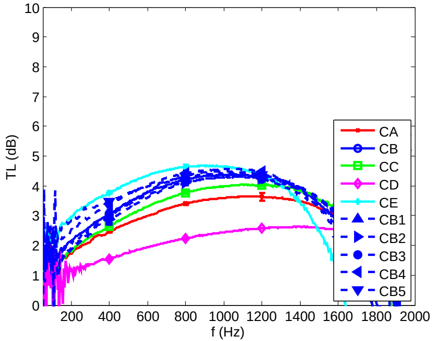
⇒ Increase of α with smaller particles

⇒ *TL* not function of particle size for a given shiv

Effect of constituents : Origin and granulometry of shiv

On shiv

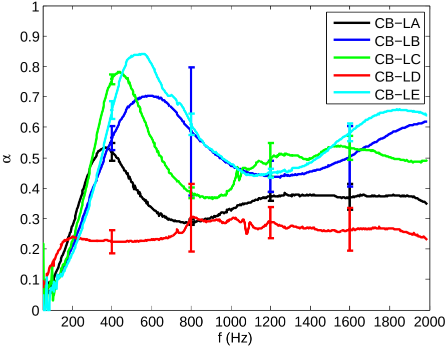


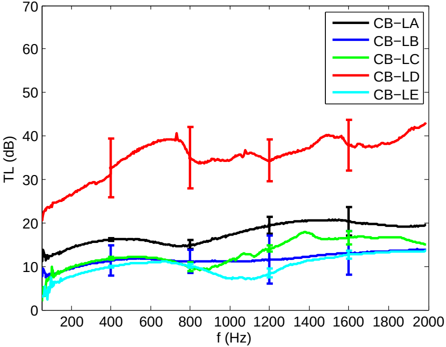


⇒ Increase of α with smaller particles
⇒ *TL* not function of particle size for a given shiv

Effect of constituents : Type of binder

On hemp concretes





⇒ Acoustical properties controlled by permeability

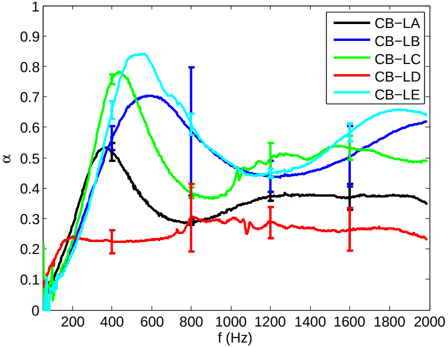
-LD ↦ high σ,

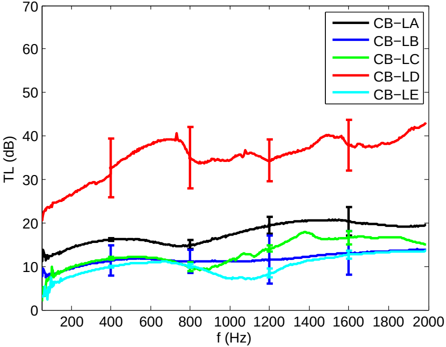
-LA and LC ↦ intermediate σ,

-LB and LE ↦ low σ

Effect of constituents : Type of binder

On hemp concretes





$\Rightarrow$ Acoustical properties controlled by permeability

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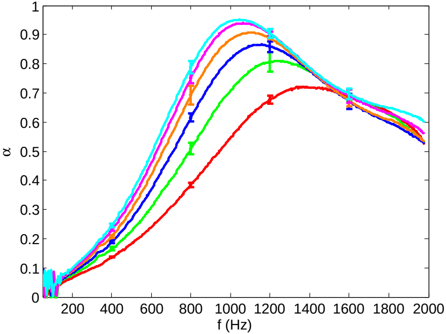
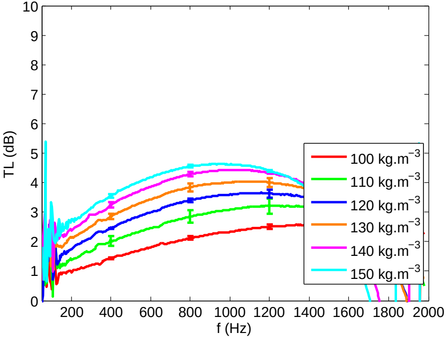
-LA and LC $\mapsto$ intermediate σ,

-LB and LE $\mapsto$ low σ

Effect of implementation : Density

On shiv



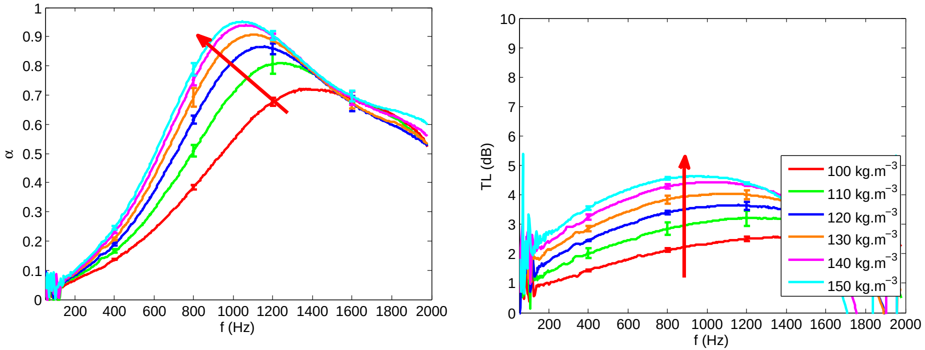


⇒ Gain of α and *TL* in the tested frequency range

⇒ Move of absorption peak to lower frequencies

Effect of implementation : Density

On shiv



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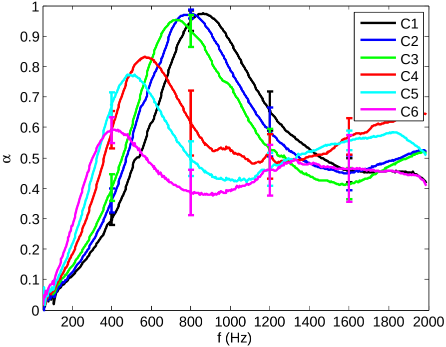
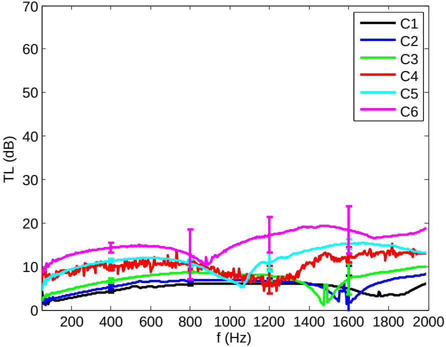
Effect of implementation : Density

On hemp concretes





⇒ Decrease of α and increase of *TL* in the tested frequency range

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Effect of implementation : Density

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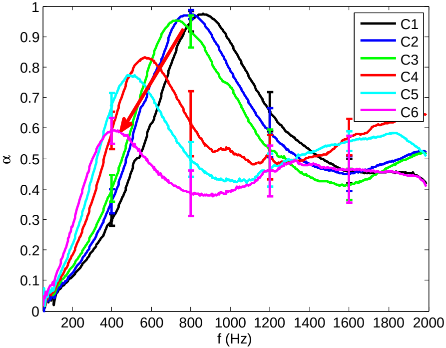

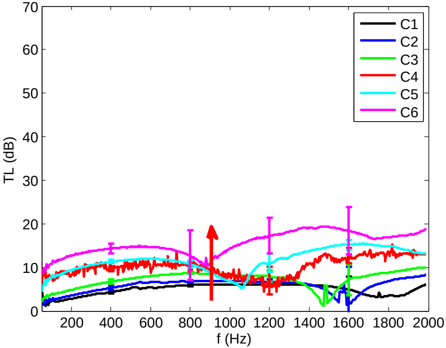

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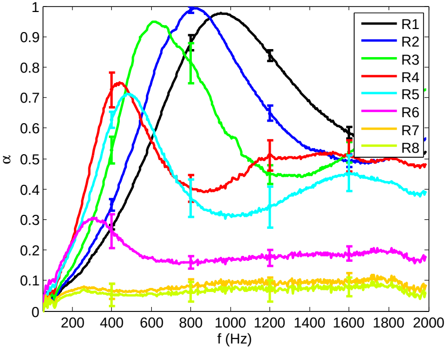
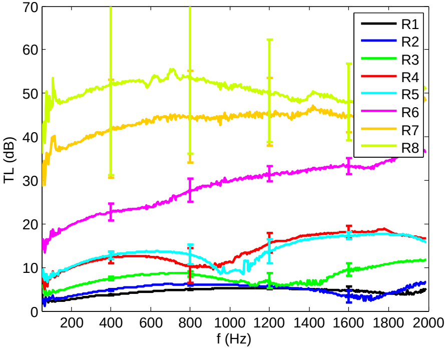
Effect of implementation : Binder content

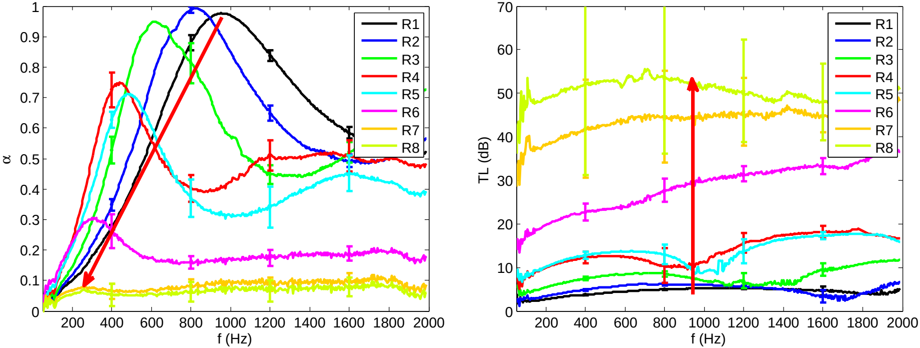




⇒ Gradually change from (high α, low TL) to (low α, high TL)

See : Glé, Gourdon, Arnaud. *Acoustical properties of materials made of vegetable particles with several scales of porosity*, Appl. Acoust., 2011

Effect of implementation : Binder content



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Content

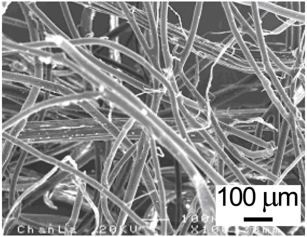
Wools : Description

- Characteristics

	Mineral wools	Plant wools
ρ_{frame} $(kg.m^{-3})$	$\approx$ 2600	1000-1500
Diameter (μm)	1-10	20-40
Micro-porosity	-	2-16 %

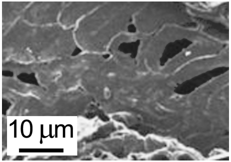
- Multiscale porosity

Inter-fibers pores



[Collet, 2004]

Intra-fiber pores



[Garcia-Jaldon et al., 1998]

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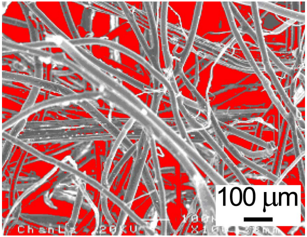

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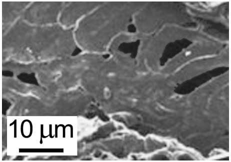

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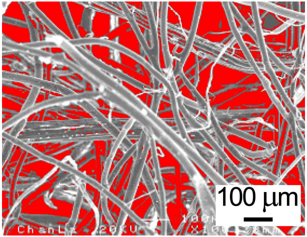

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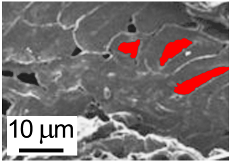
Intra-fiber pores



[Garcia-Jaldon et al., 1998]

Wools : Modelling

Rigid frame hypothesis

- $f_{dec} < 200\ Hz$ for most samples

Analysis of the double porosity behaviour

Viscous and isothermal behaviours in intra-fiber pores

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

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

Models used and parameters

- Fibrous models [Delany & Bazley, 1970, Garai & Pompoli, 2005, Tarnow, 1996] : ϕ and σ measured
- JCAL model [Johnson et al., 1987, Lafarge et al., 1997] : ϕ and σ measured, α_∞, Λ, Λ', and Θ_0 indirectly measured from (ρ, K) [Panneton & Olny, 2006, Olny & Panneton, 2008]

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Analysis of the double porosity behaviour

Viscous and isothermal behaviours in intra-fiber pores

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

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

Models used and parameters

- Fibrous models [Delany & Bazley, 1970, Garai & Pompoli, 2005, Tarnow, 1996] : ϕ and σ measured
- JCAL model [Johnson et al., 1987, Lafarge et al., 1997] : ϕ and σ measured, α_∞, Λ, Λ', and Θ_0 indirectly measured from (ρ, K) [Panneton & Olny, 2006, Olny & Panneton, 2008]

Wools : Modelling

Rigid frame hypothesis

- $f_{dec} < 200\ Hz$ for most samples

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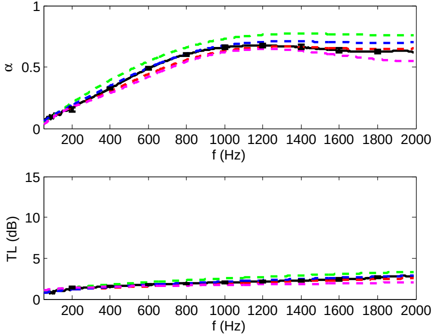
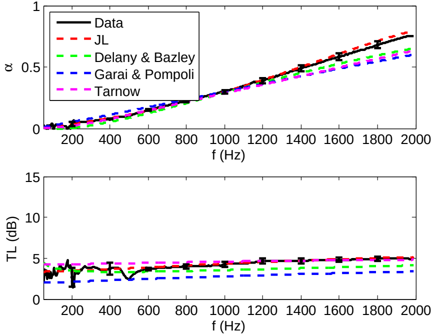
Wools : Results

Green hemp



Hemp wool/shiv



⇒ Accuracy of $\pm 10\%$ on α and $\pm 2dB$ on *TL* for all models (except for resistive samples)

⇒ Use of JCAL model not relevant for such materials

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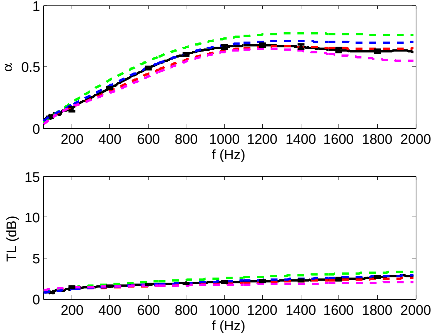

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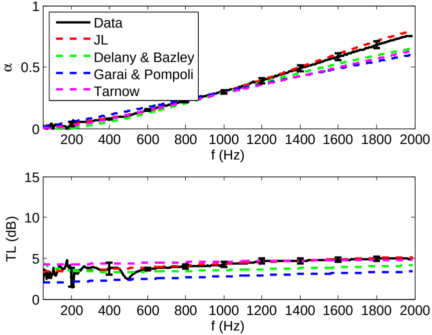

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Shiv : Description

- Characteristics

Classical beds

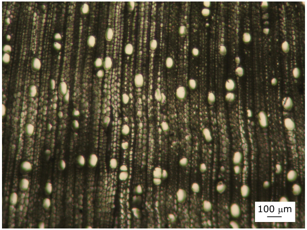
Shiv

	Classical beds	Shiv
Shape	Spherical	Parallelepipedical
Particle size distribution	Single-sized	Lognormal
Micro-porosity	-	57-78 %

- Multiscale porosity

Inter-particle pores

Intra-particle pores



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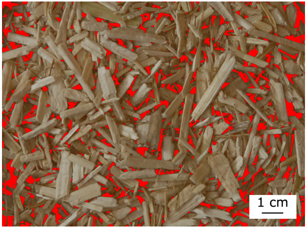

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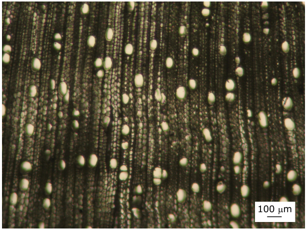

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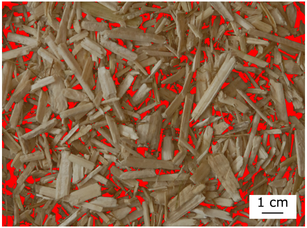

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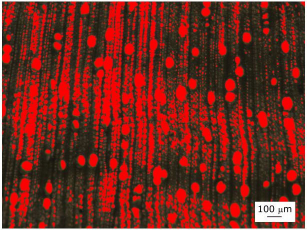


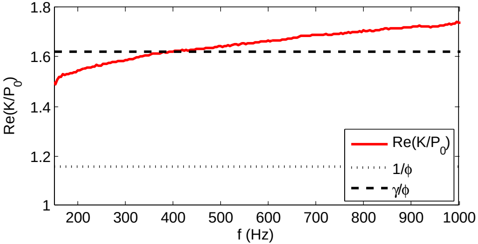
Shiv : Analysis of the double porosity behaviour

$\Re(\frac{K}{P_0}) > \frac{\gamma}{\phi}$

⇒ Classical porous models do not work in this case

⇒ Multiscale analysis

- Intra-particles pores
- Inter-particles pores



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  $\Rightarrow K \approx K_{inter}$
- $\omega \gg \omega_d \Rightarrow \sigma_{intra} \gg \frac{P_0}{\phi_{intra}\omega l^2_{inter}} > 80000 N.m^{-4}.s$
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⇒ Only inter-particle pores take part in the dissipation

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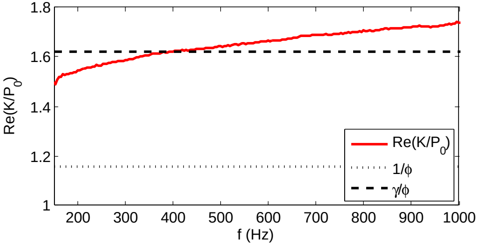

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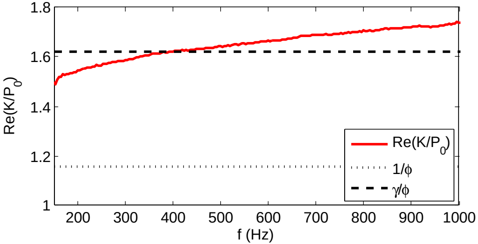

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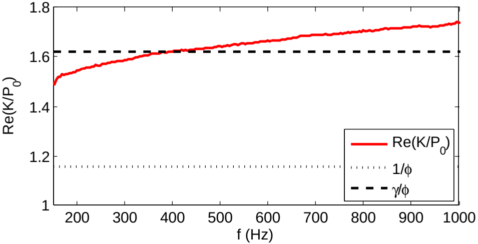

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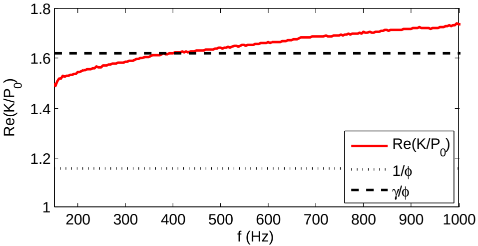

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Shiv : Models used and parameters

Models

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- Visco-inertial effects : [Johnson et al., 1987]
- Thermal effects : [Zwikker & Kosten, 1949]

Characterization process

1. Impedance tube measurement using three positions of microphone [Iwase et al., 1998] $[100; 2000Hz]$
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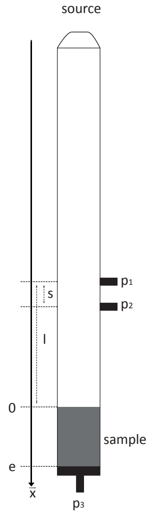

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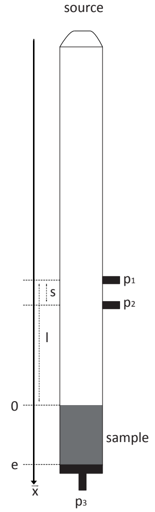
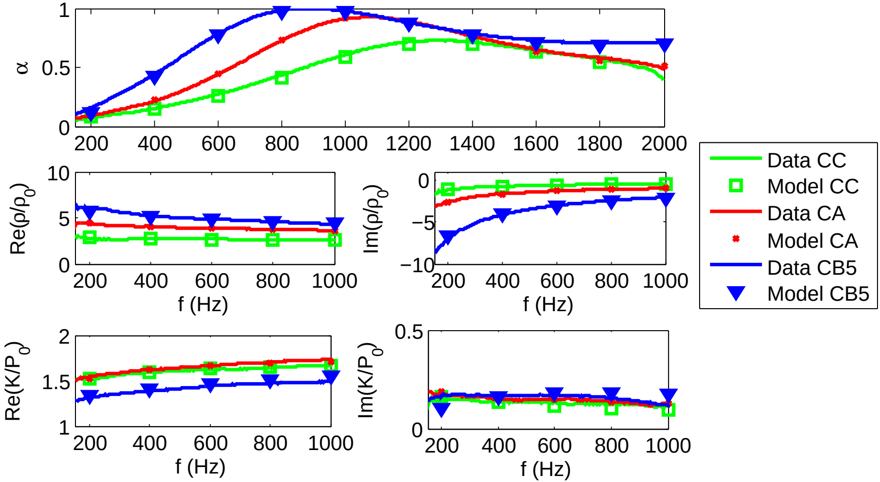


Shiv : Results



Hemp concretes : Modelling

- Behaviour of binder

Binder	σ (10^6 $N.m^{-4}.s$)	r (μm)
LA	125	1.51
LB	135	1.71
LC	143	3.11
LD	56	2.12
LE	201	1.99

Binders are very resistive with small pores
⇒ High contrast of permeability between intra-binder and inter-particle pores ?

- Identification of the effective porosity

Three hypothesis :

- H1 : Intra-particule pores do not participate
- H2 : Intra-binder pores do not participate
- H3 : Neither intra-particule nor intra-binder pores do participate

⇒ For most samples, only inter-particle pores take part in the dissipation

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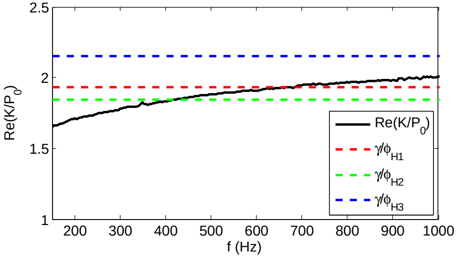

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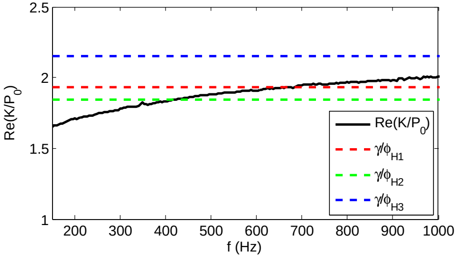

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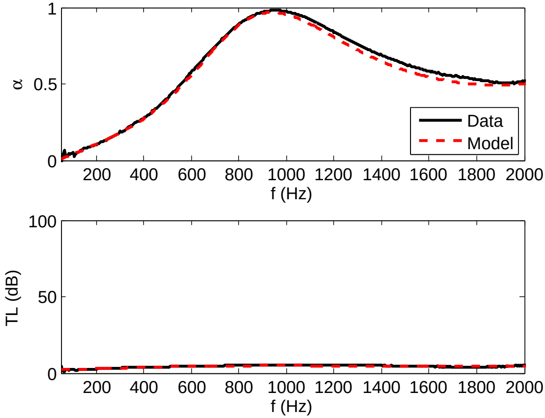
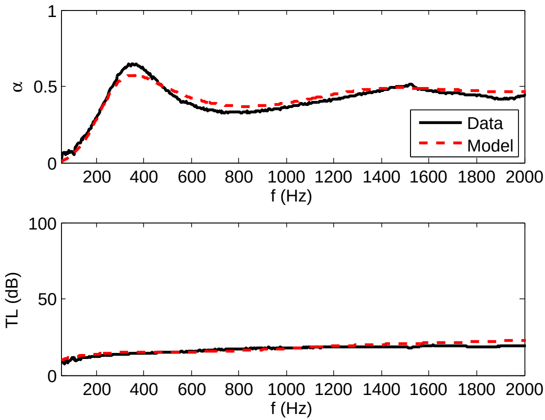
Hemp concretes : Results

Roof formulation : Ratio Binder/Shiv = 0.5



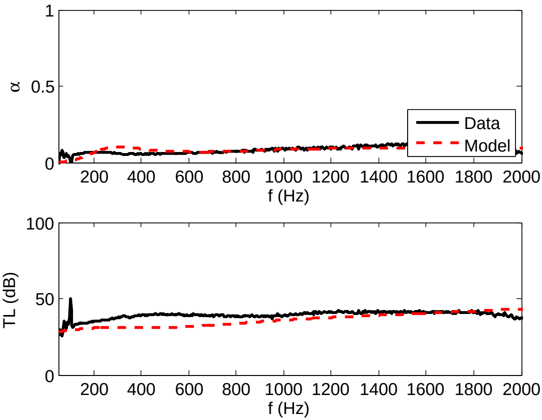
Hemp concretes : Results

Wall formulation : Ratio Binder/Shiv = 2



Hemp concretes : Results

Coating formulation : Ratio Binder/Shiv = 4



Content

Apparent density, porosity and thickness of particles from ϕ_{inter}

- Inter-particle porosity

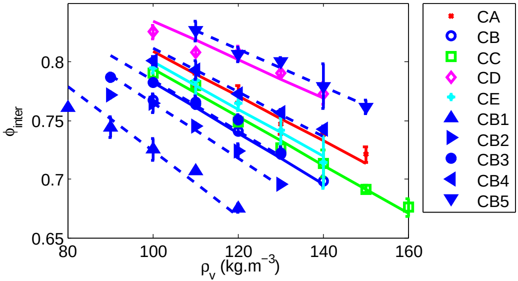
$$\phi_{inter} = 1 - \frac{\rho_v}{\rho_{particle}}$$

- Intra-particle porosity

$$\phi_{intra} = 1 - \frac{\rho_{particle}}{\rho_{frame}}$$

- Mean thickness of particles

$$\bar{E} = \rho_s / \rho_{particle}$$



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$\rho_{particule}$ $(kg.m^{-3})$	523	460	486	605	499	362	425	463	531	633

See : Glé, Gourdon, Arnaud. *Modelling of the acoustical properties of hemp particles*, Const. Build. Mat., 2012

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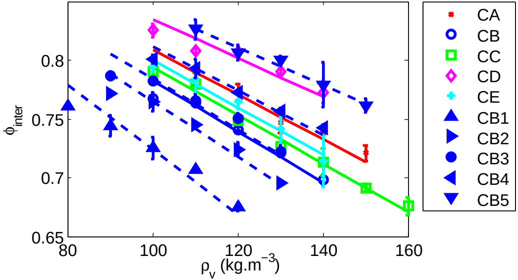

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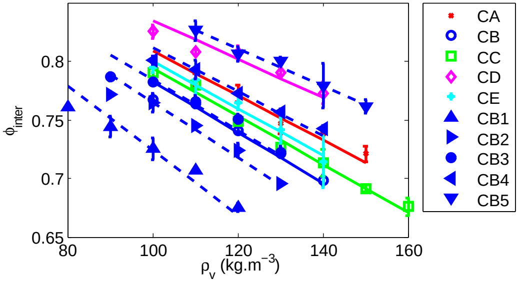

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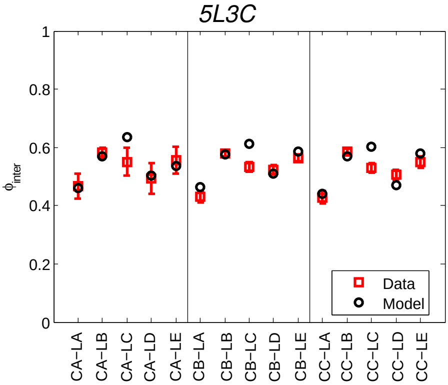
Behavior of hemp concrete for ϕ_{inter}

- Inter-particle porosity

$$\phi_{inter} = 1 - \frac{C_{binder}}{\rho_{apparent\ binder}} - \frac{C_{hemp}}{\rho_{particle}}$$



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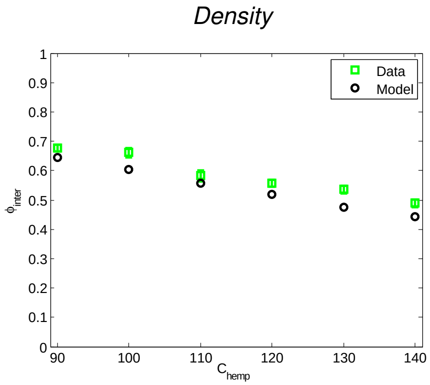

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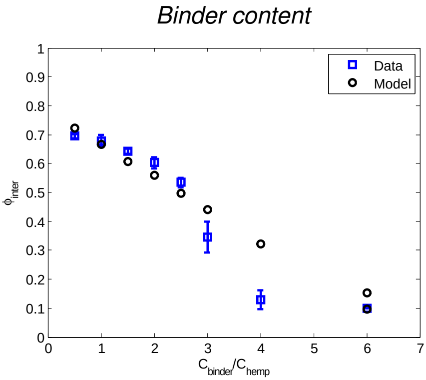

Identification of the radius of fibers from σ

- Empirical and theorical fibrous models
  [Mechel, 1976, Bies & Hansen, 1980, Garai & Pompoli, 2005, Tarnow, 1996]

$$\sigma = A\mu \frac{F(\phi)}{R_f^2}$$

⇒ Can yield to an estimate of the fiber radius R_f

⇒ Results with Tarnow model

Material	R_f (μm) Estimated from σ	R_f (μm) [Olesen & Plackett, 1999]
Green hemp	32	5-25
Hemp wool/shiv (5 *cm*)	29	5-25
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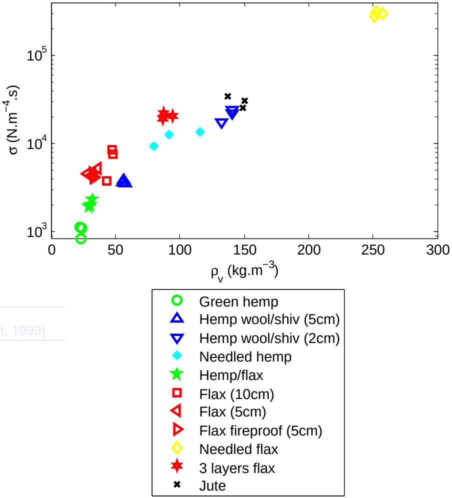
Needled hemp	19	5-25
Hemp/flax	26	3-25
Flax (10 *cm*)	17	3-19
Flax (5 *cm*)	15	3-19
Flax fireproof (5 *cm*)	19	3-19
Needled flax	9	3-19
Jute	17	5-13



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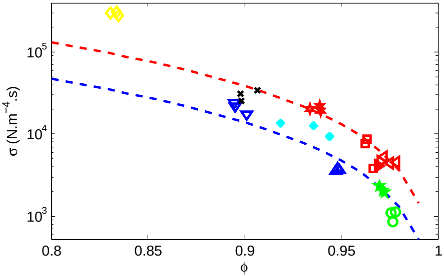
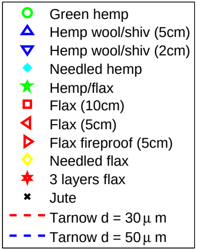


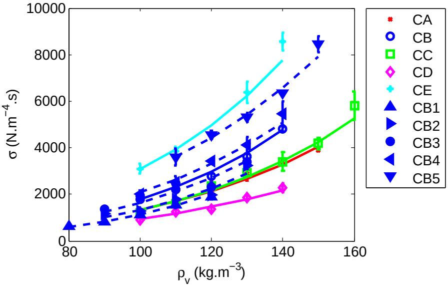


Identification of a characteristic particle size from σ

- Empirical and theorical granular models

[Attenborough, 1993, Prieur du Plessis & Woudberg, 2008, Voronina & Horoshenkov, 2003, Umnova et al., 2000, Boutin & Geindreau, 2010]

$$\sigma = A\mu \frac{F(\phi)}{R^2_{particle}}$$



⇒ Can yield to an estimate of the particle size $R_{particle}$

⇒ Results with Boutin & Geindreau model

Shiv	CA	CB	CC	CD	CE	CB1	CB2	CB3	CB4	CB5
$R_{particle}$	384	389	421	384	268	688	502	404	302	208

⇒ Correlation between $R_{particle}$ and $\bar{E}$ (mean thickness)

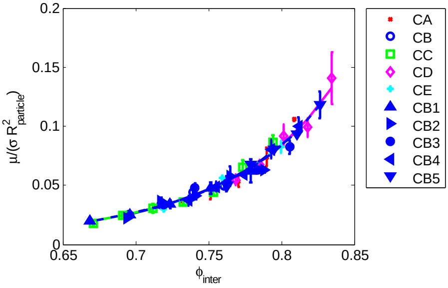
$$R_{particle} = 0.642\bar{E} + 0.130 \qquad (R^2 = 0.939)$$

Identification of a characteristic particle size from σ

- Empirical and theorical granular models

[Attenborough, 1993, Prieur du Plessis & Woudberg, 2008, Voronina & Horoshenkov, 2003, Umnova et al., 2000, Boutin & Geindreau, 2010]

$$\sigma = A\mu \frac{F(\phi)}{R^2_{particle}}$$



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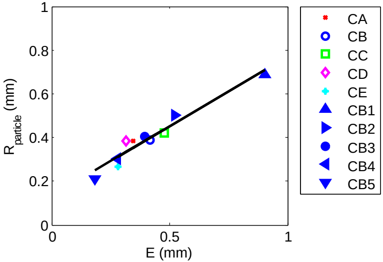

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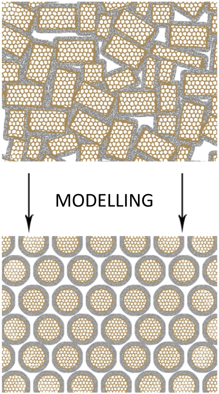
Extension of the resistivity model to hemp concretes

- Evaluation of the equivalent aggregate size



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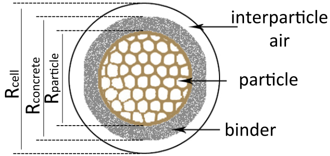

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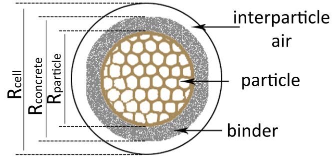

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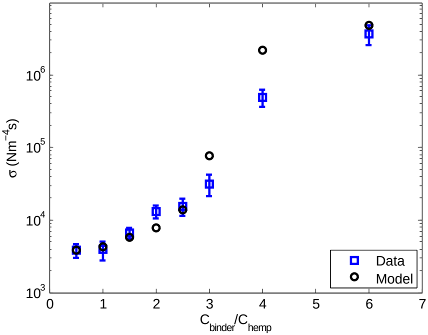
Binder content



Identification of a shape factor of shiv from α_∞

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⇒ Results with Attenborough model

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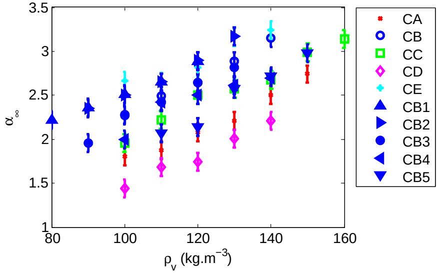

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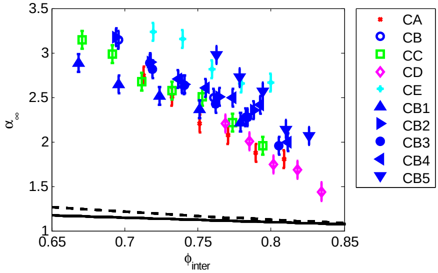

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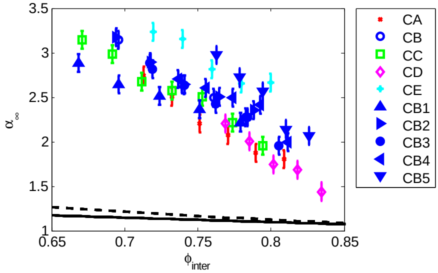

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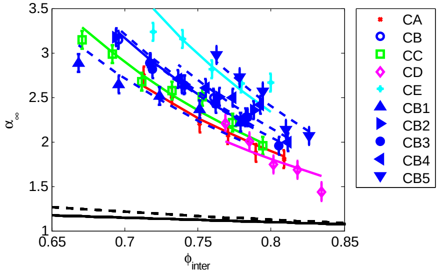

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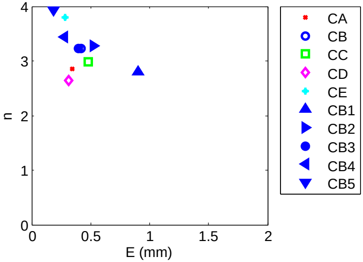

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Content

Models and parameters

Granular model with single-sized spherical aggregates [Boutin & Geindreau, 2010]

- ϕ_{inter} : Estimate from $\Re(K)$ using Zwikker and Kosten model
- $R_{particle}$: Inversion from σ

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- σ : Indirect characterization from $\Im(\rho)$
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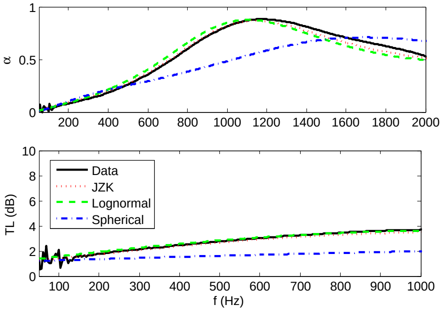
Suitability of the models

- Suitability of the models & discussion
  - ⇒ Granular approach is not suitable for this material (shape and PSD are not taken into account)
  - ⇒ For a given (ϕ_{inter}, $R_{particle}$), shiv has greater α (LF) and *TL* than spherical aggregates



Pore size distribution : Image analysis and acoustical data

- Limitations of image analysis
  - Sensitivity to the threshold
  - Representativity of the top surface ?
    $\Rightarrow$ Need of further investigations (3D)
- Acoustical investigation
  - $\Rightarrow$ σ_s from acoustical properties
  - $\Rightarrow$ $\bar{r}$ from [Horoshenkov et al., 2007]

$$\bar{r} = \left(\frac{8\alpha_\infty \mu}{\sigma \phi_{inter} e^{\left(2(\sigma_s \ln 2)^2\right)}} \right)^{1/2}$$

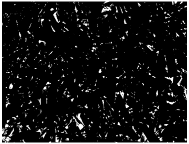
- Consistence with JZK approach

[Horoshenkov et al., 2012]

$$\Lambda = \bar{r} e^{\left(-3/2(\sigma_s \ln 2)^2\right)}$$

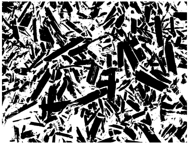
Original picture

Pores, Thresh = 0.2



Pores, Thresh = 0.3

Pores, Thresh = 0.4



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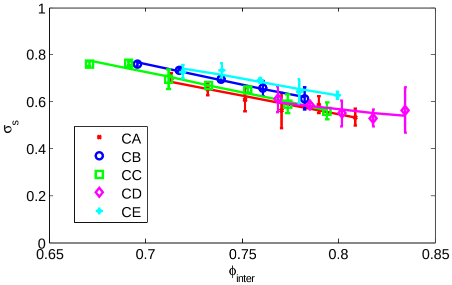

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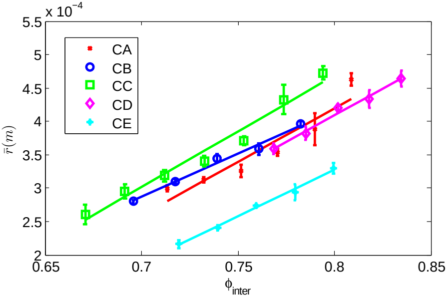

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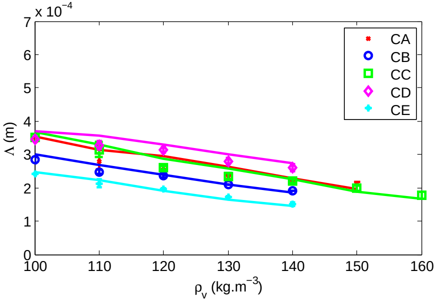

Relationship between pore and particle size

- Lognormal particle size distribution ($\bar{R}$, σ_R)
- Lognormal pore size distribution ($\bar{r}$, σ_s)
- Linear or nonlinear relationship considered [Hwang & Choi, 2006] : $r = \left(\frac{R}{u}\right)^{1/v}$
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$\Rightarrow$ Comparison for shiv ($\phi_{inter} = 0.78$)

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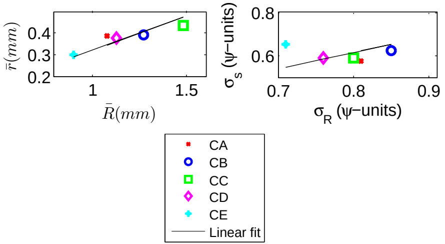

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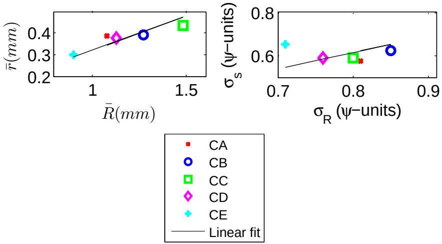

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Investigation of the variability of particles characteristics

- Sources of variability
  - Environment parameters
    - Weather and climate
    - Ground properties and history
  - Cultivation parameters
    - Planting
    - Harvesting
    - Post-treatment
- Experimental program
  - 50 shiv from FNPC (2009 → 2011)
  - 7 variability factors controlled
    ⇒ Variety, Planting date, Planting density, Nitrogen quantity
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- Approach
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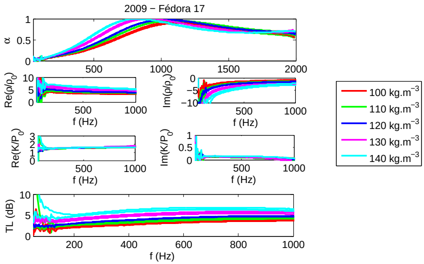

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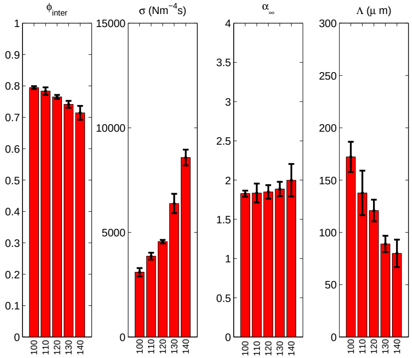

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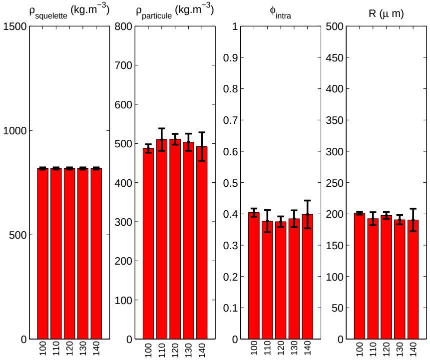
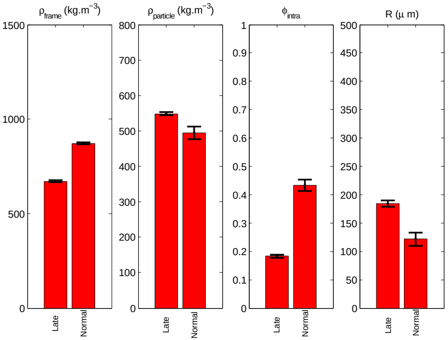


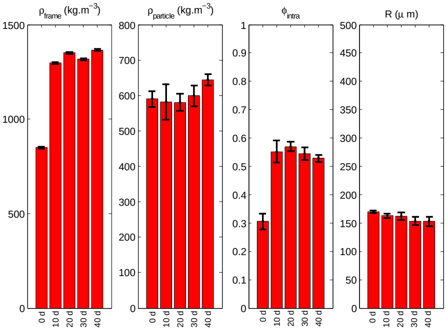
Cultivation parameters : Planting

- Planting date
  ⇒ Significant effect on density, porosity and particle size



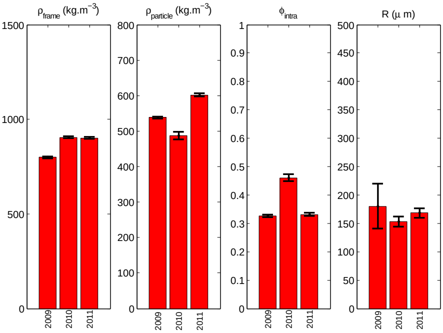
Cultivation parameters : Harvesting

- Retting
  ⇒ Significant effect on frame density and porosity



Environment parameters : Meteorological aspect

- Evolution between 2009 and 2011
  ⇒ Signifiant effect on density, porosity and particle size
- Meteorogical data
  ⇒ 2010 more wet and sunny



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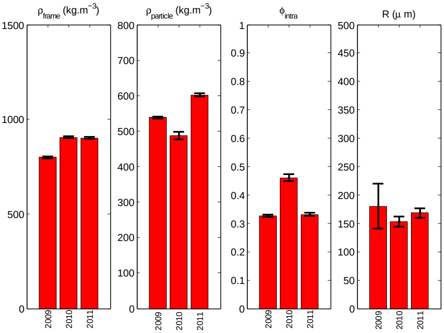


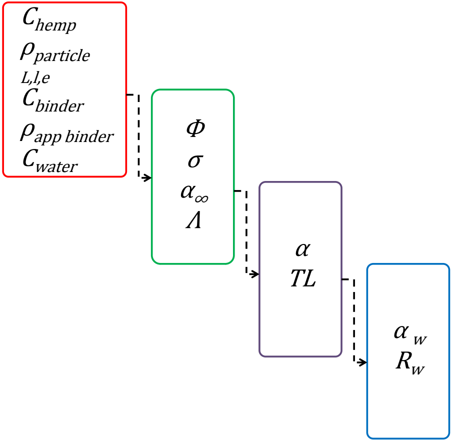
Content

Optimizing the formulation

- Range of variation of basic parameters

Parameters	[min ; max]
C_{hemp}	[100 ; 150] $kg.m^{-3}$
$\rho_{particle}$	[400 ; 600] $kg.m^{-3}$
$\bar{E}$	[0,2 ; 0,5] mm
n	[2 ; 3]
C_{binder}	[0 ; 900] $kg.m^{-3}$
$\rho_{apparent\ binder}$	[1000 ; 2000] $kg.m^{-3}$

- Evaluation of acoustical performance
  1. Random selection of basic parameters
  2. Calcul of corresponding acoustical parameters
  3. Evaluation of acoustical properties
  4. Calcul of acoustical indicators
- Results for thickness of 20 and 30 cm
  - ⇒ α_W up to 0.95 and R_W up to 50 dB
  - ⇒ Difficulty of combining good α_W and R_W



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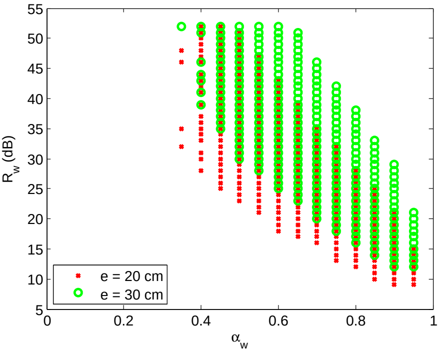

Optimizing the multilayer structure [Perrin, 2011]

- Samples
  - 3 samples : 1m × 1.4m
  - Coating(2*cm*)/Hemp concrete(20*cm*)/Coating(2*cm*)
  - Use of a timber frame (1 sample), different coatings & densities
- Experimental results
  - ⇒ Effect of density, but none of timber frame
  - ⇒ Gain of about 10 *dB* thanks to coatings
  - ⇒ Apparition of a new resonance
- Fluid-equivalent and poroelastic multilayer modellings
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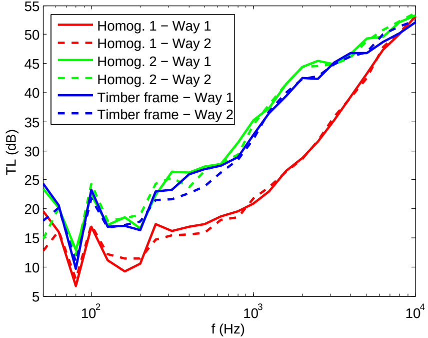

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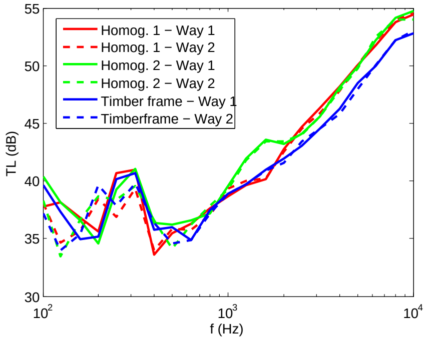

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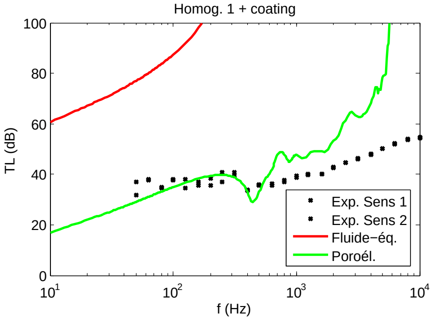

Optimizing the geometry using surface irregularities [Debrabant, 2010]

- Process
  1. Experimental investigations using arbitrary shapes
  2. Research of the optimal configurations (genetic algorithm)
     - Excitation at normal incidence
     - Criterion = Max $\int_{50Hz}^{550Hz} \alpha(f)df$
     - Constrained geometry : symetry, free or crenel shape.
- Results
  1. First experimental investigations
  2. Research of the optimal configurations
     - Free shape

     ⇒ Apparition of resonators
     ⇒ Difficulty of conception

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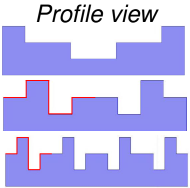
     ⇒ α lowers (<10%)
     ⇒ Friendly shape for conception



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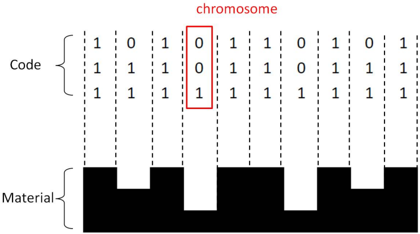

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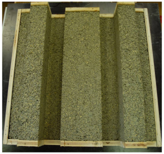
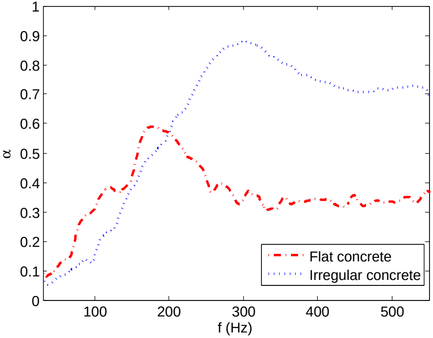
Flat concrete

Irregular concrete





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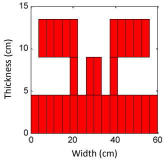

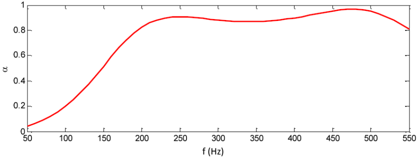

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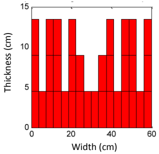

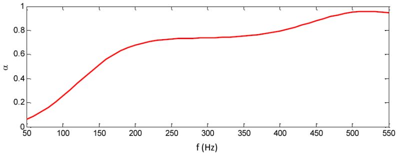

In situ application of plant wool for acoustic correction

- The project
  - Develop a bio-based wool for acoustic correction in a shopping mall
  - Multifunctional challenge
    - Optimizing sound absorption
    - Providing fireproof properties
    - Mechanical resistance
- Selection of the type of sample
- Initial samples testings, 2 kinds of fibers
  - ⇒ Minor effect of the kind of fiber
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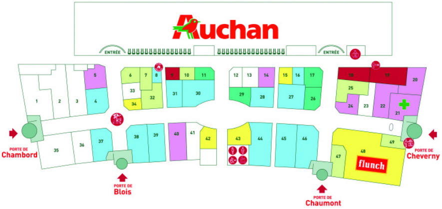

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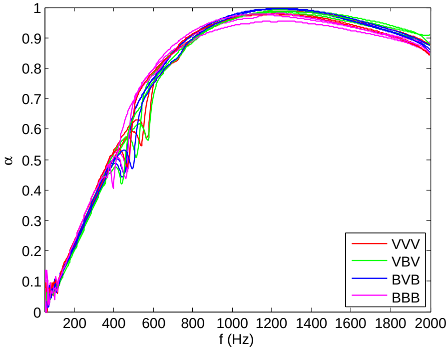

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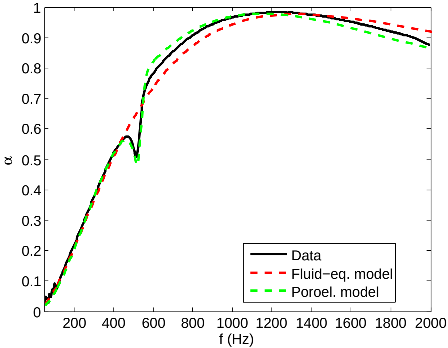

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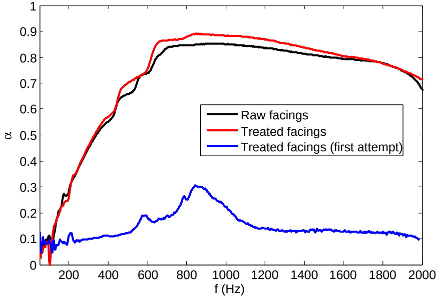

Content

Conclusions and Outlooks

Characterization

✓ Wide range of acoustical properties

✓ Identification of the key levers (binder content)

↪ Study water content as optimization way

↪ Characterize larger samples for high binder contents

↪ Comparison of acoustical characterization with imagery data

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Modelling

✓ ϕ_{intra} masked by ϕ_{inter}

✓ Characterization of microstructure from acoustical data

✓ Effect of shape and size distribution of particles

↪ Further investigation for high binder contents

↪ Introduce more parameters ?

↪ Effect of anisotropy of shiv

Optimization

✓ Controlling the formulation can yield to high level acoustical properties

✓ Possibility of improving TL with coatings

✓ Particularly strong effect of surface irregularities

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Thank you for your attention !

Acoustics of Building Materials based on Plant Fibers and Particles : Tools for Characterization, Modelling and Optimization

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February 15th, 2013

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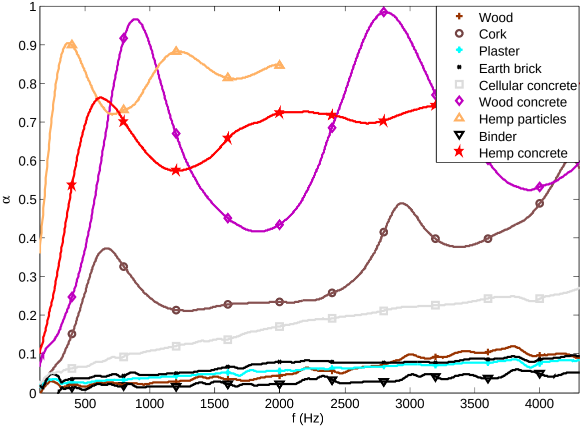
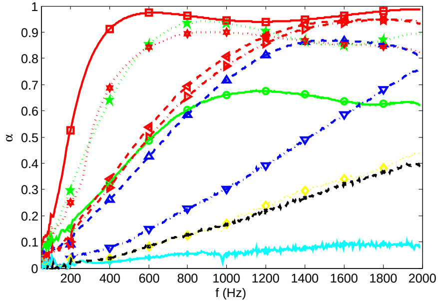
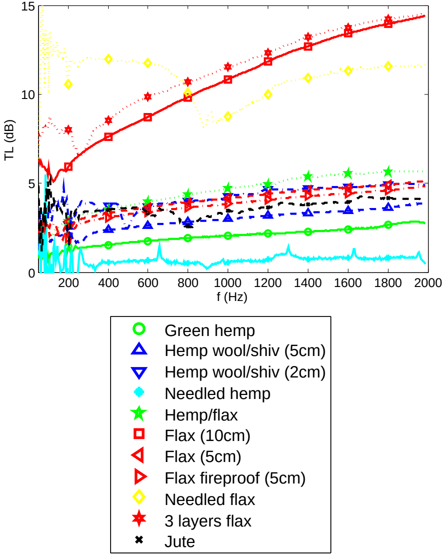
Acoustical comparison of building materials



Samples	e (cm)	ρ (kg/m^3)	ϕ	σ $(10^6 Nm^{-4}s)$
Wood	4.5	427	0.64	3.3
Cork	3.9	114	0.27	0.24
Plaster	4.7	722	0.50	12
Earth brick	5	1625	0.39	7.0
Cellular concrete	3.9	475	0.80	4.0
Wood concrete	5	415	0.50	0.0037
Hemp particles	5	153	0.85	0.010
Binder matrix	5	1500	0.39	3.3
Hemp concrete	5	260	0.70	0.025

Effect of the type of fibers



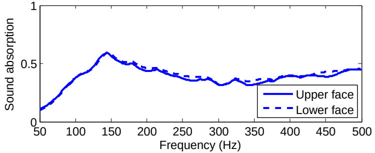


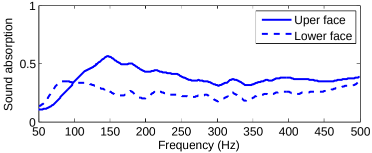
(Thickness ∈ [5mm;10cm])

⇒ Good α but medium TL

⇒ Gain due to multilayer optimization

Effect of implementation : Water content





Upper face

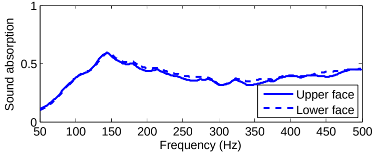
Lower face

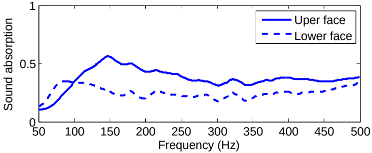
Upper face

Lower face

$\Rightarrow$ Sensitivity of α to surface aspect

Effect of implementation : Water content





Upper face

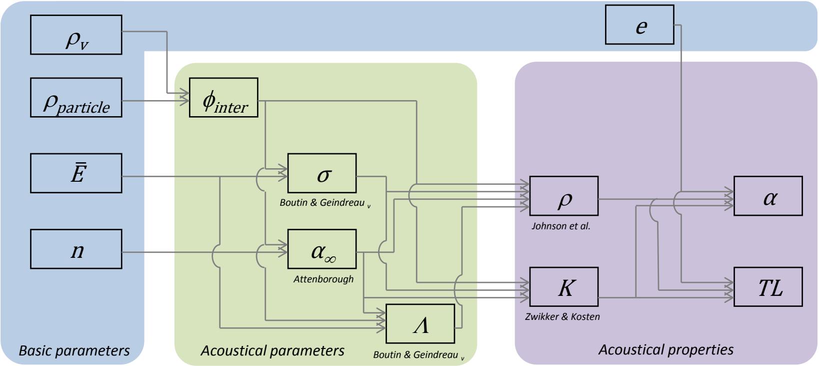
Lower face

Upper face

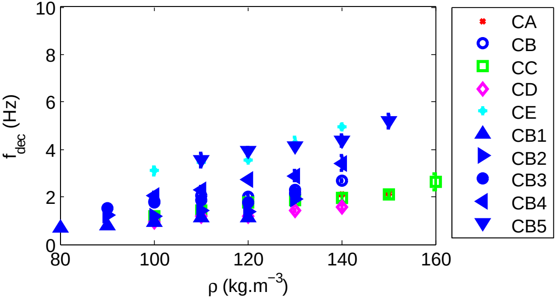
Lower face

$\Rightarrow$ Sensitivity of α to surface aspect

Modelling shiv : From basic parameters to acoustical properties

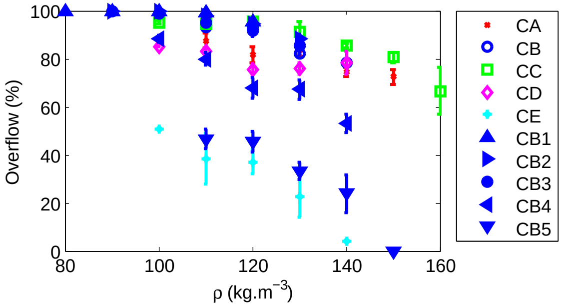


Modelling shiv : Rigid frame hypothesis



$\Rightarrow f_{dec} < 200\ Hz$ for all samples

Modelling shiv : Double porosity analysis



Extension of tortuosity modelling to hemp concretes

- Use of shiv's shape factor

$$\alpha_\infty = \phi_{inter}^{-n}$$

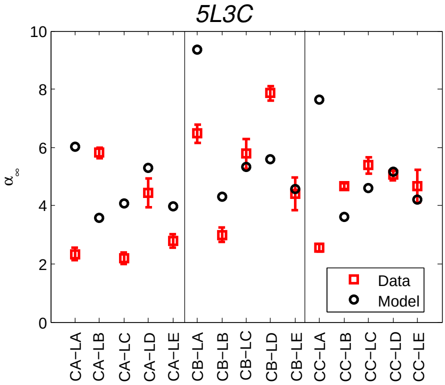
- Only possible for low binder contents

Extension of tortuosity modelling to hemp concretes

- Use of shiv's shape factor

$$\alpha_\infty = \phi_{inter}^{-n}$$

- Only possible for low binder contents

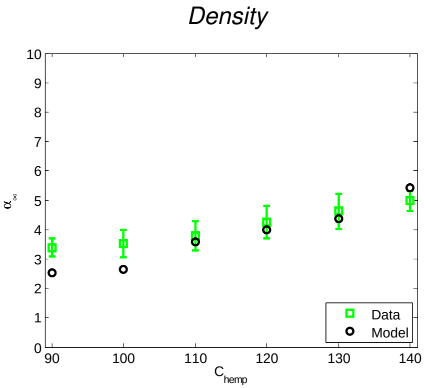


Extension of tortuosity modelling to hemp concretes

- Use of shiv's shape factor

$$\alpha_\infty = \phi_{inter}^{-n}$$

- Only possible for low binder contents

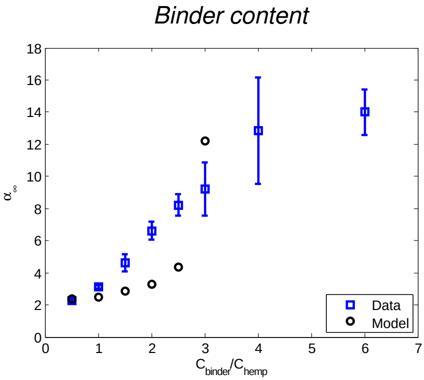


Extension of tortuosity modelling to hemp concretes

- Use of shiv's shape factor

$$\alpha_\infty = \phi_{inter}^{-n}$$

- Only possible for low binder contents



Extension of tortuosity modelling to hemp concretes

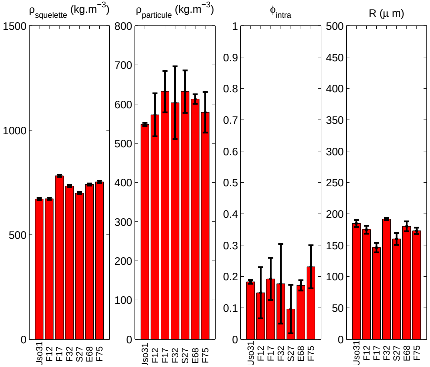
- Use of shiv's shape factor

$$\alpha_\infty = \phi_{inter}^{-n}$$

- Only possible for low binder contents

Cultivation parameters : Planting

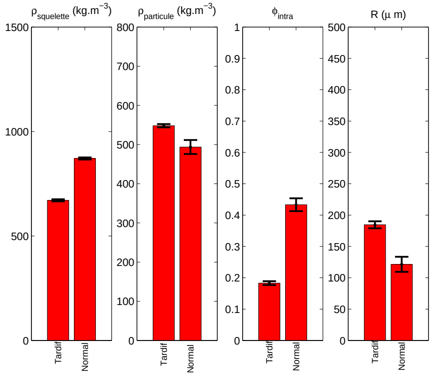
- Variety
  $\Rightarrow$ Significant effect on the particle size
- Planting date
  $\Rightarrow$ Significant effect on density, porosity and particle size
- Planting density
  $\Rightarrow$ Significant effect on the particle size
- Nitrogen quantity
  $\Rightarrow$ Minor effect on the particle size



	$\rho_{particle}$	ϕ_{intra}	R	ϕ_{inter}	σ	α_∞	Λ
p_{value}(2009 - Normal planting)	0.911	0.738	0.183	0.823	0.174	0.004	<0.001
p_{value}(2010 - Normal planting)	0.010	0.001	0.001	0.010	0.006	<0.001	<0.001
p_{value}(2010 - Late planting)	0.443	0.492	<0.001	0.421	0.539	<0.001	0.018

Cultivation parameters : Planting

- Variety
  ⇒ Significant effect on the particle size
- Planting date
  ⇒ Significant effect on density, porosity and particle size
- Planting density
  ⇒ Significant effect on the particle size
- Nitrogen quantity
  ⇒ Minor effect on the particle size



	$\rho_{particle}$	ϕ_{intra}	R	ϕ_{inter}	σ	α_∞	Λ
p_{value}(F17)	0.018	0.008	0.074	0.014	0.063	0.701	0.018
p_{value}(F32)	0.266	0.075	<0.001	0.242	0.004	0.005	0.038
p_{value}(Uso31)	0.007	<0.001	0.001	0.010	<0.001	0.002	0.585

Cultivation parameters : Planting

- Variety
  ⇒ Significant effect on the particle size
- Planting date
  ⇒ Significant effect on density, porosity and particle size
- Planting density
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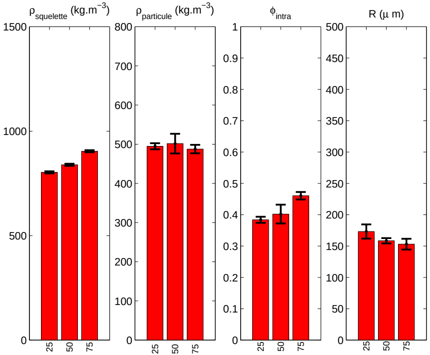
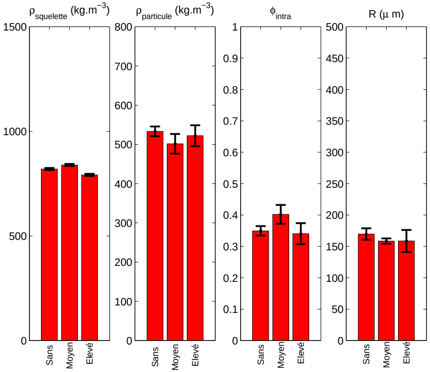
- Nitrogen quantity
  ⇒ Minor effect on the particle size



	$\rho_{particle}$	ϕ_{intra}	R	ϕ_{inter}	σ	α_∞	Λ
p_{value}(2009)	0.313	0.458	0.403	0.370	0.145	0.029	0.646
p_{value}(2010)	0.272	0.300	<0.001	0.267	<0.001	0.171	0.343
p_{value}(2011)	0.948	0.396	0.001	0.929	0.429	0.587	0.047

Cultivation parameters : Planting

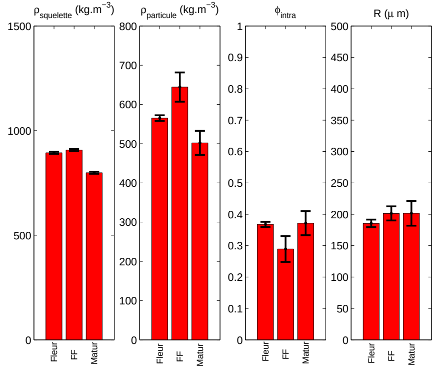
- Variety
  ⇒ Significant effect on the particle size
- Planting date
  ⇒ Significant effect on density, porosity and particle size
- Planting density
  ⇒ Significant effect on the particle size
- Nitrogen quantity
  ⇒ Minor effect on the particle size



	$\rho_{particle}$	ϕ_{intra}	R	ϕ_{inter}	σ	α_∞	Λ
p_{value}(2009)	0.095	0.184	0.010	0.080	0.199	0.119	0.618
p_{value}(2010)	0.276	0.065	0.459	0.272	0.051	0.242	0.041

Cultivation parameters : Harvesting

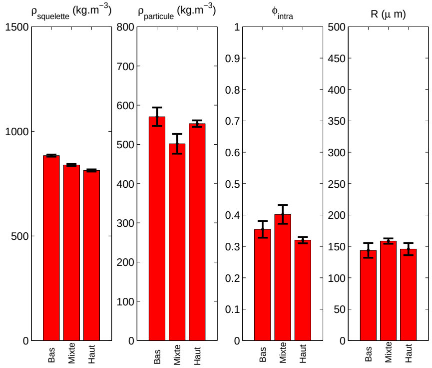
- Harvesting date
  $\Rightarrow$ Minor effects
- Position in the stem
  $\Rightarrow$ Minor effects
- Retting
  $\Rightarrow$ Significant effect on frame density and porosity



	$\rho_{particle}$	ϕ_{intra}	R	ϕ_{inter}	σ	α_∞	Λ
p_{value}(2009)	0.001	0.018	0.304	0.002	0.001	0.107	0.118
p_{value}(2010)	0.603	0.539	0.016	0.599	0.079	0.228	0.007

Cultivation parameters : Harvesting

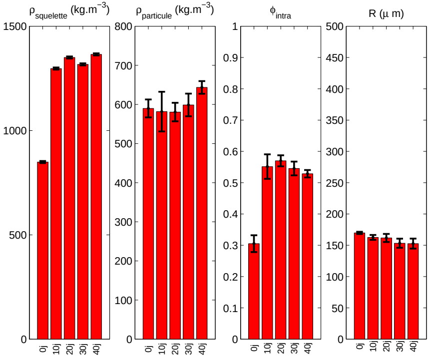
- Harvesting date
  ⇒ Minor effects
- Position in the stem
  ⇒ Minor effects
- Retting
  ⇒ Significant effect on frame density and porosity



	$\rho_{particle}$	ϕ_{intra}	R	ϕ_{inter}	σ	α_∞	Λ
p_{value}(2009)	0.120	0.283	0.014	0.102	0.227	0.805	0.670
p_{value}(2010)	0.015	0.016	0.175	0.015	0.657	0.002	0.002

Cultivation parameters : Harvesting

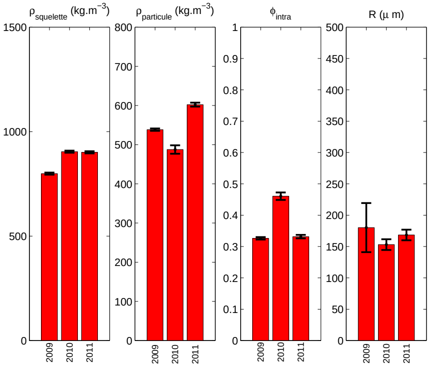
- Harvesting date
  ⇒ Minor effects
- Position in the stem
  ⇒ Minor effects
- Retting
  ⇒ Significant effect on frame density and porosity



	$\rho_{particle}$	ϕ_{intra}	R	ϕ_{inter}	σ	α_∞	Λ
p_{value}(2009)	0.212	<0.001	0.012	0.202	0.110	0.168	0.040
p_{value}(2010)	0.018	0.001	0.019	0.021	0.120	0.032	0.007
p_{value}(2011)	0.153	<0.001	0.024	0.171	0.532	<0.001	<0.001

Environment parameters : Meteorological aspect

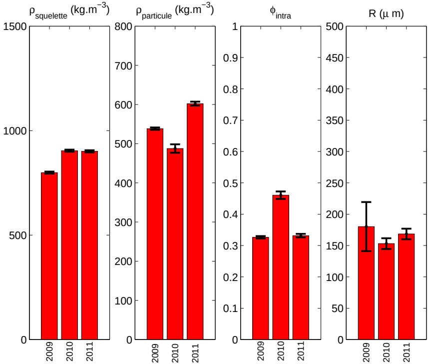
- Evolution between 2009 and 2011
  ⇒ Signifiant effect on density, porosity and particle size
- Meteorogical data
  ⇒ 2010 more wet and sunny



	$\rho_{particle}$	ϕ_{intra}	R	ϕ_{inter}	σ	α_∞	Λ
p_{value}(F17-25)	0.291	0.457	0.855	0.261	0.039	0.006	0.930
p_{value}(F17-50)	0.010	0.026	0.010	0.014	0.002	0.006	0.141
p_{value}(F17-75)	<0.001	<0.001	0.421	<0.001	0.018	0.005	0.107
p_{value}(Retting)	0.362	0.397	0.001	0.342	0.166	<0.001	0.022

Environment parameters : Meteorological aspect

- Evolution between 2009 and 2011
  ⇒ Signifiant effect on density, porosity and particle size
- Meteorogical data
  ⇒ 2010 more wet and sunny



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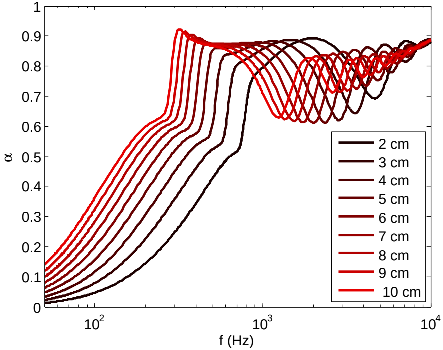
In situ application of plant wool for acoustic correction

- Optimization
  - Thickness of central layer
  - Facings resistivity
  - Perforations ...



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