



Coupling phenomenological model of expansion with mechanical model of starchy products extrusion (Projet AIC 'QualExp')

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Coupling phenomenological model of expansion with mechanical model of starchy products extrusion: Projet AIC-QualExp

Magdalena KRISTIAWAN (BIA-MC2)

Problème d'application concerné: *Itinéraire multi-étape & couplage de modèle*

Recall of Objectives

To build **a phenomenological model of expansion by extrusion** that allows to predict foam structure from process variables and material properties.

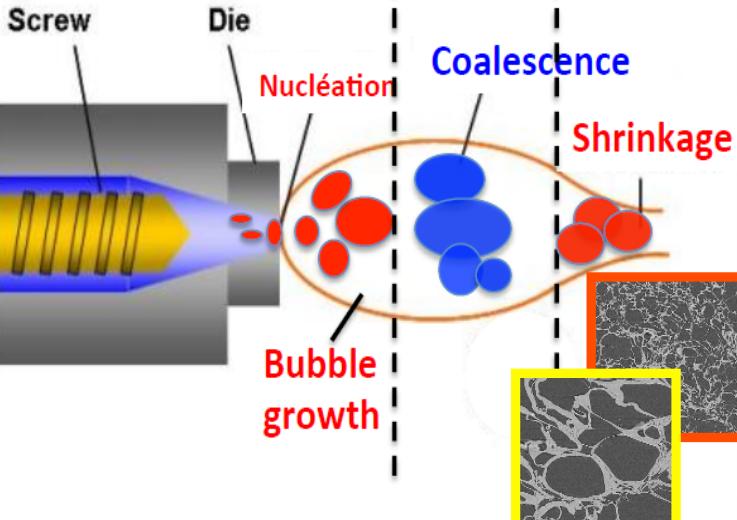
Delivrables

- 1/ **Phenomenological model of expansion** by extrusion for predicting macro and cellular structure of starchy solid foam.
- 2/ **Coupling** this phenomenological model with **mechanical model of extrusion** (Ludovic® software)



Context: Expansion by extrusion

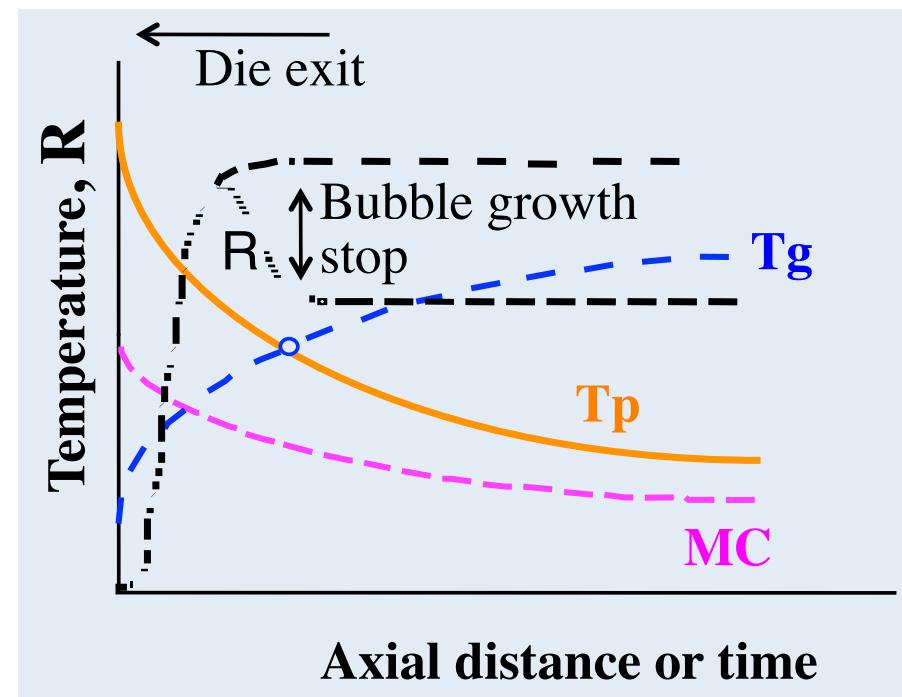
Acquisition of texture



The bubble growth stops (setting) at $T_p > T_g + \dots ^\circ C$

T_g : glass transition temperature

State diagram



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Applications

- Innovative starchy foods, with modulated shape and digestibility
- Starch based shape memory biopolymers for medical devices

Partners : BIA, I2M, externals

■ M. Kristiawan :

Modeling implementation

■ B. Vergnes (CEMEF-MinesParisTech) :

Extrusion and plastic foam manufacturing

■ G. Della Valle :

Expertise on extrusion, rheology, process modeling

■ Ch. David /L. Ratte (SCC) :

Software development for extrusion (Ludovic®)

■ L. Chaunier :

Expertise on extrusion, experiments & physics measurements

■ Allaf / V. Sobolik (ULR) :

Expansion by instant pressure drop, rheology, fluid mechanics

■ K. Kansou :

Qualitative modeling and reasoning

■ A. Ndiaye :

Qualitative modeling and reasoning

■ C. Fernandez :

Software development for Knowledge Base System:
Qualis©; Make Book



Methods and Resources

Modeling

Phenomenological models of **bubble growth** (+ nucleation, coalescence, setting, shrinkage) in a **viscoelastic** biopolymer matrix **in the transition state from rubbery to solid phase**.

Macro and **Cellular** structure = f (Water%, $T_p^\circ C$, SME kWh/t, $\eta(\dot{\gamma})$, $\eta(\dot{\varepsilon})$)

Approach

1. Collection of scientific knowledge (SK)
2. Representation of knowledge (Concept map / causal graph)
3. Establishment of **phenomenological models of expansion**
 - *2/3 of experimental data:* *Model establishment*
 - *1/3 of experimental data & scientific articles:* *Model validation*
4. **Coupling mechanical model of extrusion (Ludovic®) with expansion models**
5. Simulation and validation with experiments



• Experimental data: Extrusion of maize starch

(Della Valle et al., 1996, 1997; Babin et al., 2007)

– Input variables: (400 points)

- Amylose (0 – 70%) ($E'(T_\alpha)$); Plasticizer: Water % (MC)
- $T^\circ\text{C}$ of product at die exit (Tp), SME kWh/t, shear viscosity

– Output variables

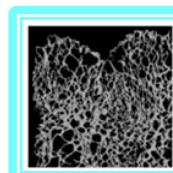
- Macrostructure
 - Volumetric Expansion Indices (VEI) ($\text{VEI} = \text{LEI} \times \text{SEI}$)
 - Radial Expansion Indices (SEI)
 - Longitudinal Expansion Indices (LEI)
 - Anisotropy Factor (AF)
- Cellular structure

- Mean cell size (MCS) (mm)
- Mean cell wall thickness (MWT) (μm)

Fineness



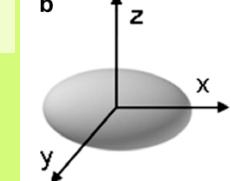
Fine



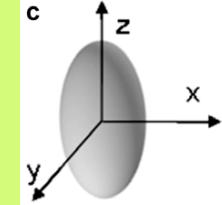
$$AF = \frac{LEI}{\sqrt{SEI}}$$

$AF = 1$
Isotropic

Coarse

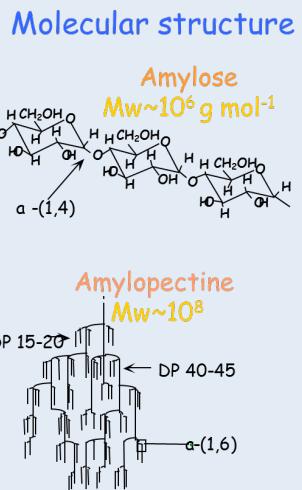


$AF > 1$
Longitudinal



$AF < 1$
Radial

Flow direction →



X-Ray
tomography



Results

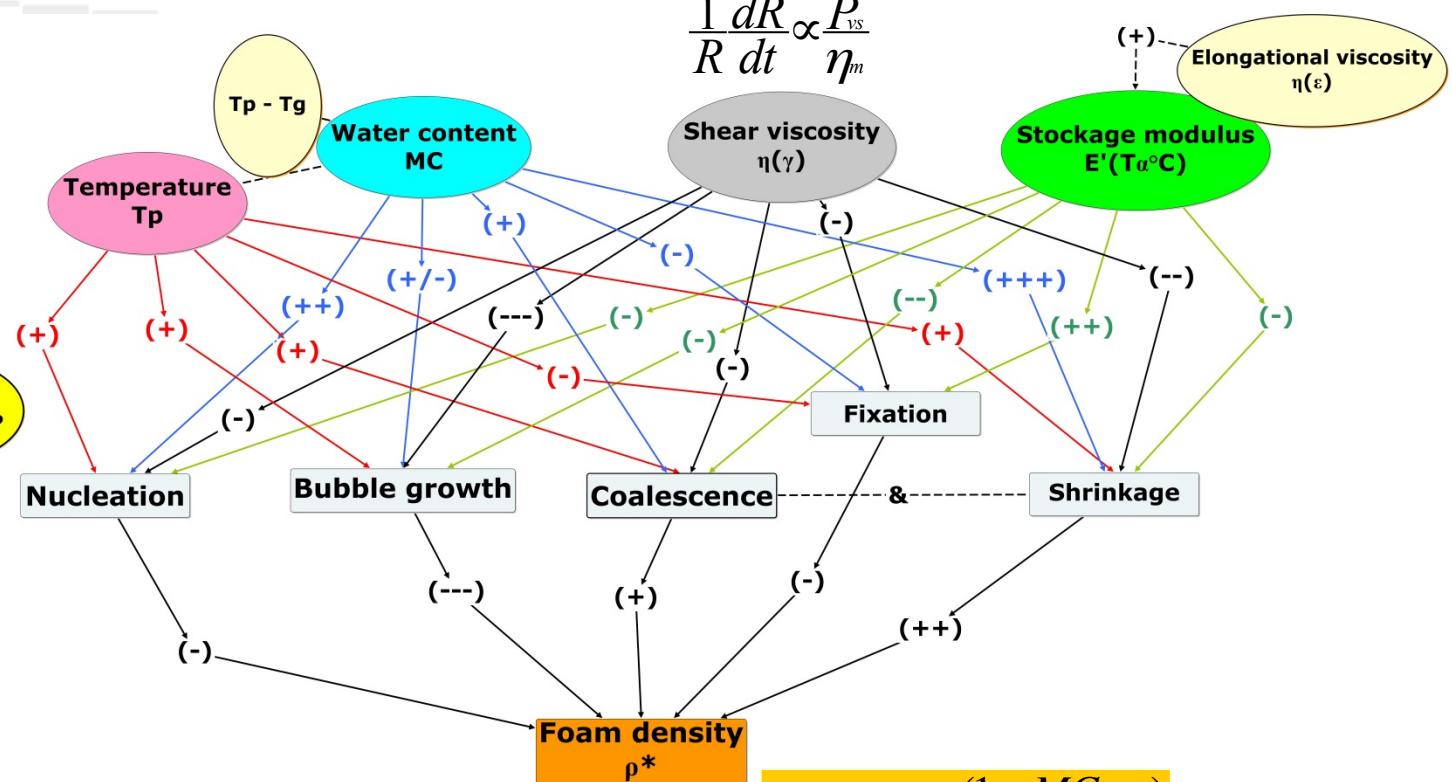


Concept map: Phenomenological model of expansion

Input variables

Mechanical Energy SME ??????
Die profil L / D ????

Expansion phenomena



$$VEI \approx [MC/MC_o]^x \otimes [Tp/Tp_o]^y \otimes [\eta(\dot{\gamma})/\eta_o(\dot{\gamma})]^z \otimes [E'(T_\alpha)/E'_o(T_\alpha)]^t$$

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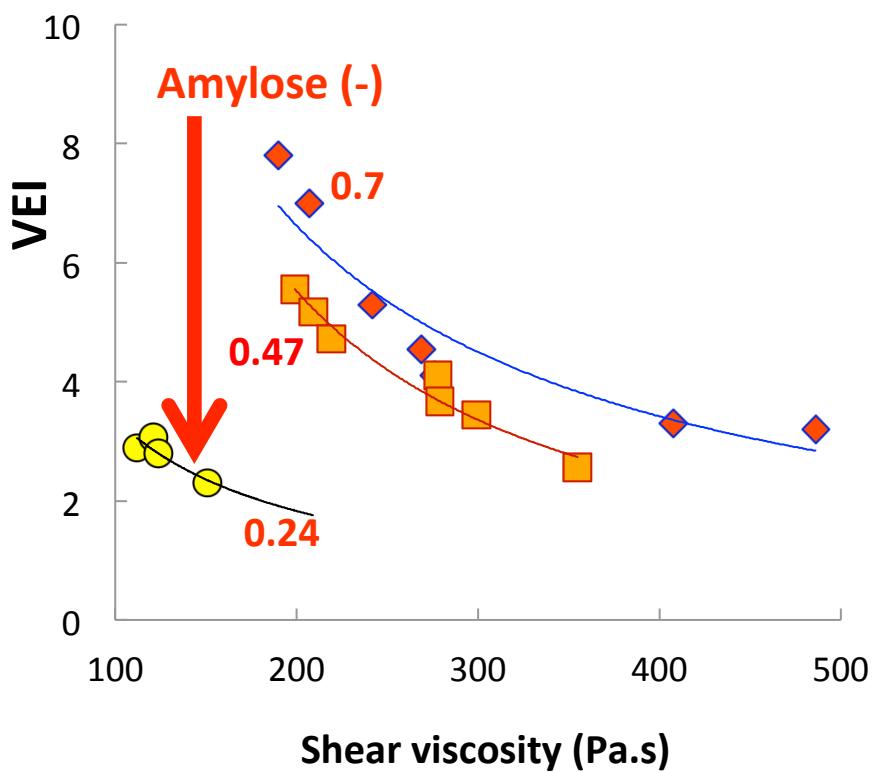


Volumetric expansion indices VEI

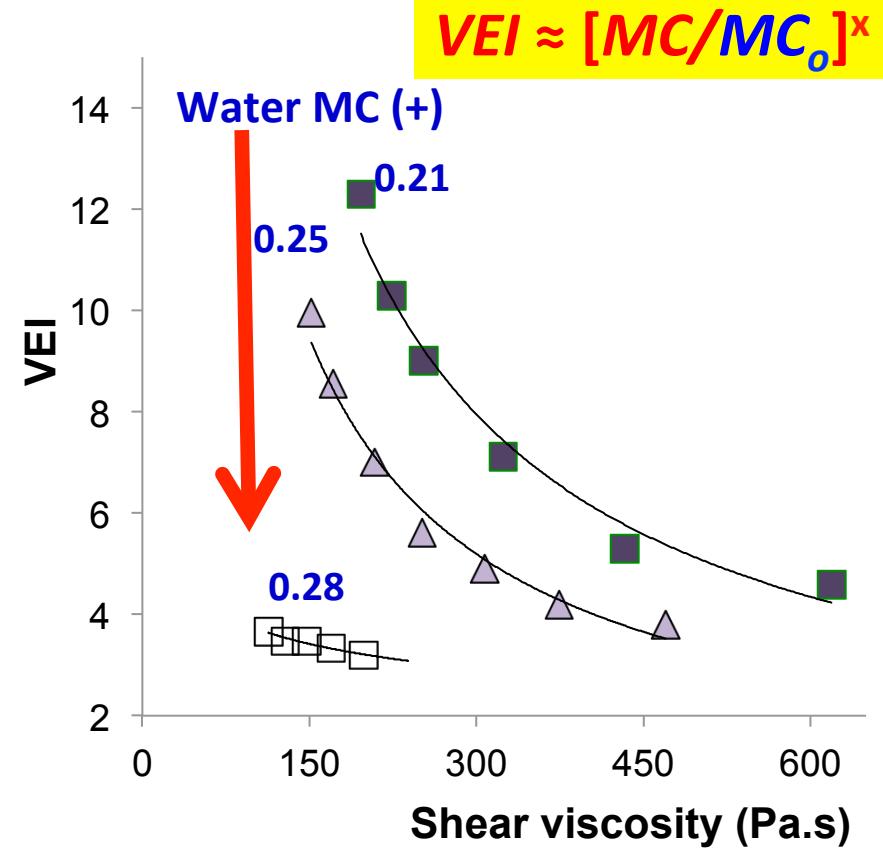
$$VEI = \frac{\rho_{melt}(1 - MC_{melt})}{\rho^*(1 - MC_{foam})}$$

$$VEI \approx [E'(T_\alpha)/E_o'(T_\alpha)]^t$$

Water = 0.245, 185°C, 150 kWh/t, h die = 3 mm



Amylose 70%, 165°C, 200 kWh/t, h die = 3 mm



Cellular fineness (F):

$$F = \sqrt{\frac{\left(\frac{250}{MWT}\right)^2 + \left(\frac{1}{MCS}\right)^2}{2}}$$

$F < 1 \rightarrow$ Coarse

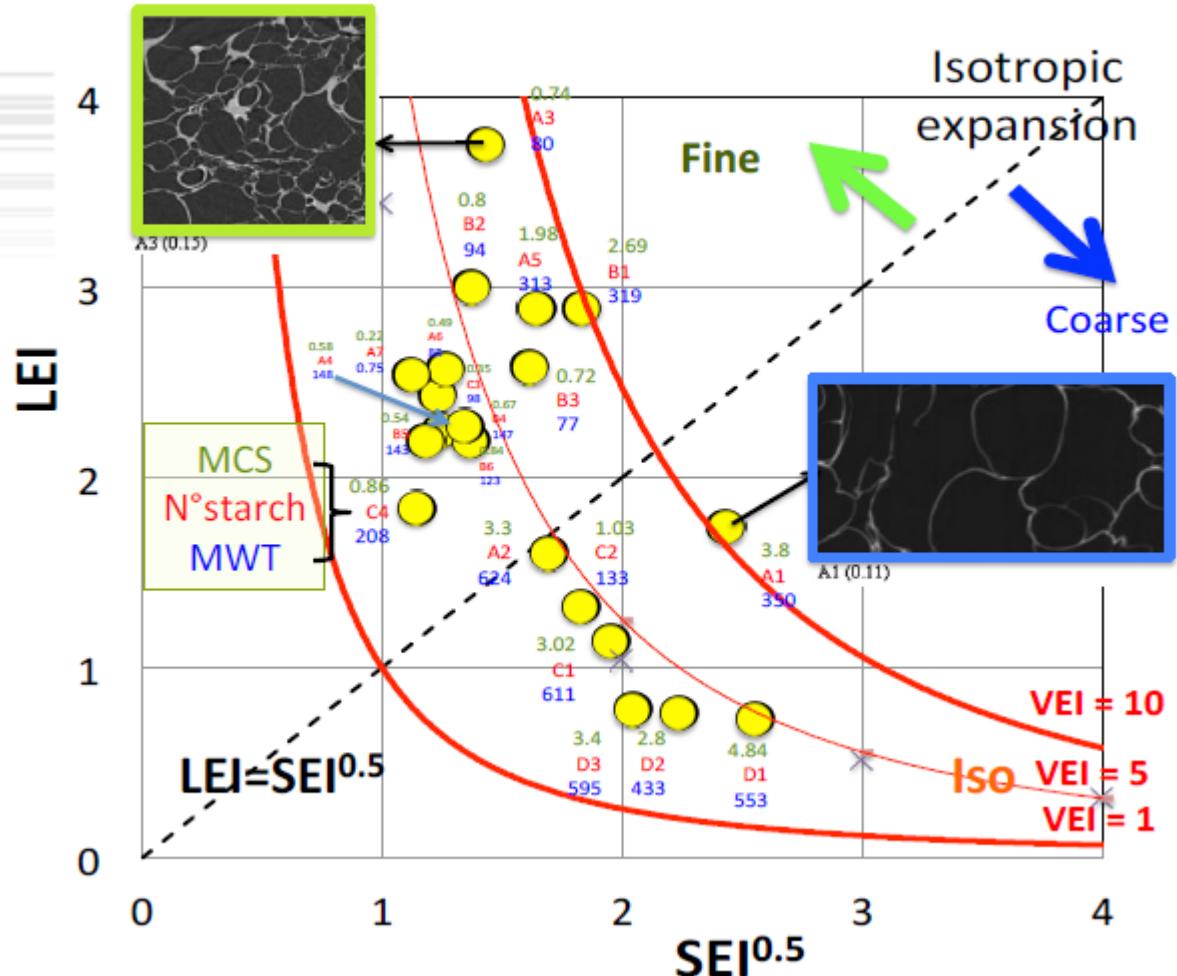
$F > 1 \rightarrow$ Fine

MWT in μm ; *MCS* in mm

The cellular structure can be deducted from the knowledge of anisotropy

Mapping of Anisotropy & Structure Cellular

Data from Babin et al. (2007)²



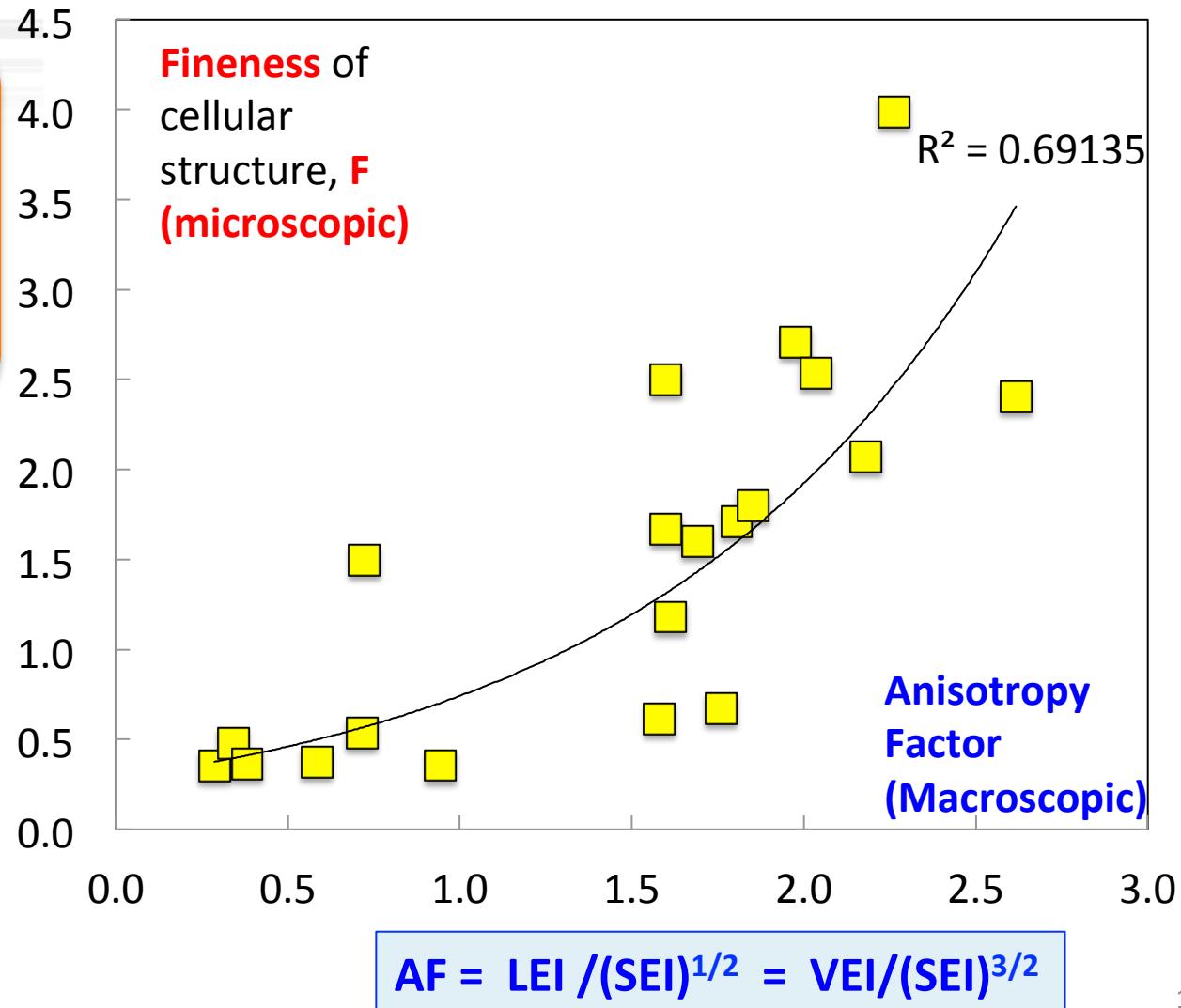
Scaling down: from macroscopic (anisotropy, AF) to microscopic (cellular structure, Fineness)

$$F = \sqrt{\frac{\left(\frac{250}{MWT}\right)^2 + \left(\frac{1}{MCS}\right)^2}{2}}$$

$F < 1 \rightarrow$ Coarse

$F > 1 \rightarrow$ Fine

MWT in μm ; MCS in mm

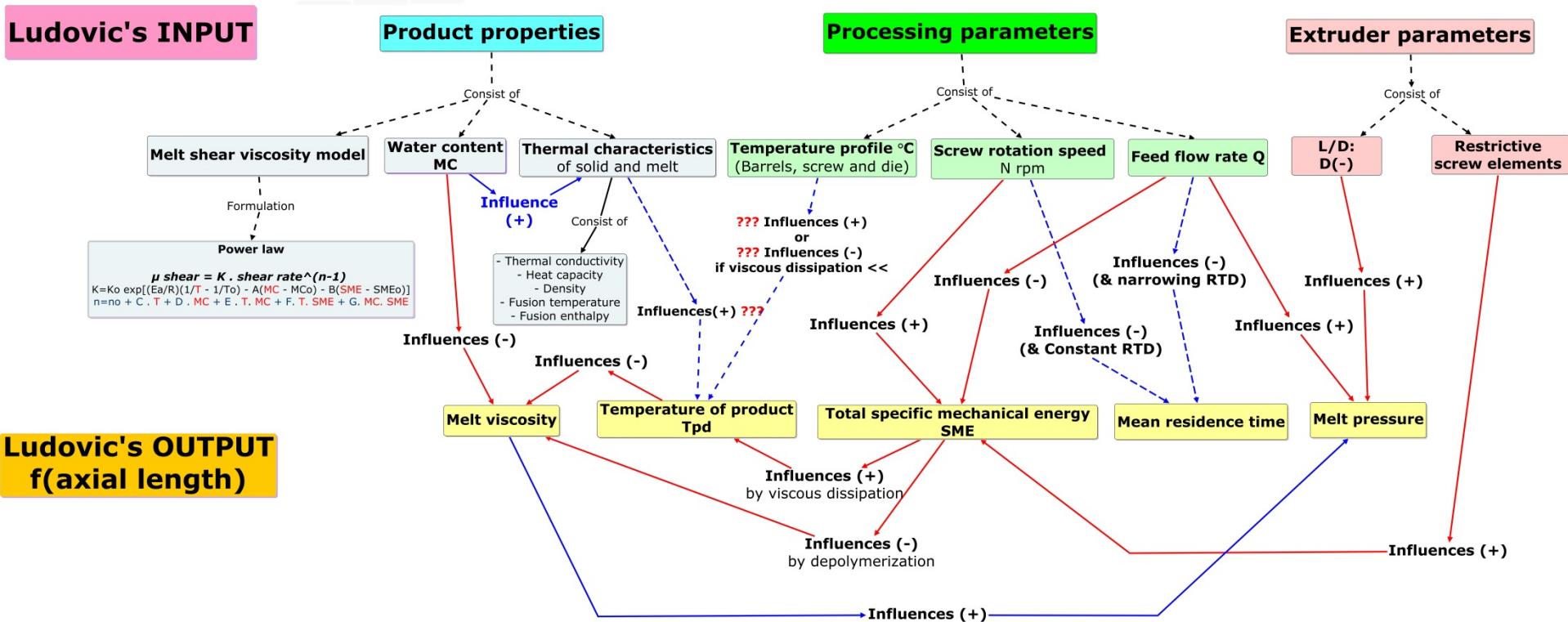


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Concept map: Structure of Ludovic®

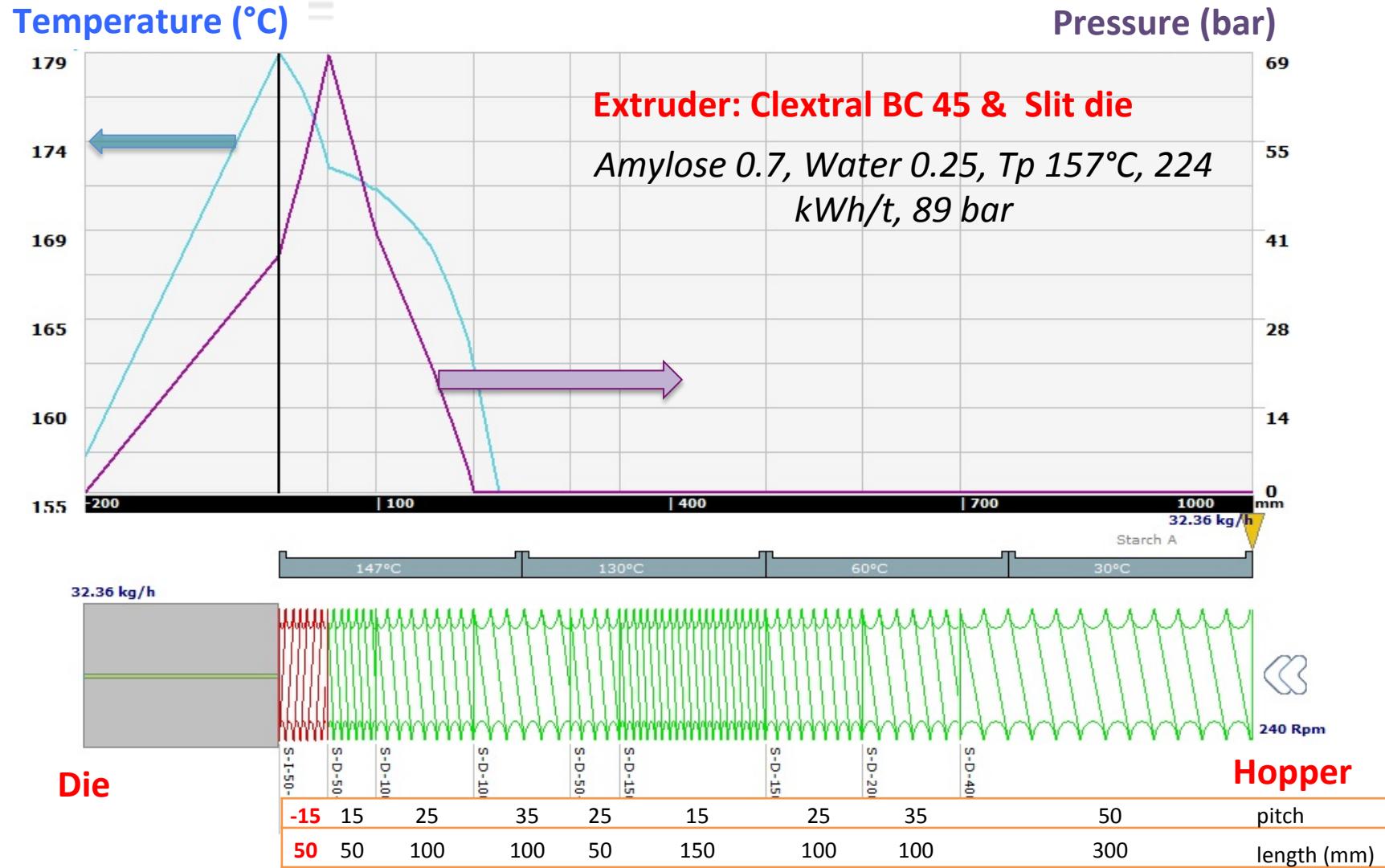
« Software for simulation of co-rotating twin-screw extrusion »



« Ludovic®'s output variables = input of expansion model »



Flow parameters of extrusion process computed by Ludovic®



Evaluation

Realized:

- Collection & integration of scientific knowledge
- Experiments on extrusion of starchy foams having shape memory
(the part of CR2 project, for familiarization with extrusion)
- Representation of knowledge
« Concept map with causalities »

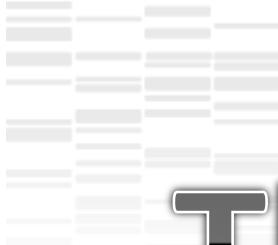
On going:

- Establishment of phenomenological models of expansion

Perspective:

- Coupling mechanical model of extrusion (Ludovic®) with phenomenological models of expansion
- The new Ludovic®'s outputs: Macro and cellular structures of foams



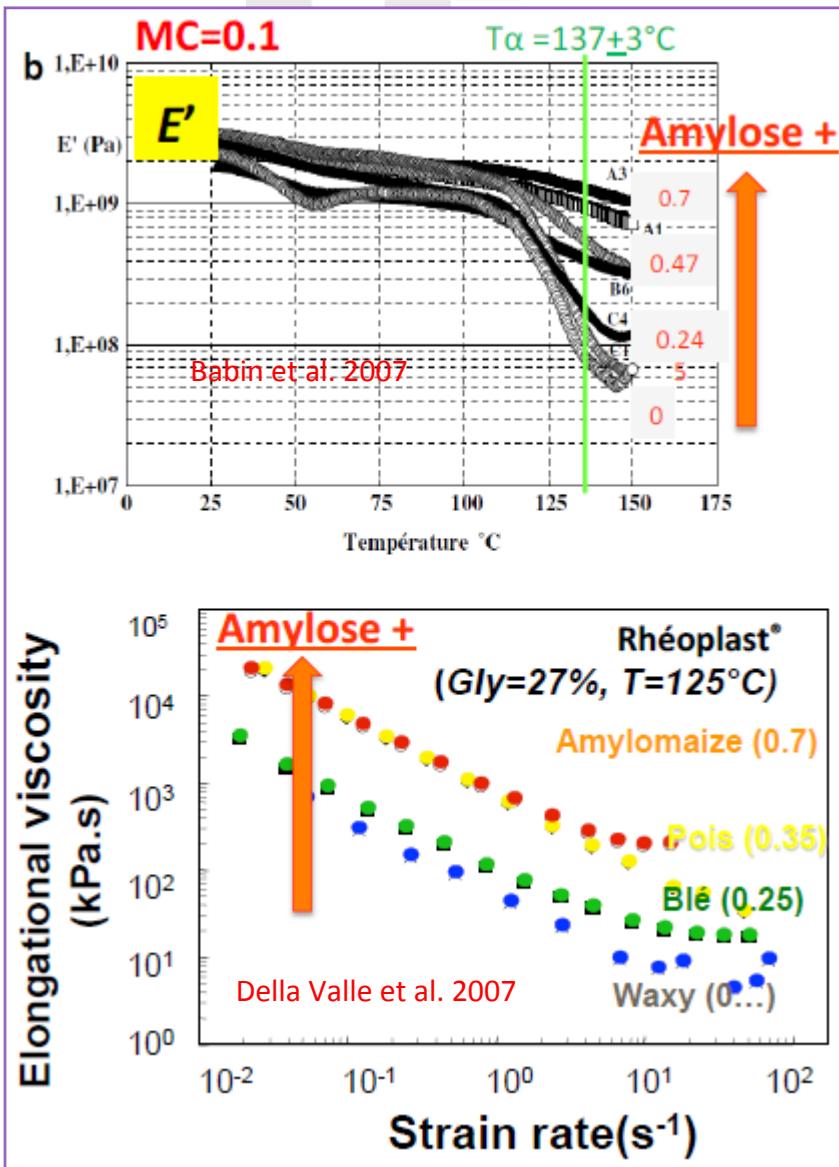


Thank you for your attention

Discussion...

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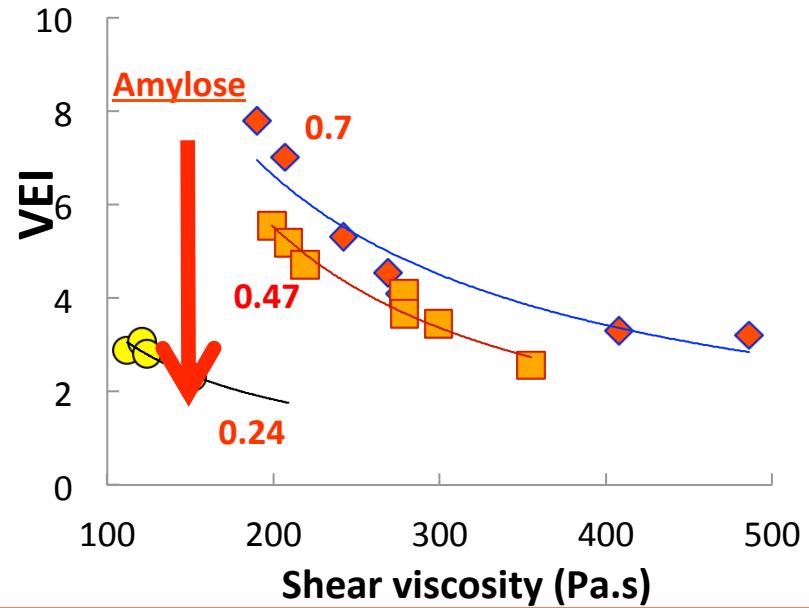


Elongational viscosity & $E'(T_\alpha)$ as f(Amylose%)

1) Variations of $E'(T_\alpha)$ and $\eta(\dot{\varepsilon})$ with amylose% follow the same pattern

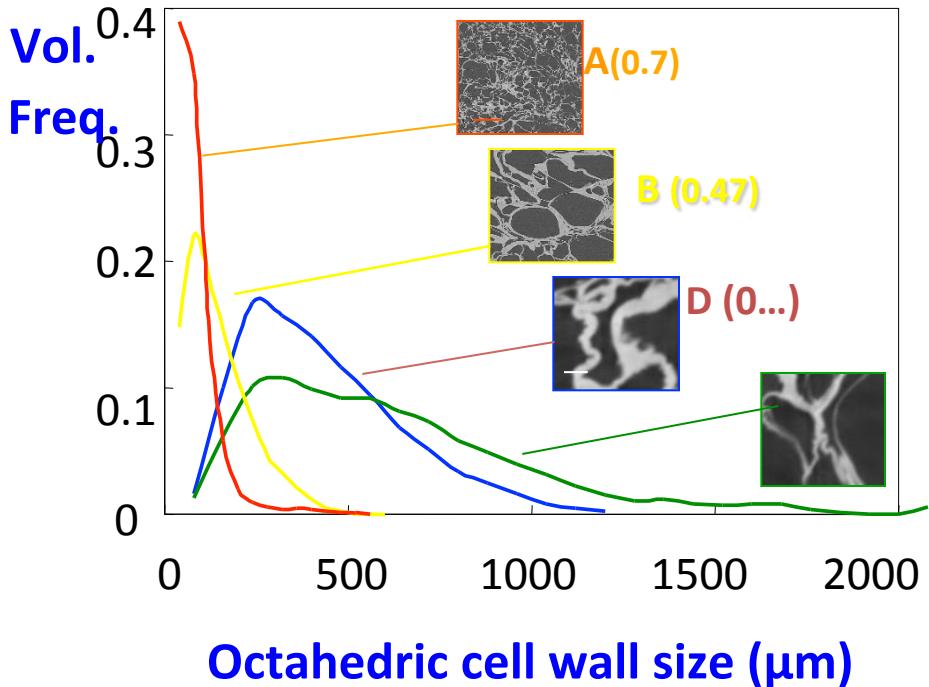
2) If E' (+) then Coalescence (-) & VEI (+)

Water = 0.245, 185°C, 150 kWh/t, h die = 3 mm



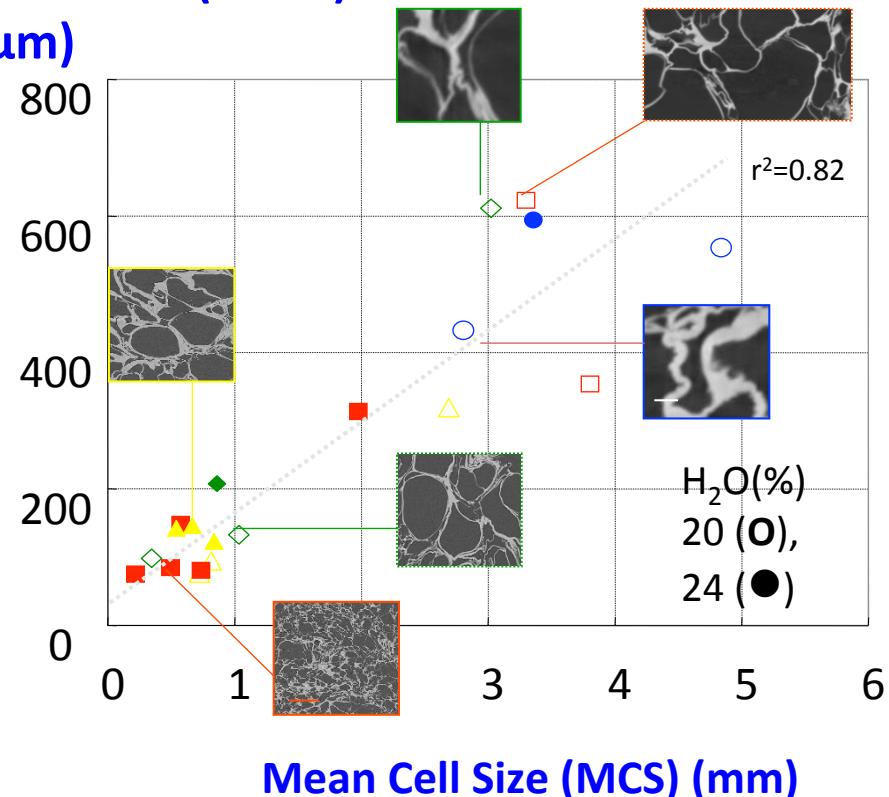
Babin et al., 2007

Distribution of Cell Wall Thickness



If the Cells «more coarse » then
MWT dist. « more heterogeneous »

Mean Cell Wall Thickness (MWT) (μm)



If MCS (+) then MWT (+)

