Bio^{3}composites

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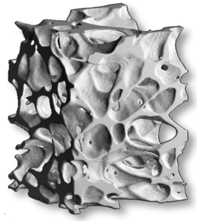
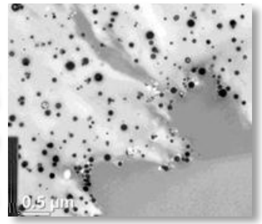
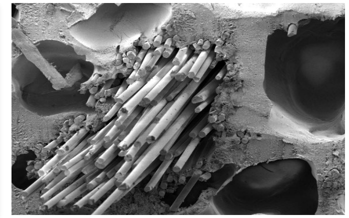
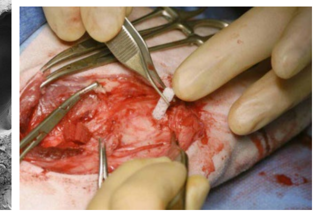
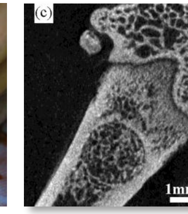
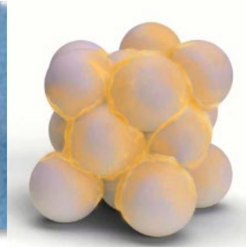
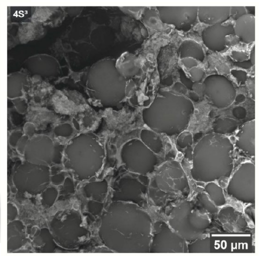
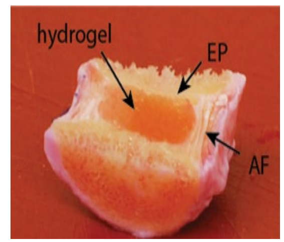
Bio³composites

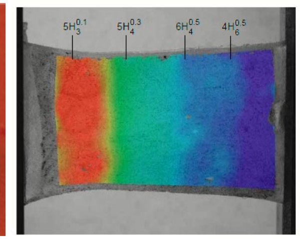
Polymer composites for biomedical applications

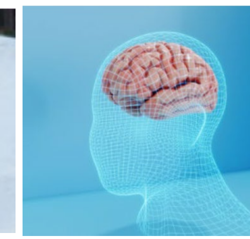



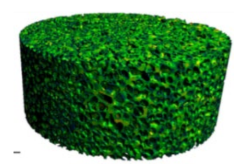
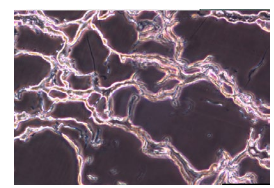
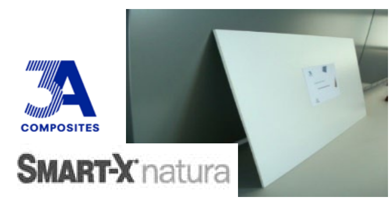






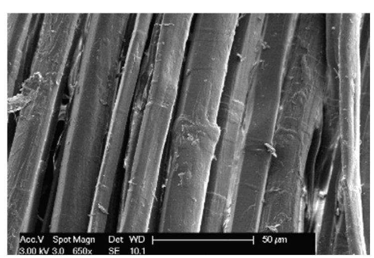


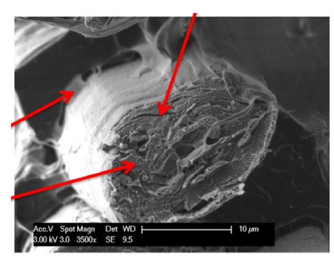


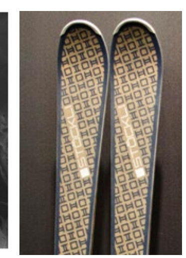
Biodegradable composites from renewable resources

Natural fibre biocomposites





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Polymer composites in biomedical devices

- Introduction
- Bulk biocomposites
  - Dental applications
  - Prosthesis
- Porous biocomposites
  - Textiles
  - Foams
  - Bone tissue engineering
- Composite hydrogels
  - Synthesis
  - Mechanical performance
  - Nucleus pulposus, cartilages…

Definition

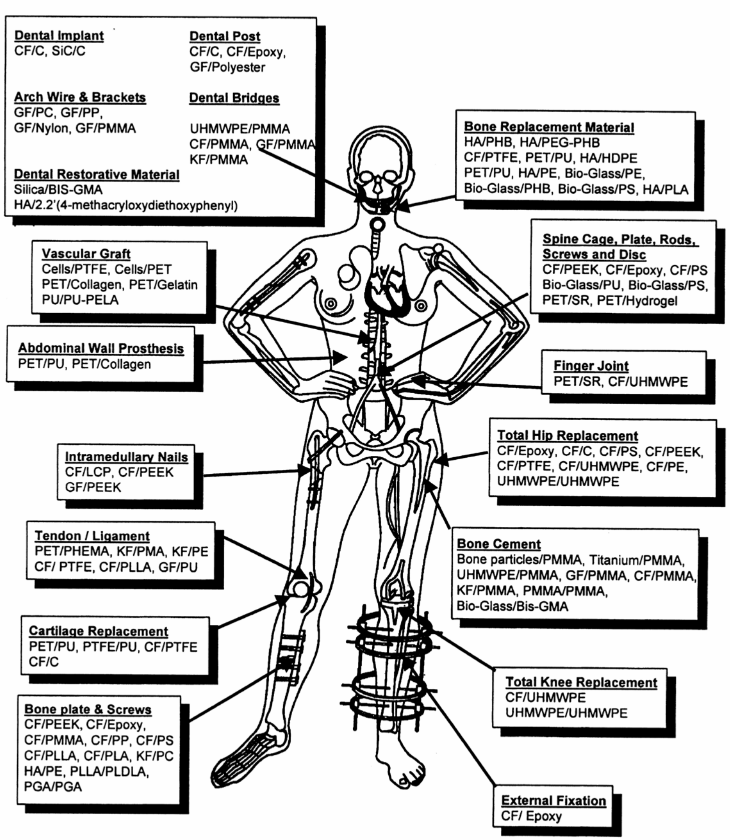
- **Biomaterials** : natural or synthetic materials used to complete or replace tissue functionality in the body
- **Biocomposites**: combined materials, based on a polymer matrix and applied to the biomedical field
  Ex: implants, medical devices, internal or external body uses

Stryker Knee Replacement System

Medtronic Talent Abdominal Stent Graft

ICRC Limb prosthesis

Why polymer based biocomposites ?



Ramakrishna et al 2001

+ biomimetic
+ bioactive
…

	Advantages	Drawbacks
Metals	- High resistance - Ductility	- Corrosion, low biocompatibility - High modulus compared to tissues - High density - Release of metallic ions
Ceramics	- Good biocompatibility - Resistance to corrosion - Resistance in compression	- Brittleness - Difficult to machine, high density - Lack of impact strength
Polymers	- Variety of compositions, properties and shapes - Possibility of complex shapes	- Sterilization - Absorption of liquid, swelling - Release of small molecules - Too « soft » for some applications (e.g. bone)

Polymer composites

- Advantages
  - Native human tissues are anisotropic composites
  - Design freedom and tailored mechanical properties
  - Control of reinforcement volume fraction and placement adjusted to natural tissue properties
  - Adapted to medical analyses techniques (CT or MRI)
  - May completely resorb
- Drawbacks
  - Interface: diffusion of the physiological medium, mechanical stresses
  - Sterilization: risks of polymer degradation
  - Surface treatment: difficult to improve biocompatibility

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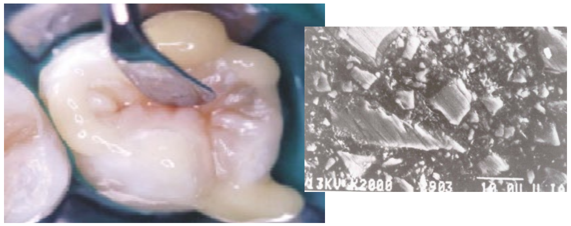
Composites for dental restoration

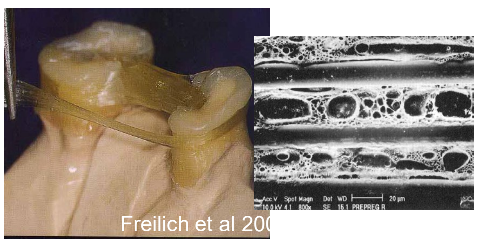
- **Dental filling**: Acrylate resin +33-78 wt% (quartz,baryum glass,colloidal silica)



Material	E_c (GPa)	σ_c (MPa)
Composite resin	10-16	170-260
Dentin	11.0	39.3

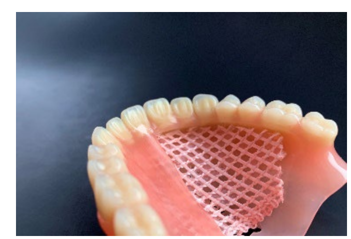
Challenges : wear, brittleness, shrinkage

- **Dental bridge, crowns, restorations**: dental resins + glass fibers, Kevlar or UHMWPE



Fibers	vol%	$\sigma_{transverse}$ (MPa)
UHMWPE	48	188
glass	33	265

Challenges : impregnation, interfaces, shrinkage, conversion degree…



https://www.dentapreg.com

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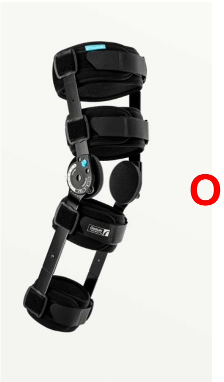
Ortheses and prostheses



Ortheses

https://www.ossur.com https://www.ottobock.ch

Prostheses for sports

https://www.plusport.ch/fr/

https://www.sofia-g.ch/

Prostheses

Preimpregnated carbon-epoxy

(+) • lightness, tailored stiffnesses,minimum dimensions
- fiber quality, quantity and orientation : prices
- deformable parts, very elastic, strain energy
- improved reliability and comfort

(-) longer manufacturing, cost, testing device required

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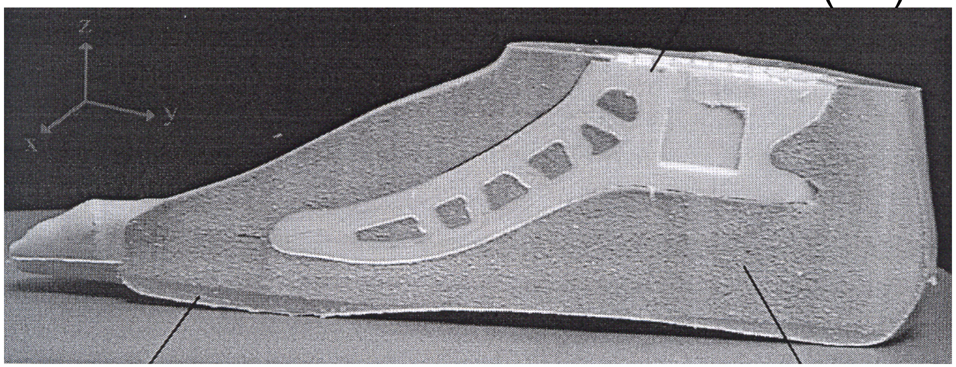
Affordable Prostheses

Minimal cost and maximal life time: feet for ICCR

Center rib (PP)



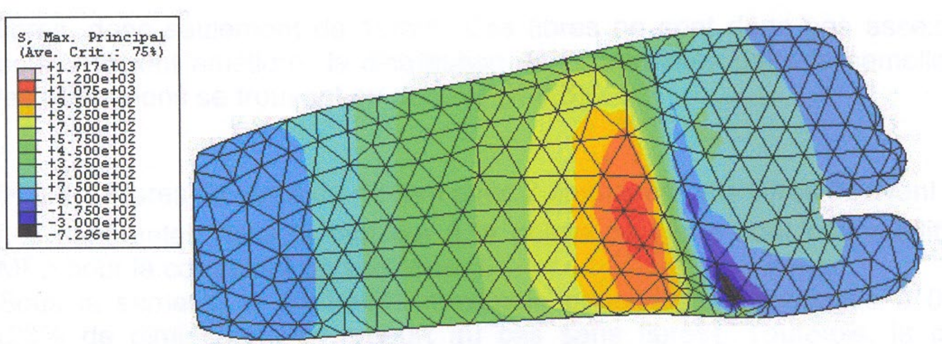
Sole (PU)

Foot core (PU foam)

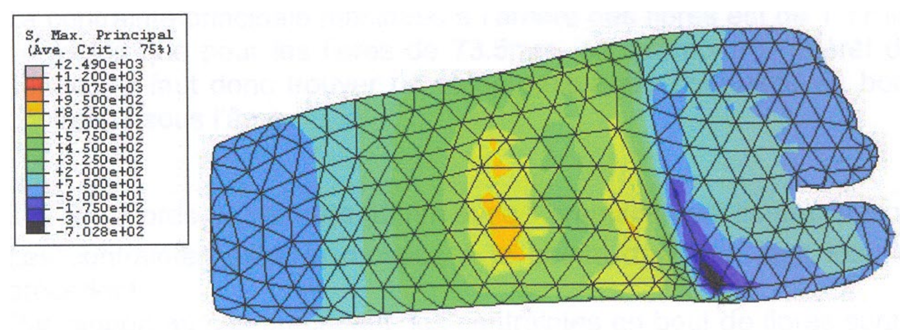
ICRC

CR ÉQUIPEMENTS SA

Challenge: fatigue cracks at the top of the center rib



Without additional reinforcement σ_{max}=1.2 MPa



With UD glass fibers σ_{max}=0.85 MPa

Gugolz, Rion, EPFL,2002

https://www.rehabimpulse.org/index.php/en/products/prosthetic

EPFL-ICRC

https://blogs.icrc.org/inspired/2019/05/05/affordable-feet-icrc-agilis-prostheses/

Bulk biocomposites - summary

- **Structural bio-inert composites** are an answer to mechanical requirements of tissues to be substituted
  - Possibility to tailor implants or prosthesis properties to those of the diseased tissue
  - Balance between functionality / performance / biocompatibility

- **Tissue/ implant interface** is of growing interest
  - Poor anchorage, which may induce pain and living tissue necrosis
  - Porous layer in surface can favor tissue growth and adhesion to the implant

- **Bioactive and porous composites** for tissue engineering are required for integration and tailored properties in order to meet specific clinical requirements

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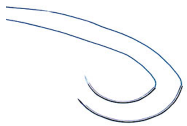
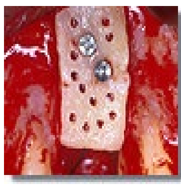
Bio(resorbable) implants

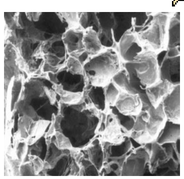
Sutures



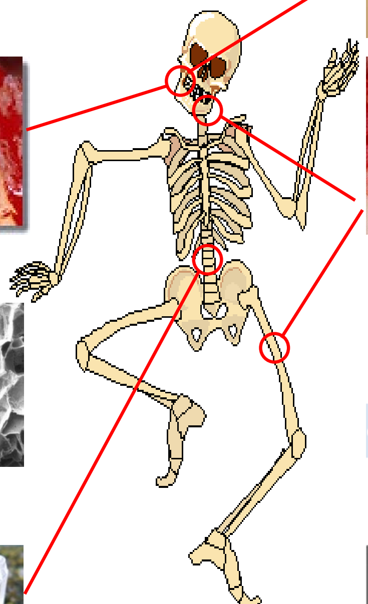
Dental membranes



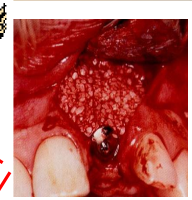
Matrices for tissue engineering



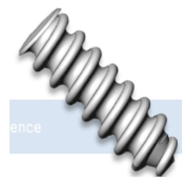
Vertebral cages



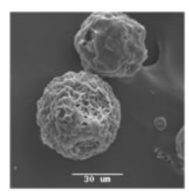
Fixation elements for maxillofacial surgery



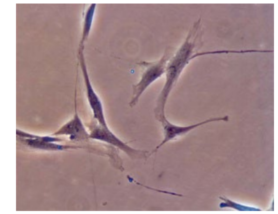
Biomaterials for bone augmentation

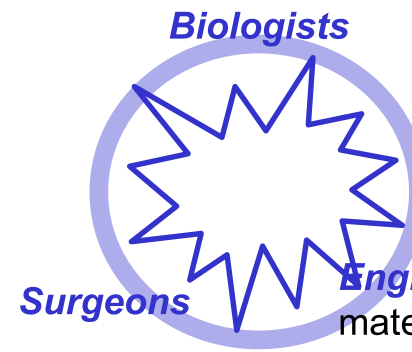


Bioresorbable screws (fixation)

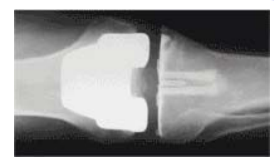


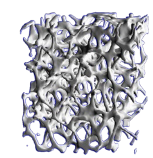
Drug release

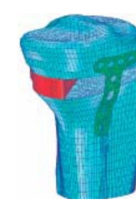




Engineers: materials, chemistry, mechanics…

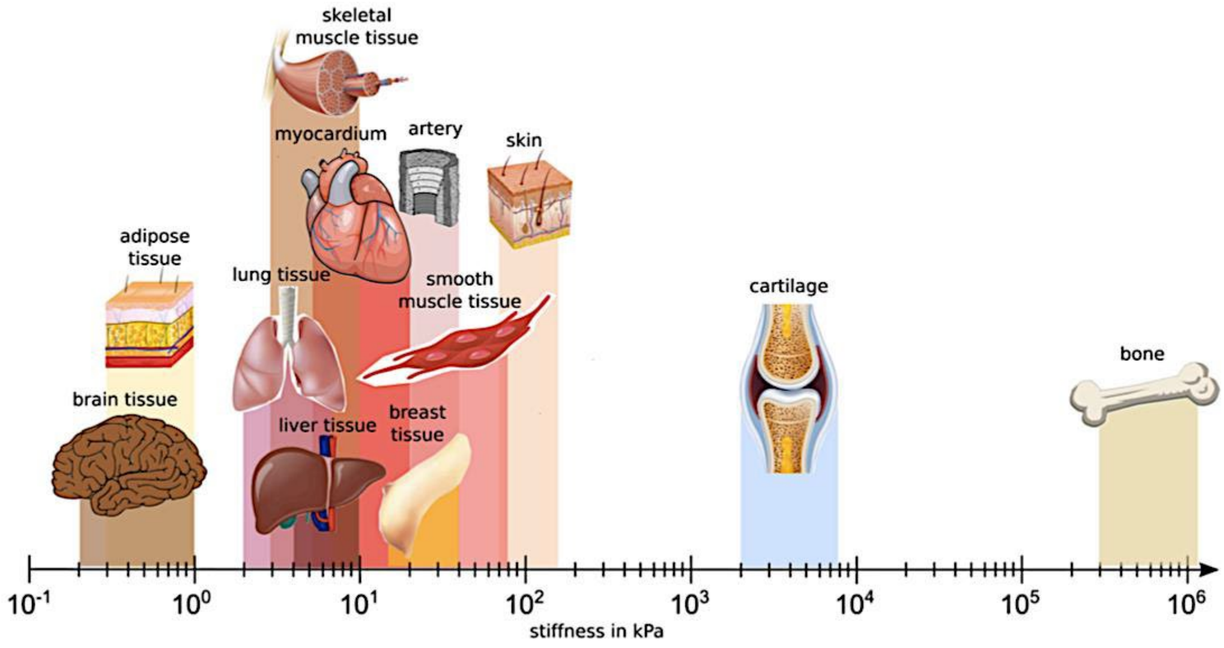






↳ **Multidisciplinary projects**

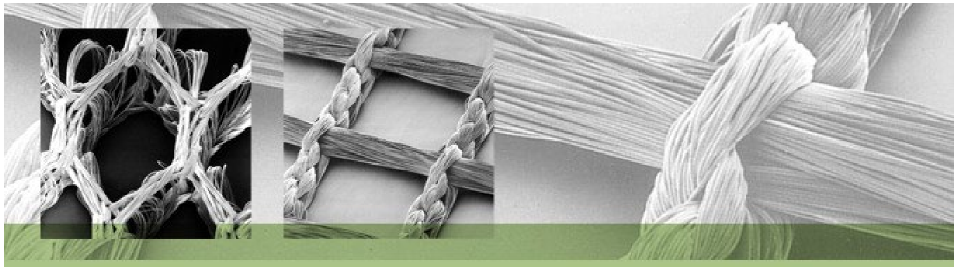
Elastic modulus of biological tissues



S. Budday, T. C. Ovaert, G. A. Holzapfel, P. Steinmann, E. Kuhl, *Fifty Shades of Brain: A Review on the Mechanical Testing and Modeling of Brain Tissue*, Springer Netherlands, 2019.

Textiles

- **Wowen or embroidered textiles**
  - 3D architectures of fibers are placed an oriented in order to optimize local resistance and rigidity
  - Angiogenesis, vascularization, hernia….



Sofradim Covidien.com

- **Non woven scaffold**
  - Low mechanical resistance
  - High porosity > 95%, but not controlled
  - Large specific surface

https://www.innovationintextiles.com/biofelt-absorbable-scaffold-for-implant-devices/

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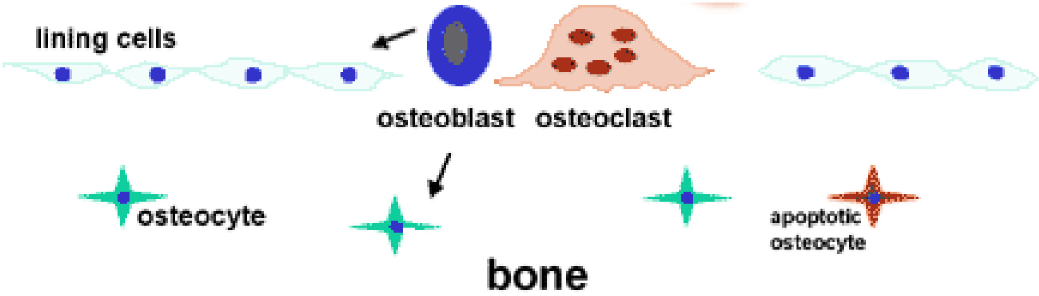
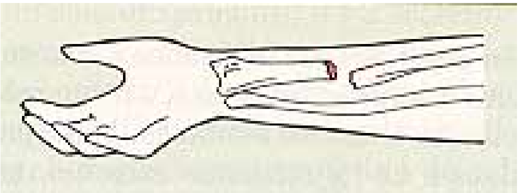
Bone

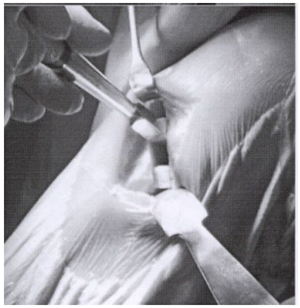
• Bone is a mineralized structure, with 3 functionalities
 - Mechanical
 - Protective
 - Metabolic

• Bone is a living material, going through remodeling

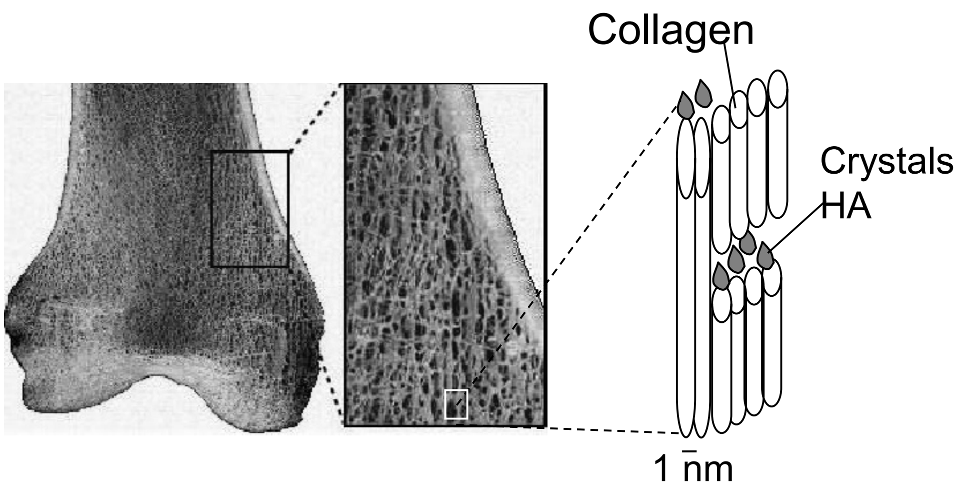


• Problems
 - Fractures
 - Bone injury/trauma
 - Osteotomy





Composite cellular structures



- *Surgeons* look for
  - Improved mechanical resistance
  - Possibility to reshape the graft during surgery
  - Toughness to screw into scaffold
  - Improved biological behavior: rapid bone growth
- *Materials* requirements
  - Composite biomaterials
  - Polymer based implants
  - Porosity > 75%
  - Pores: interconnected with Ø 200-400 μm
  - Mechanical resistance

Foams

	Porosity (%)	Ø pore (μm)	Mechanical property	Advantage	Drawback
Solvent casting / particulate leaching (SC/PL)	90-95	100-180	E_c~160kPa	- Open pores - + short fibers	- *Organic solvent* - Residual particles - Sensitive to person and material - Thin membranes
Gas foaming (GF)	90-95	~100	E_c~300kPa	- No solvent - + fillers / fibers	- Closed pores - Non porous skin
Emulsion freeze-drying (EFD)	90-95	13-35 (< 200)	/	- Open pores - No dissolution step - Thick samples	- Micropores - *Organic solvent* - Sensitive to person and material
Thermally induced phase separation (TIPS)	80-95	20-100 (< 500)	E_c~6MPa σ_c=0.23MPa	- Open pores - Many parameters to adjust pore diameter - + short fibers	- *Organic solvent*

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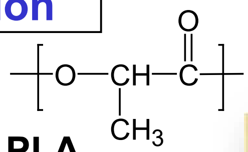
Development of a biocomposite foam

Materials

Compounding

↳ **Homogeneous reinforcement dispersion**



- Bioresorbable polymers
  Poly (L-lactic acid) **PLA**
  IV=1.6-1.8 dL/g; T_m=181.7 °C

- Bioceramics: reinforcement,resorption control,osteoconductivity
  Hydroxyapatite **HA**
  nanometric size; 50 m^2/g
  Tricalcium phosphate **β-TCP**
  micrometric size; 1-2 m^2/g

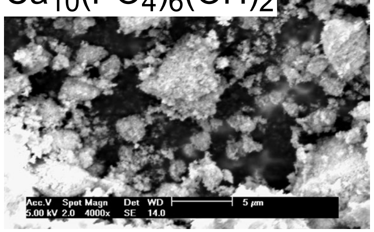
Foaming process

↳ **foaming of bioresorbable polymers filled with ceramic particles**

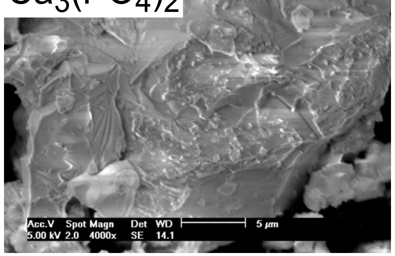
Twin- screw extruder

Autoclave $scCO_2$, P_{max} 300 bar, T_{max} 300 °C

$Ca_{10}(PO_4)_6(OH)_2$



$Ca_3(PO_4)_2$



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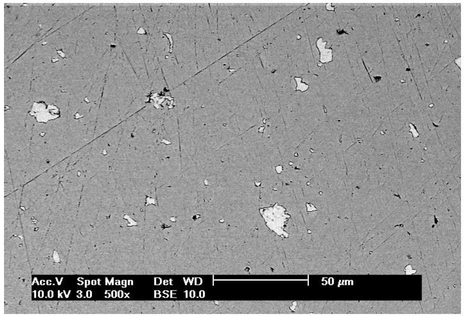
Mixing ceramic into PLA

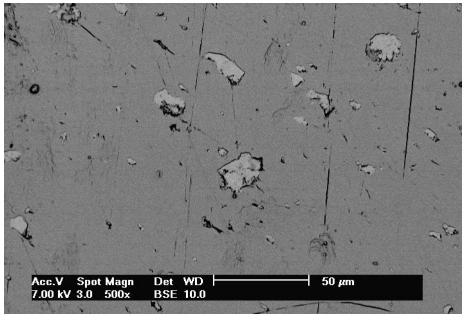
Extrusion

↳ Homogeneous dispersion



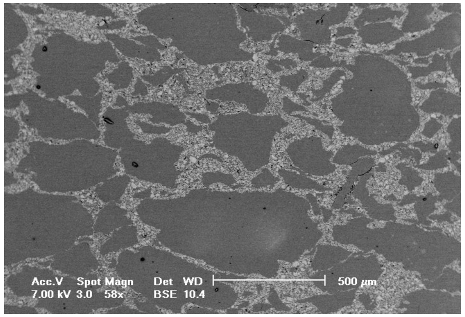
Solvent phase dispersion

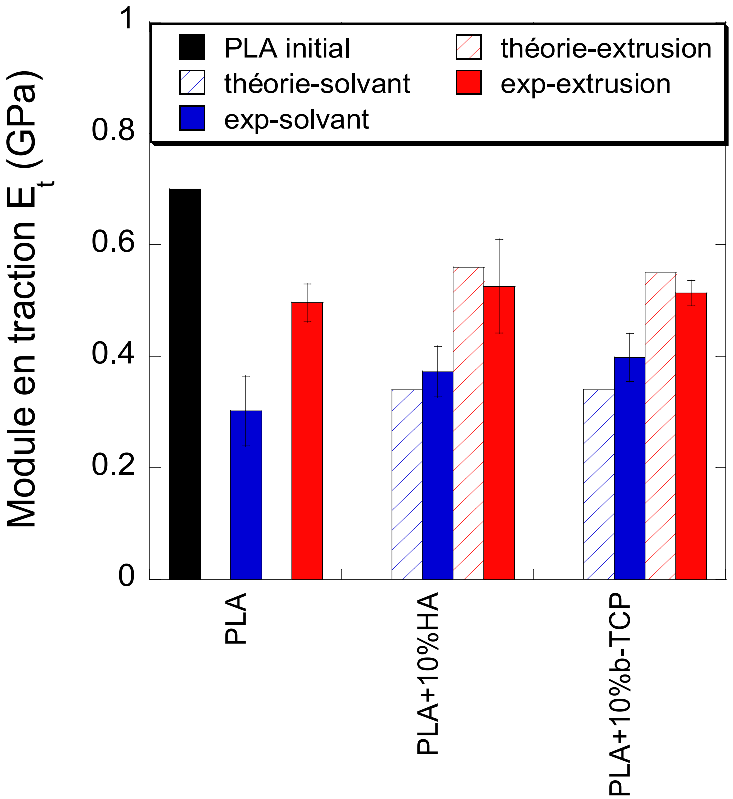
↳ Homogeneous dispersion, but solvent traces



Dry powder mixing

↳ Ceramic rich zones





↳ Extrusion mixing is the chosen method

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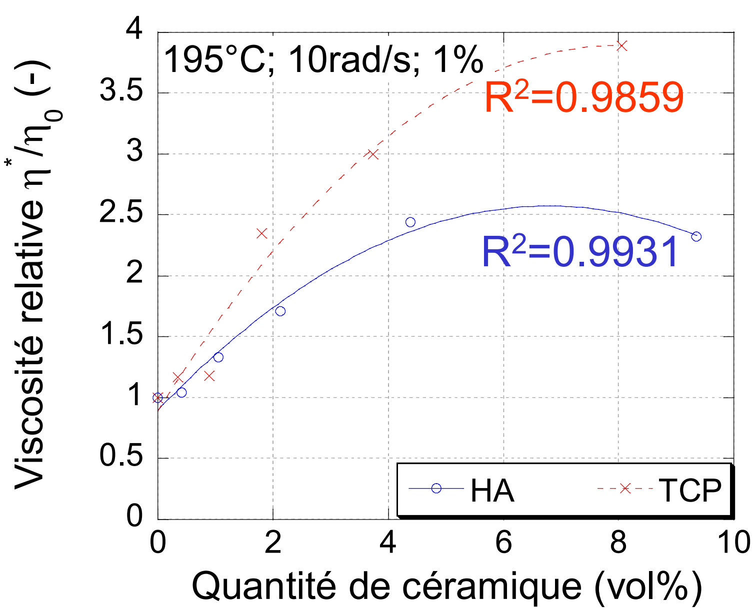
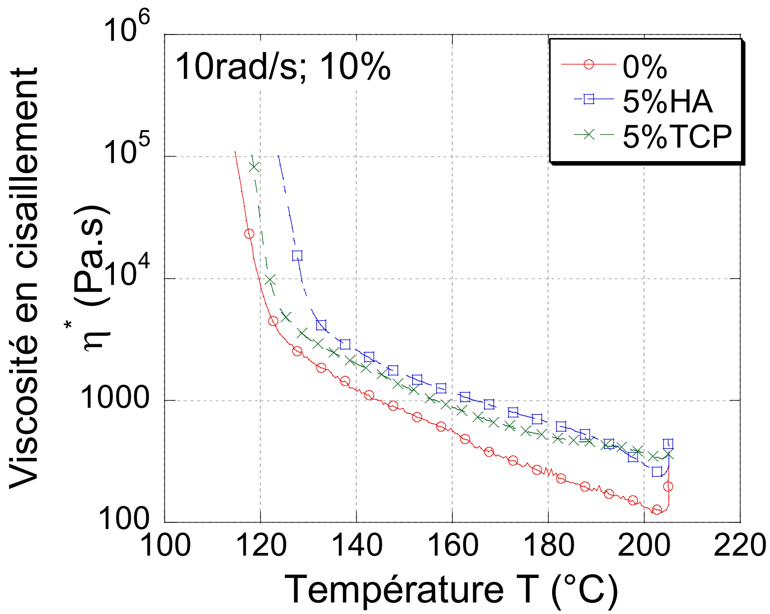
Viscosity of filled PLA





- Semi-diluted suspensions

$$\frac{\eta^*}{\eta_0} = 1 + \frac{5}{2}\Phi + k_2\Phi^2$$

- Filler amount ↗ from 0 to 8 %
  ⇨ η* ↗ by a factor of 2.5-4

- T ↘ by 80 °C ⇨ η* ↗ by a factor 10^3
- CO_2 ↘ by 6 % ⇨ η* ↗ by a factor 2-4

↳ T = main parameter affecting viscosity

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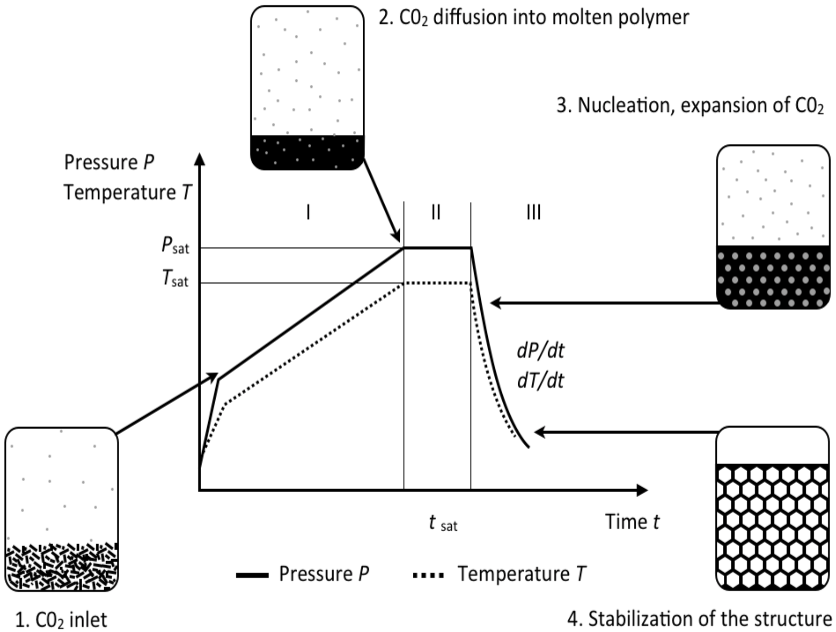
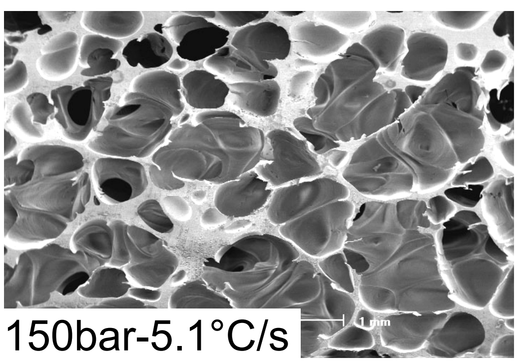
Supercritical CO_2 foaming



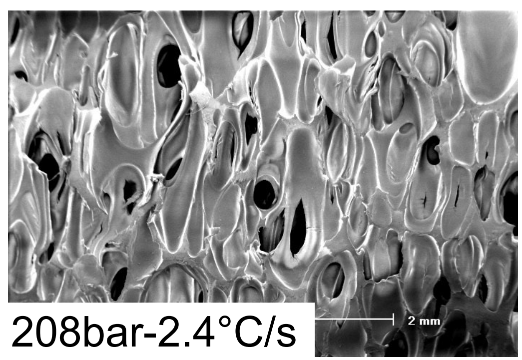
Factors affecting foaming

- External parameters
  - Saturation P_{sat}, T_{sat}, t_{sat}
  - Gas release rate *dP/dt vs cooling rate dT/dt*
- Polymer / CO_2 interactions : *Diffusion Concentration:* C_{CO2}
- Elongational viscosity μ

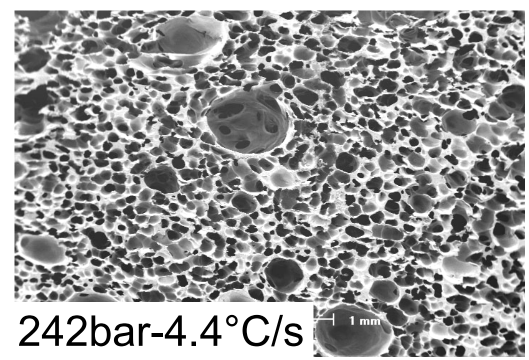
$$\mu = f(polymer, T, C_{CO2})$$



150bar-5.1°C/s



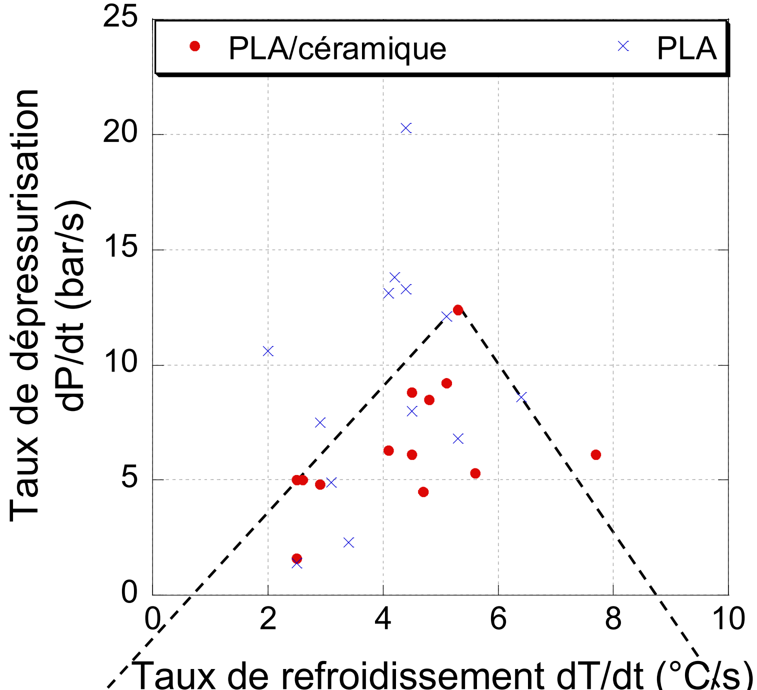
208bar-2.4°C/s

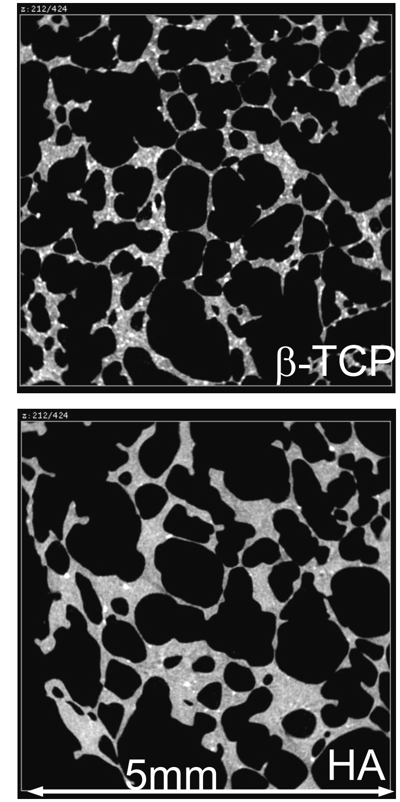


242bar-4.4°C/s

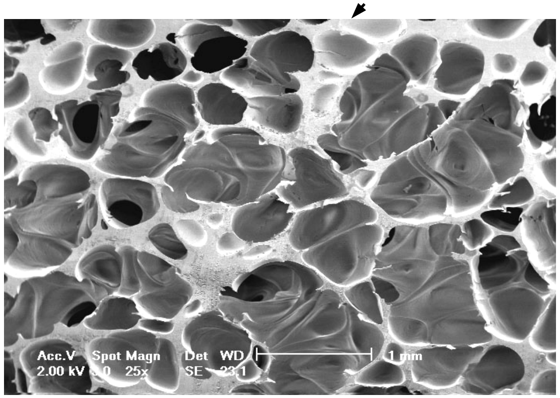
↳ Higher saturation pressure ⇨ smaller pores, higher porosity
↳ Slower cooling rate ⇨ more open porosity

Foaming biocomposite PLA

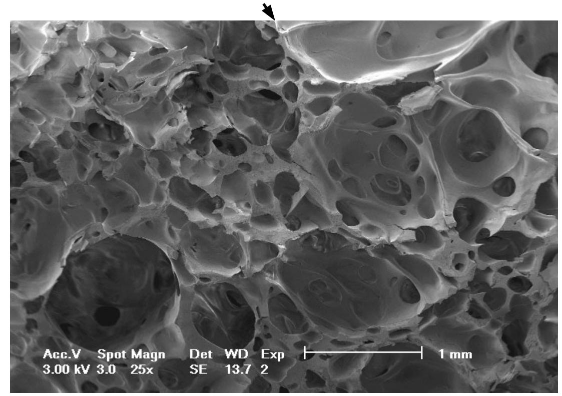




Homogeneous dispersion of fillers in pore walls

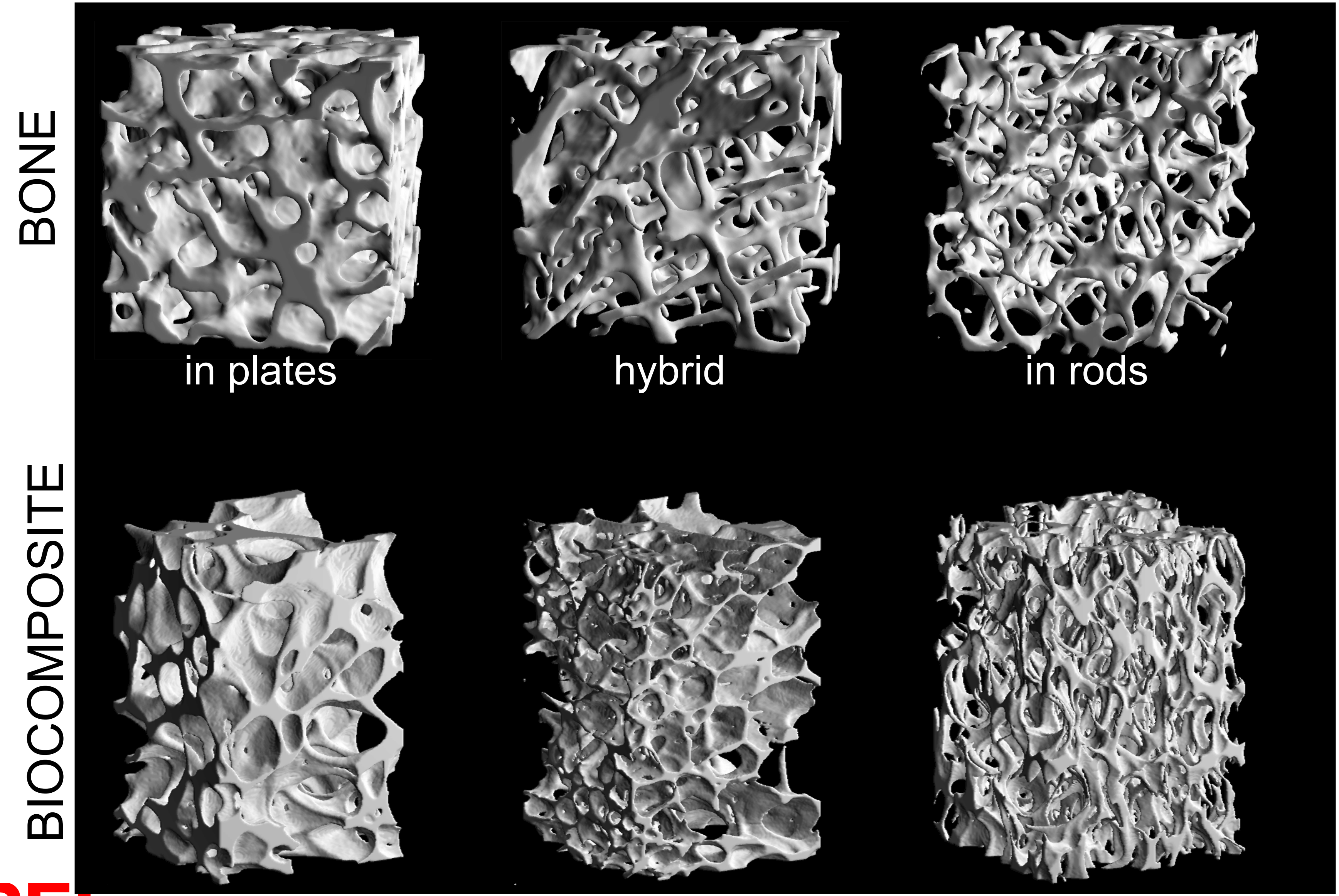


PLA



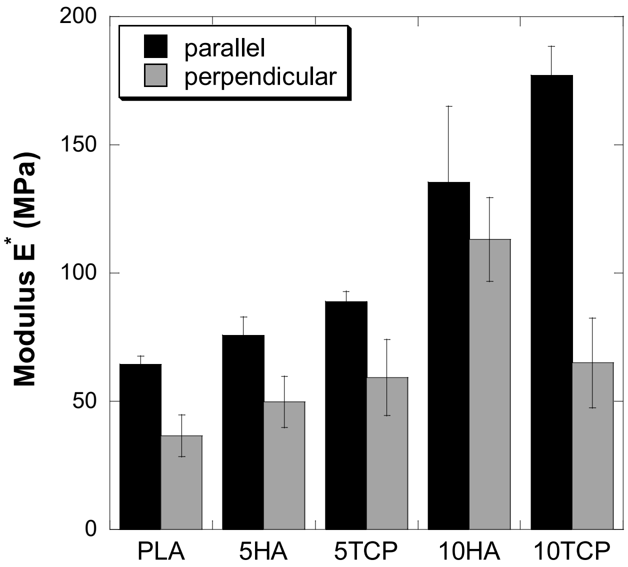
PLA + 5 wt% HA

Trabecular bone and composite foams



Mathieu et al 2006

Mechanical behavior



- Filler volume ↗
  - ⇨ modulus E^* and yield stress σ^* ↗
  - ⇨ improvement of foam mechanical resistance

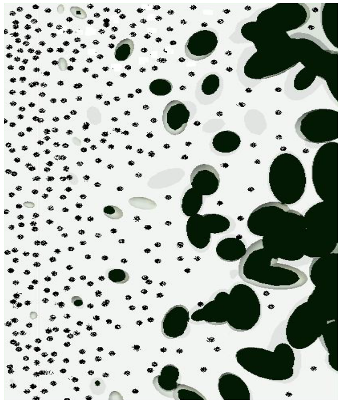
- E^* up to 250 MPa
  σ^* up to 6 MPa

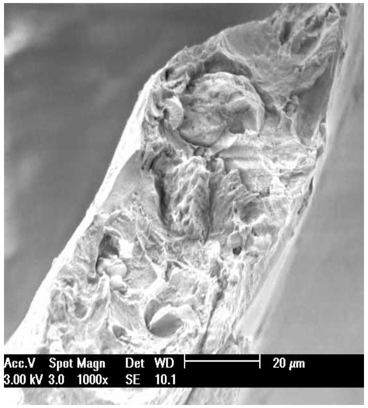
} Suitable for trabecular bone regeneration

Cellular composites with long fibres

Porosity Gradient

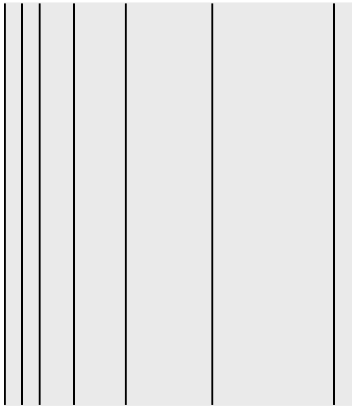
...with fillers

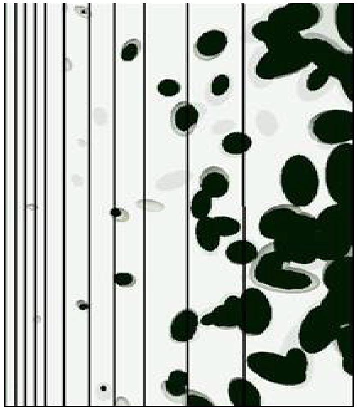




✓ **...MPa**

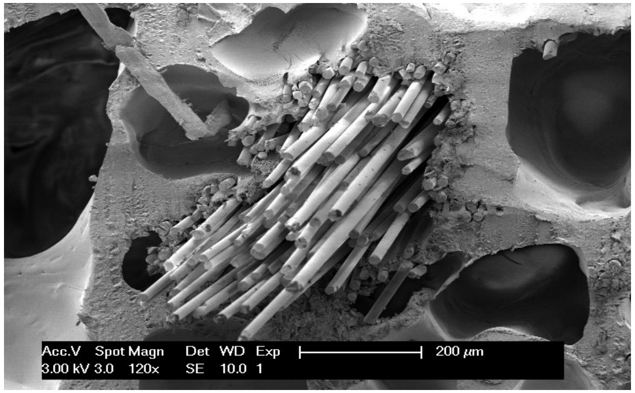
+ gradient of fibres

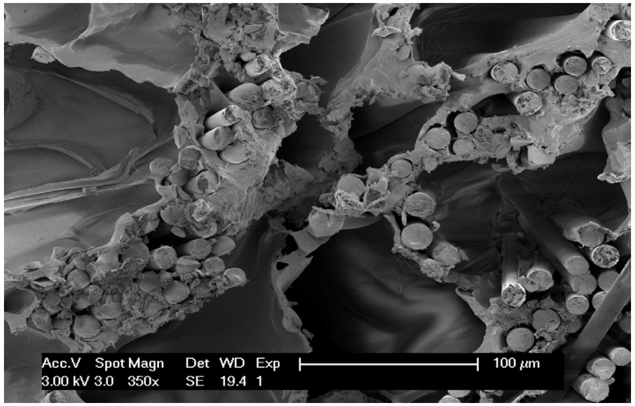




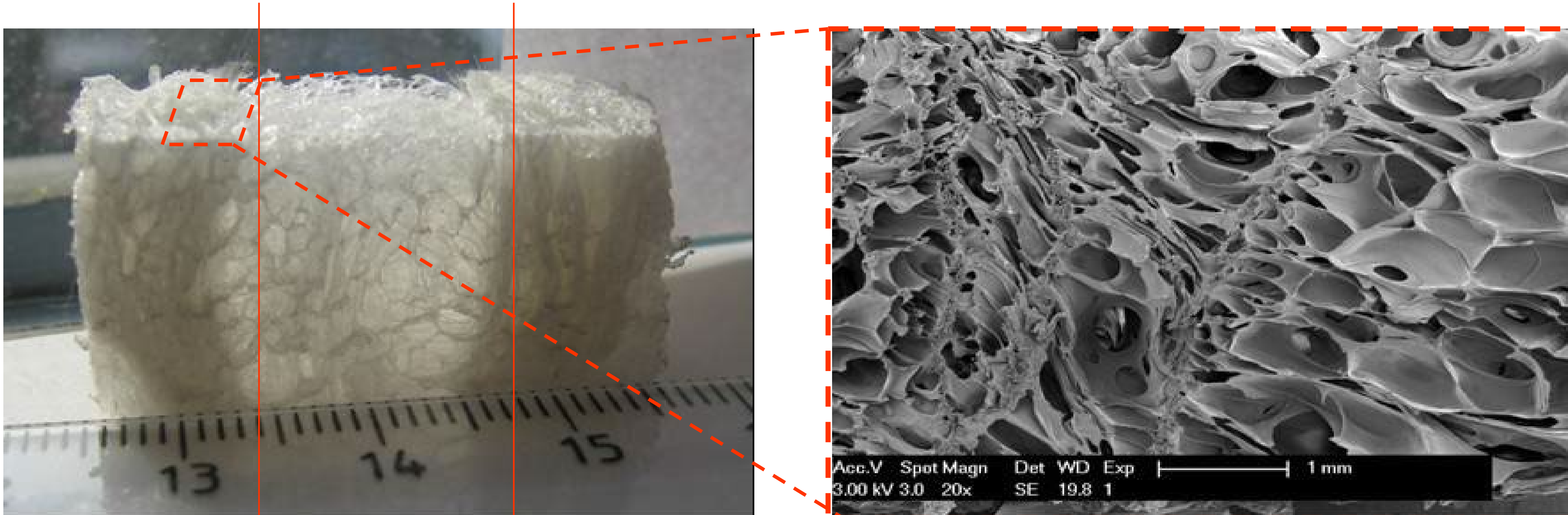
? **...GPa**

Foaming biocomposites with continuous fibres





Gradients in fibre & porosity fraction

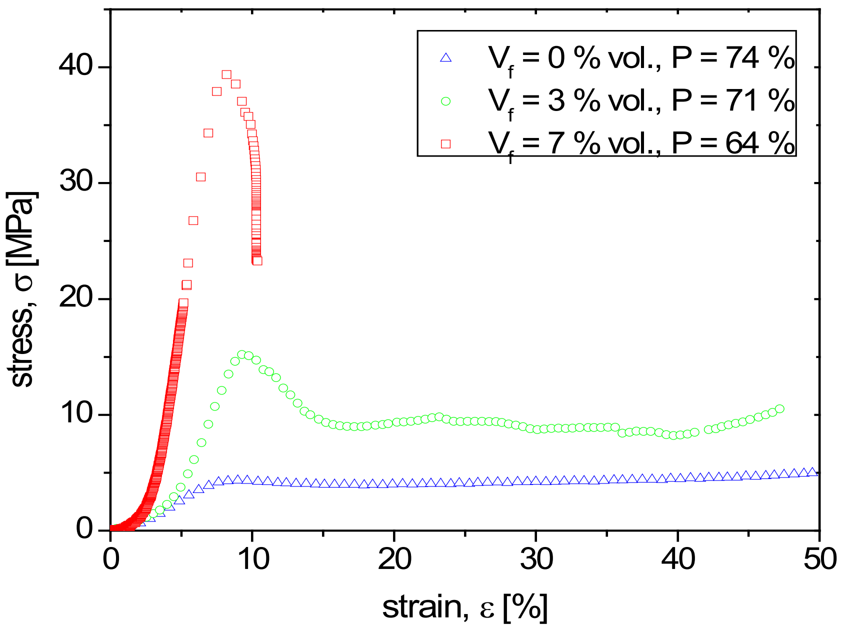


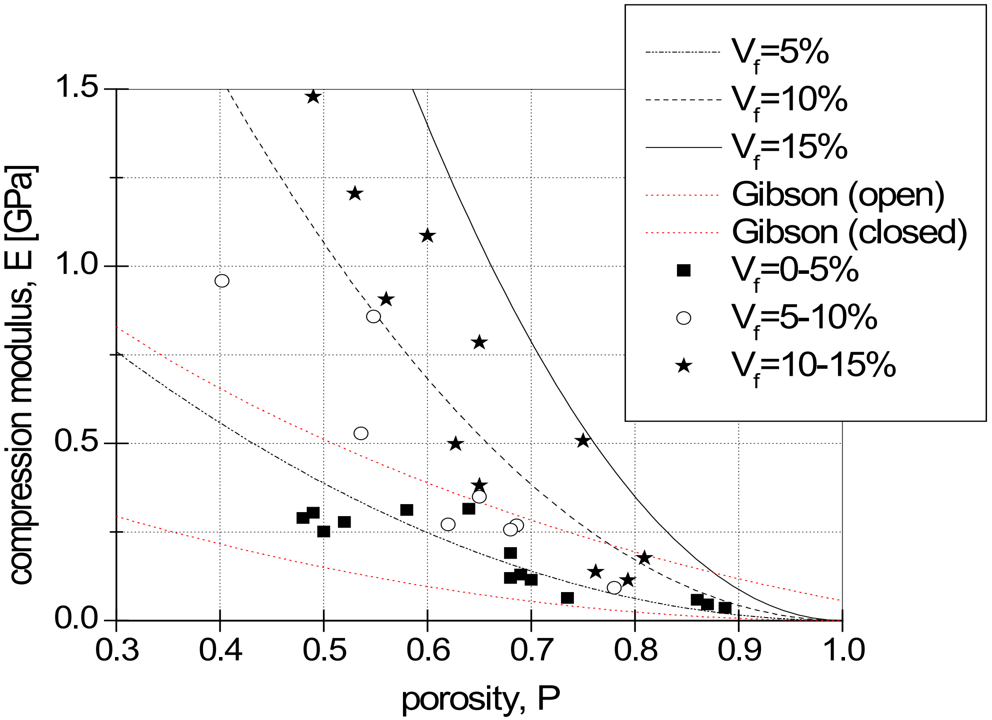
V_f [%]	4	0	4
P [%]	70	90	70
V_m [%]	26	10	26

A smooth transition of the composites architecture from skin to core entails an advantageous distribution of internal stresses.

EPFL *pierre-etienne.bourban@epfl.ch*

Fibres for mechanical performance





Even little fibre content stiffens the cellular composites.

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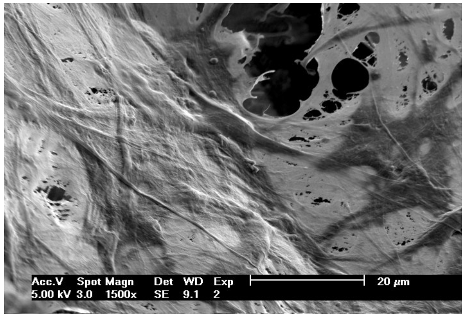
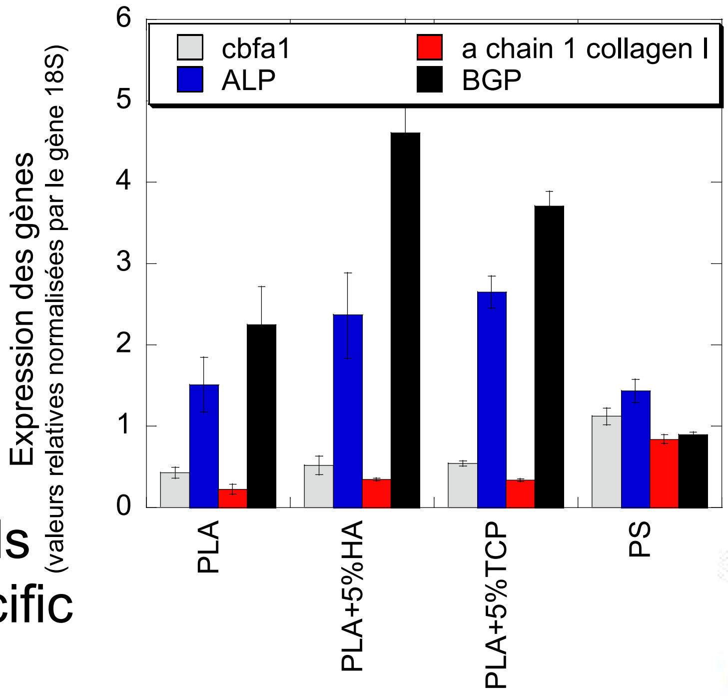
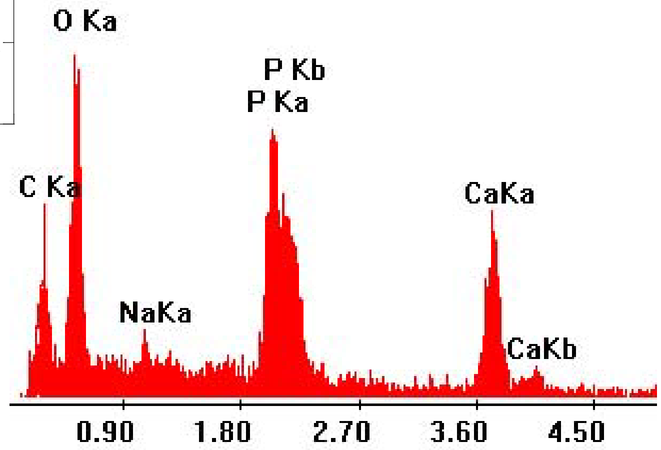
In vitro biocompatibility



• *Proliferation*: cells spread on the support



• *Mineralization*: CaP crystals are formed in presence of cells



• *Differentiation:* cells express genes specific of osteoblastic phenotype

➯ Biocomposite scaffolds are biocompatible with bone fetal cells

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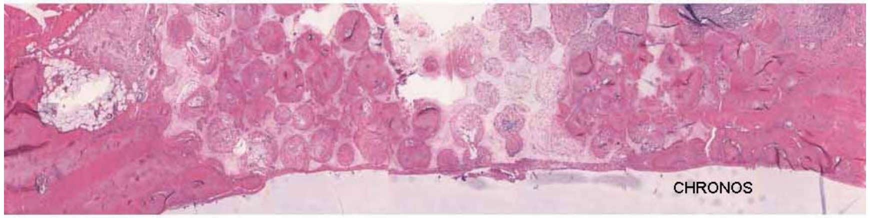
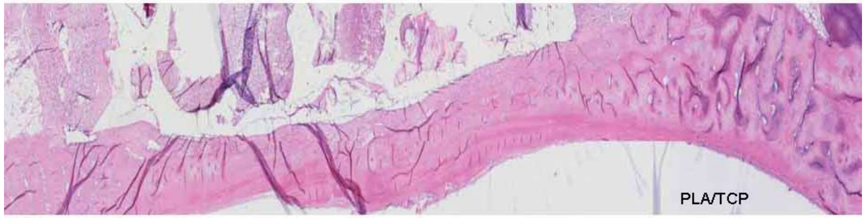
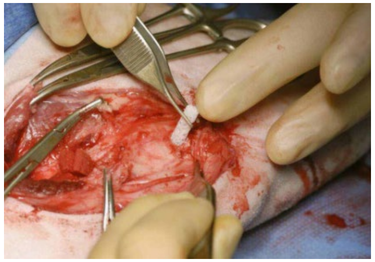
In vivo biocompatibility

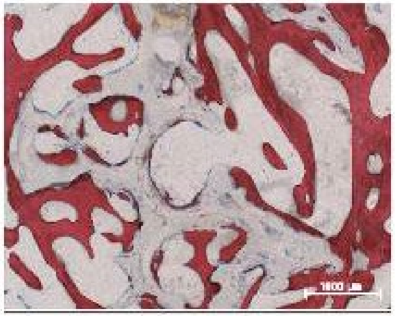
- **Rats**: cranial critical size defect





- **Sheep :** Femoral and tibial defects





➯ no inflammation, ossification

- **Human**

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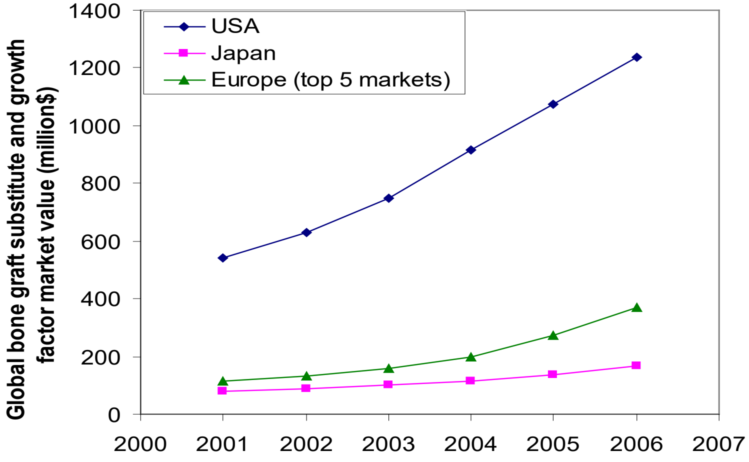
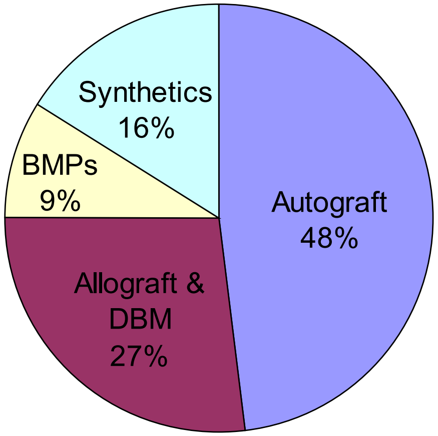
Bone grafts market

- Worldwide: 1'350'000 /year



↳ Constant growth of bone grafts: +7% per year

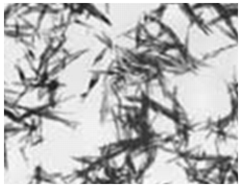
- Bone graft distribution

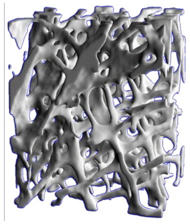


↳ Search for a synthetic substitute which favors bone regeneration

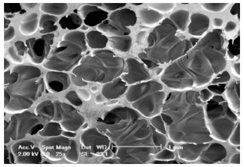
- Highly competitive & fragmented market
- A new product must demonstrate
  - Its unique selling proposition
  - Be customer oriented

Comparison with existing products





	Autografts *gold-standard*	Allografts *Osteotech*	Ceramics *Synthes*	Polymers *Macropore*	Gels *Ostim Medical*	Proteins *Stryker OP-1*	EPFL Composite
Osteocon-ductive	+++	+++	++	+	++	+++	++
Osteoin-ductive	+++	+	0	0	+?	+++	0
Qtty available	---	-	+++	+++	+++	+++	+++
Shapability	+	+	-	+	n.a.	n.a.	+++
Mech. resistance (compare to bone)	=	=	>>> (brittle)	<<	no	n.a.	=



Biocomposite A: shape your scaffold

Roadmap

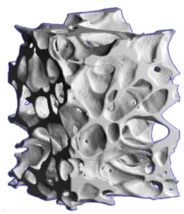
Clinical study

Add. Biotests

Sheep *in vivo* study

Rat *in vivo* study

Industrialization, distribution



Product registration
CE, ISO 10993

Research phase
Process/material

Development phase
Stability

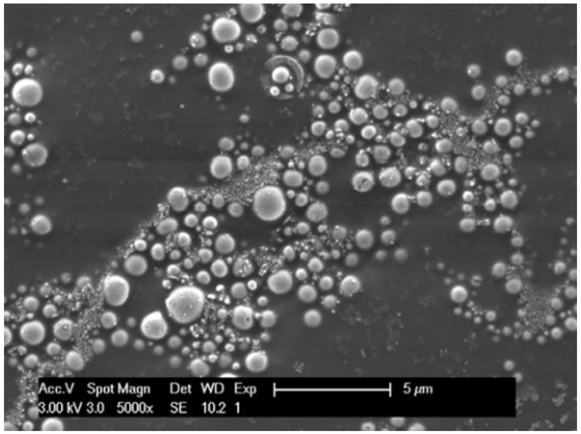
Process/material
reliability

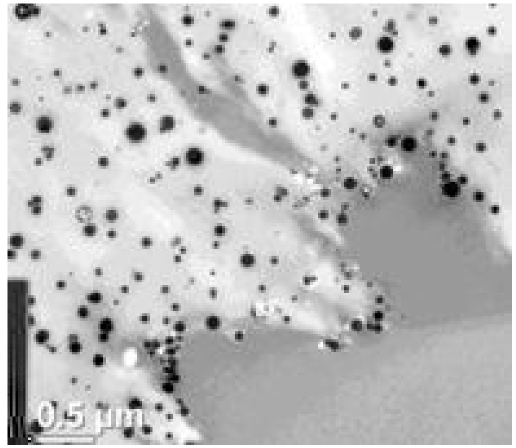
materials portfolio | processing | *in-vivo* | clinical study | product distribution

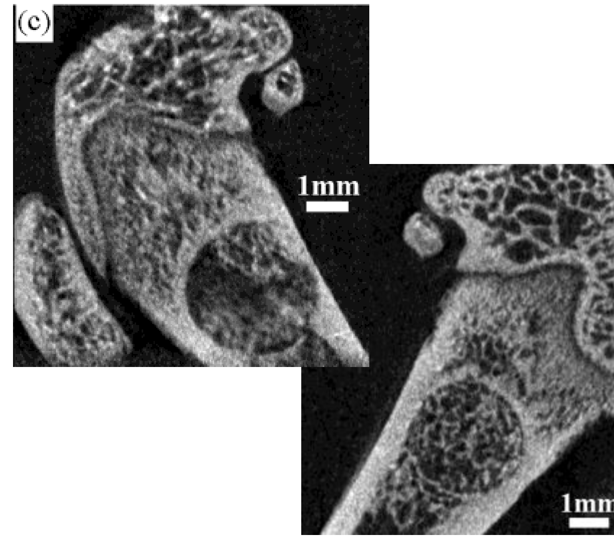
EPFL-LTC | + EPFL-LBO | +CHUV | Company

Biocomposite B : more osteoconductive

cellular nano composite







Same PLLA polymer
Same process

Biocomposite A → **Biocomposite B**

New nano filler

Delabarde, Plummer 2011

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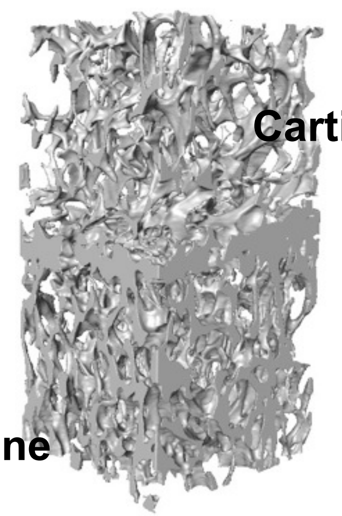
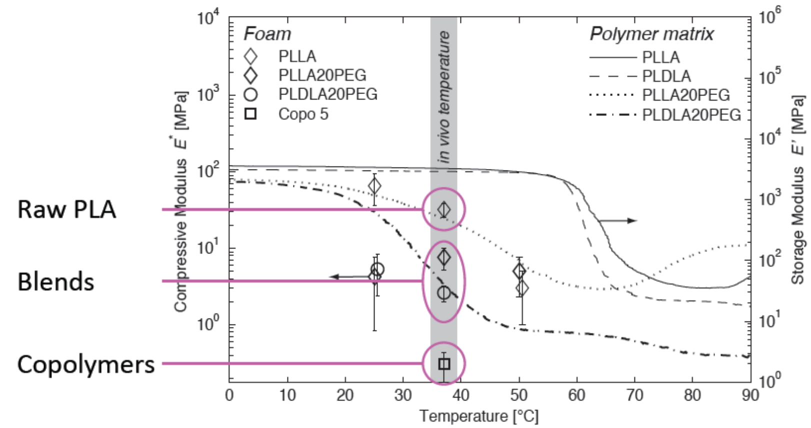
Biocomposite C : Softer cellular scaffold

PLLA blends and copolymers



Cartilage

Bone



Biocomposite A and B: 40-100 MPa

Same process

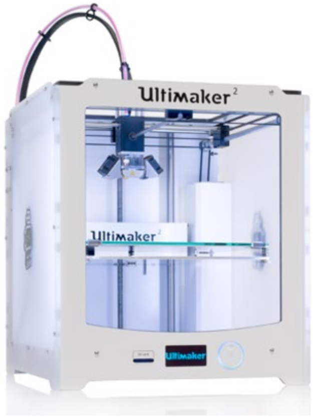
Tailoring of polymer

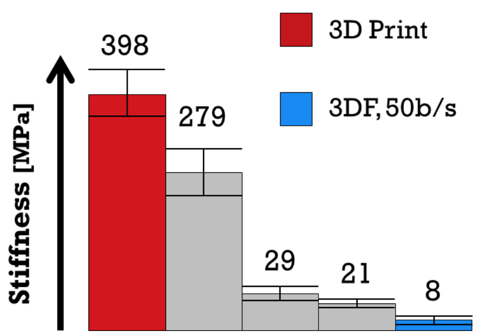
Biocomposite C: 4-15 MPa

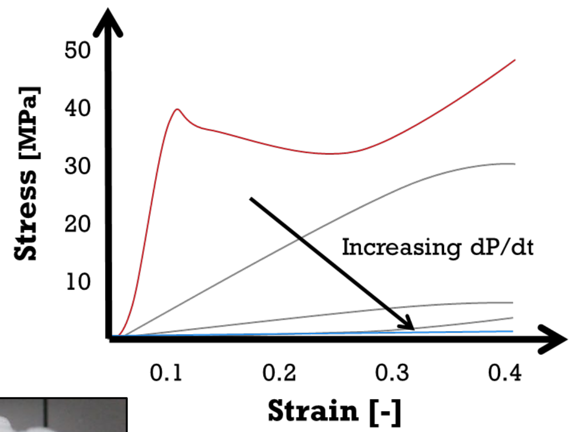
Cuénoud, 2012

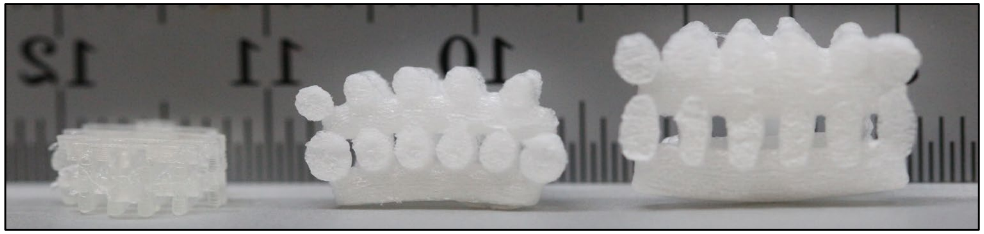
Biocomposite D : 3D printed scaffolds

- **Custom-made 3D structures**
  - Reproduce geometry of body parts, surgeon support, replica of in vivo milieu
- **In vitro platforms to study cell response and drug screening**
  - scaffold pore size, geometry, wettability, adhesion, mechanical loading on cells behavior
- **Templates/scaffolds for tissue regeneration**
  - Building inner architecture and surface properties
  - Mechanical performance, permeability, nutrients diffusion,cell response…







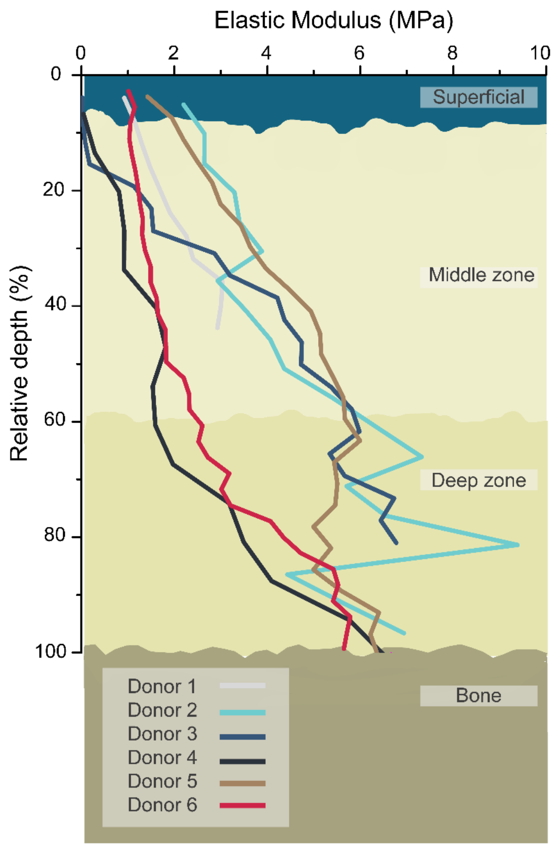


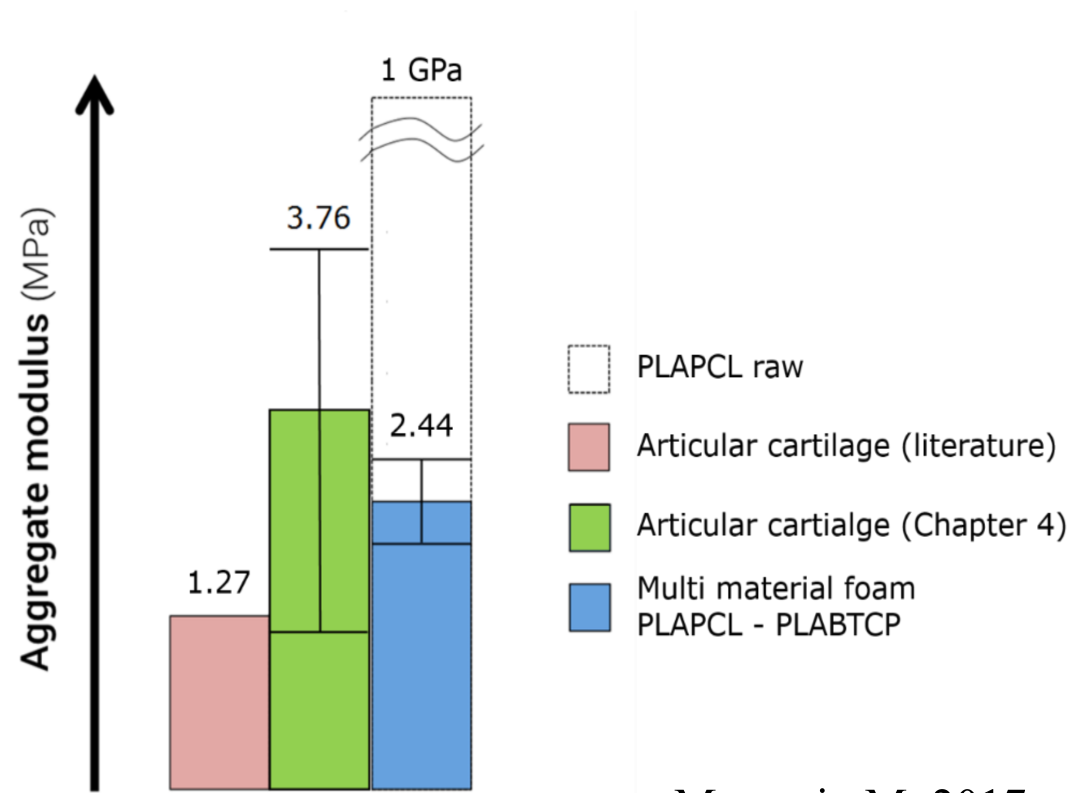
Matteo Marascio

www.rts.ch/play/tv/le-court-du-jour/video/imaginez-un-monde--os-et-cartilage-artificiels?id=8173609

FDM of different PLA based structures

Human cartilage | Model | 3D Printed | Foamed

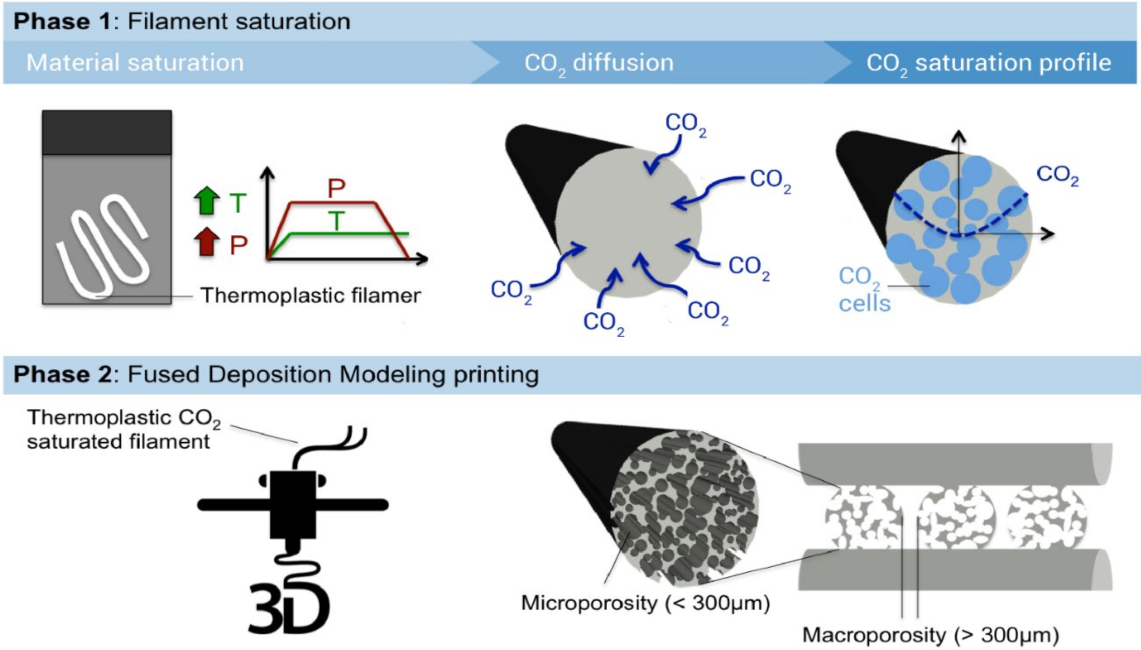


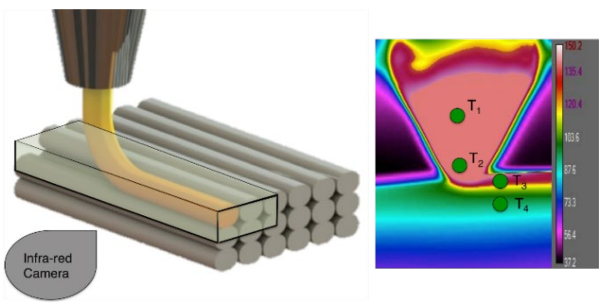


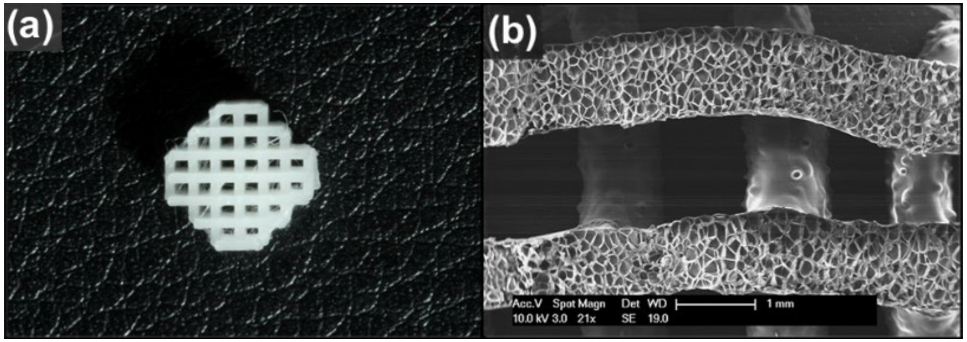
Marascio M. 2017

pierre-etienne.bourban@epfl.ch

Direct 3D Foam Printing

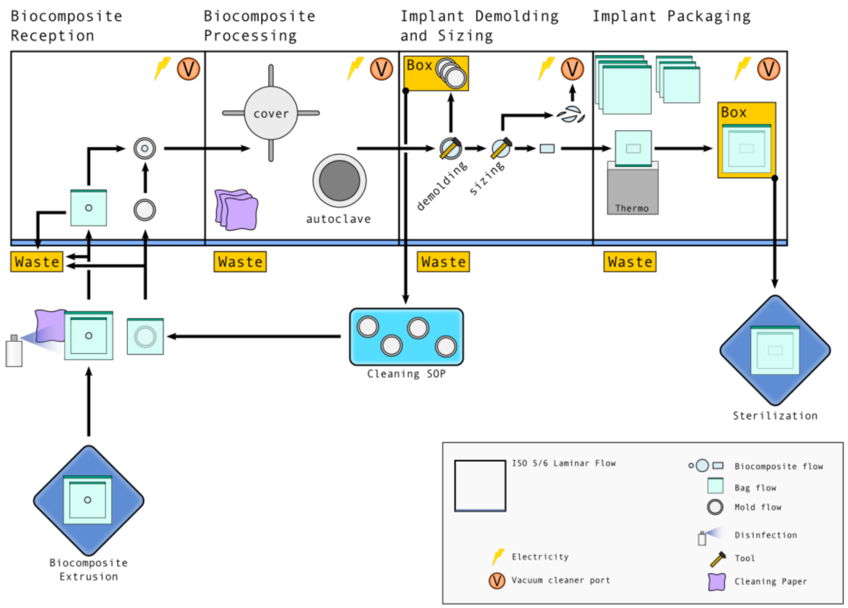






Marascio M. et al JAMT, 2017

Processing for medical devices



- **Additional phenomena to control**
  - **Degradation during processing**
    - **Drying**
    - **Molecular weigth drop**
  - **Contamination**
    - **Environment**
    - **Tools**
  - **Sterilization**
    - **EtOH**
    - **Gamma**

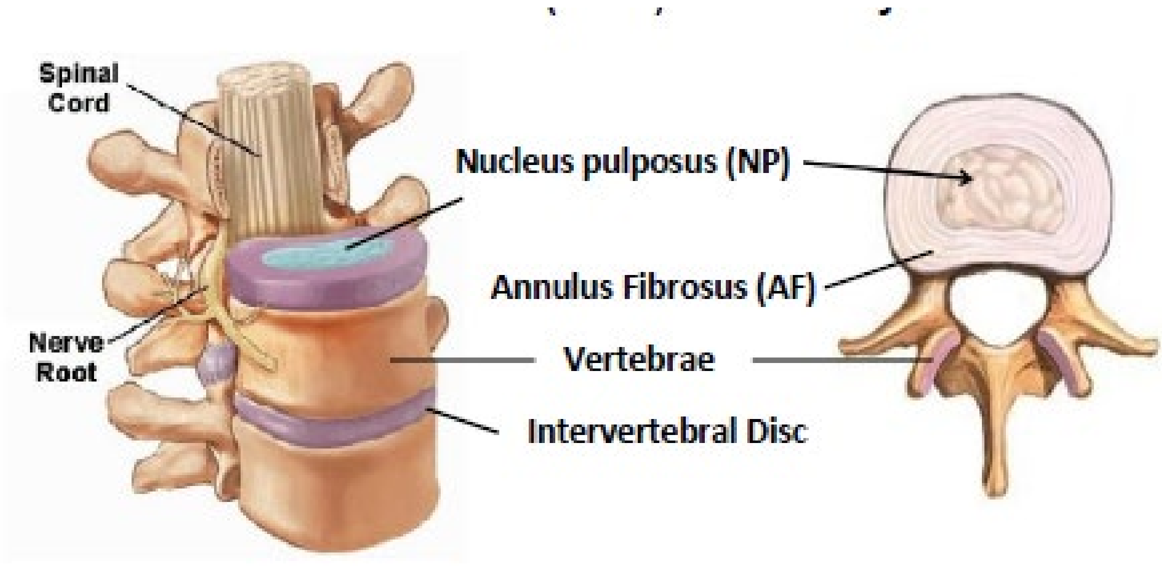
Biocomposite D : 3D printed devices

OUTLINE

- Introduction
- Bulk biocomposites
  - Dental applications
  - Prosthesis
- Porous biocomposites
  - Textiles
  - Foams
  - Bone tissue engineering
- Composite hydrogels
  - Synthesis
  - Mechanical performance
  - Nucleus pulposus, cartilages…

Why a nucleus pulposus (NP) implant ?

- 80% of world population will suffer from back pain due to degenerated discs.
- Disc degeneration starts at the age of 30.
- Recent trends in surgery are shifting toward preservation techniques.
- Spine market is growing by 15%-20% a year



Biomechanics of the healthy NP

Property	Estimated value
Water content	65%-90% (Antoniou 1996)
Swelling pressure	0.1 MPa – 3 MPa (Iatridis 1997)
Hydraulic Permeability	$6x10^{-16}$ m^4/Ns – $15x10^{-16}$ m^4/Ns (Iatridis 1998)
Hydrostatic pressure	0.1 MPa- 2.3 MPa (Wilke 1999)
pH in tissue	6.9 – 7.2 (Anderson 2005)
Young's modulus	3 kPa – 6 kPa (Cloyd 2007)
Dynamic shear modulus ($\|G^*\|$)[a]	7 kPa – 21 kPa (Iatridis 1997)
Tan (δ)	0.45 (Iatridis 1997)
Tensile/compressive strain	± 10% (max ± 25%) (Tsantrizos 2005)

[a]frequency: 1-100 rad·s^{-1}

Some examples of other types of tissue for comparison:

- Compact bone: |G*| = 4GPa tan(δ) = 0.01 (Lakes 1979)
- Spinal motion segment: |G*| = 45MPa tan(δ) = 0.1 (Ohshima 1989)
- Meniscus: |G*| = 100kPa tan(δ) = 0.40 (Zhu 1994)

Polymer hydrogels for nucleus replacement

Requirements

- Biocompatibility
- Ease of implantation
- Chemical and mechanical stability
- Mechanical properties close to natural NP
- Swelling ratio
- Fatigue and tear resistance
- Cost/risk & cost/production

Approach and Challenges

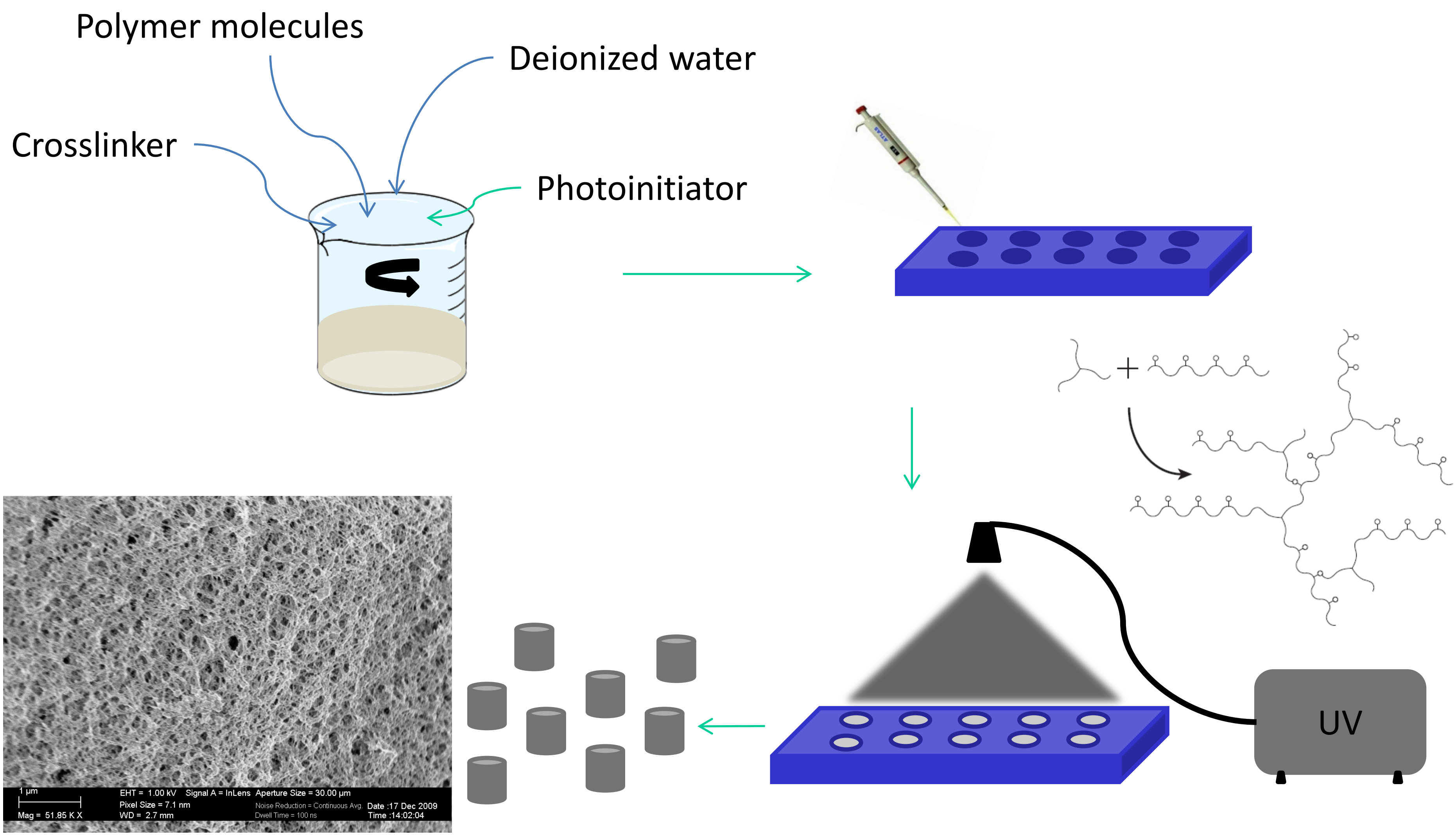
Injectable, in situ curing

New material system, UV curing

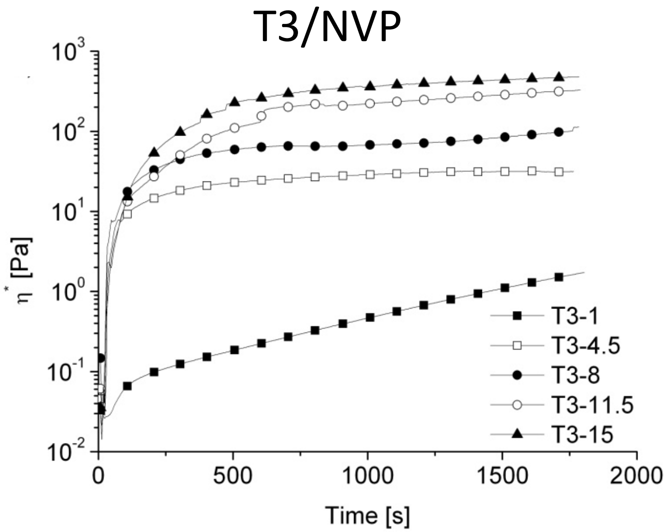
Hydrogel, composite hydrogel

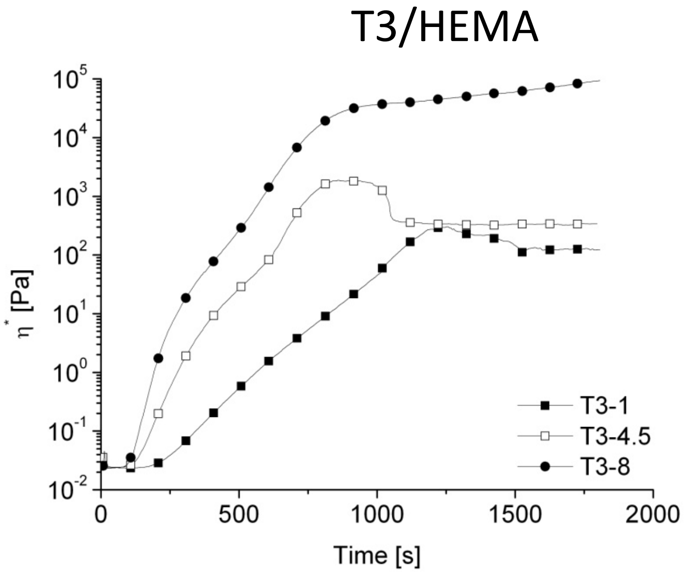
Easy to synthesize molecules

Synthesis and Curing kinetics



Influence of the crosslinker (T3) concentration

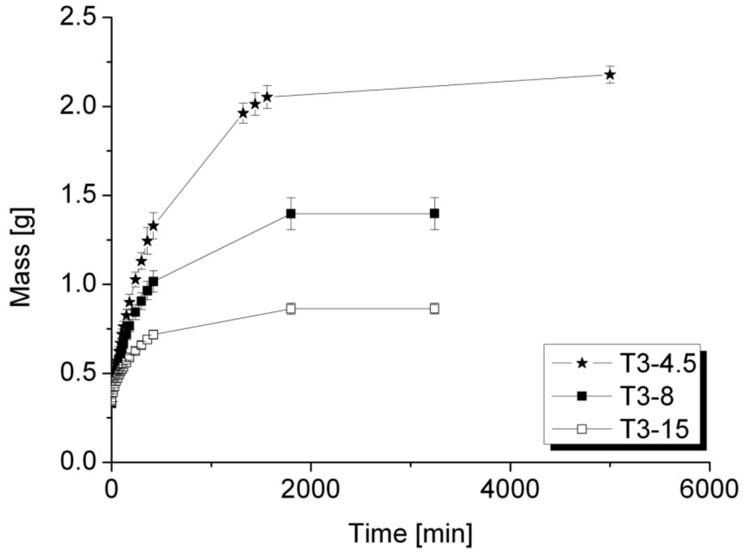




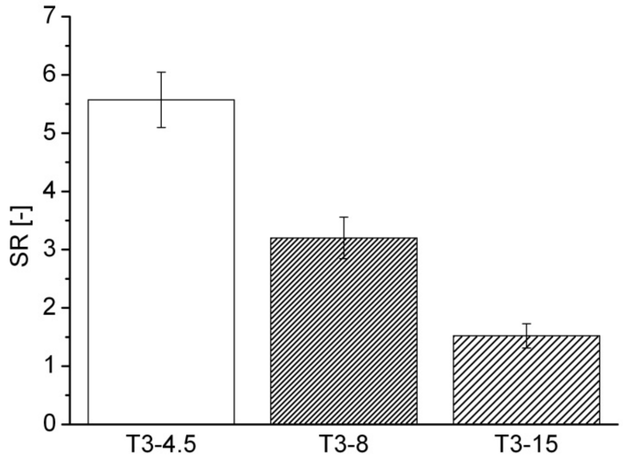
- Plateau indicates end of polymerization.
- η* increases with T3 concentration → stiffer network.
- T3/HEMA hydrogels stiffer than T3/NVP hydrogels.
- Curing time longer for T3/HEMA hydrogels.

- Stiffness of network defined by T3 concentration.
- Short curing times induce low stiffness of hydrogel network.

Swelling behavior

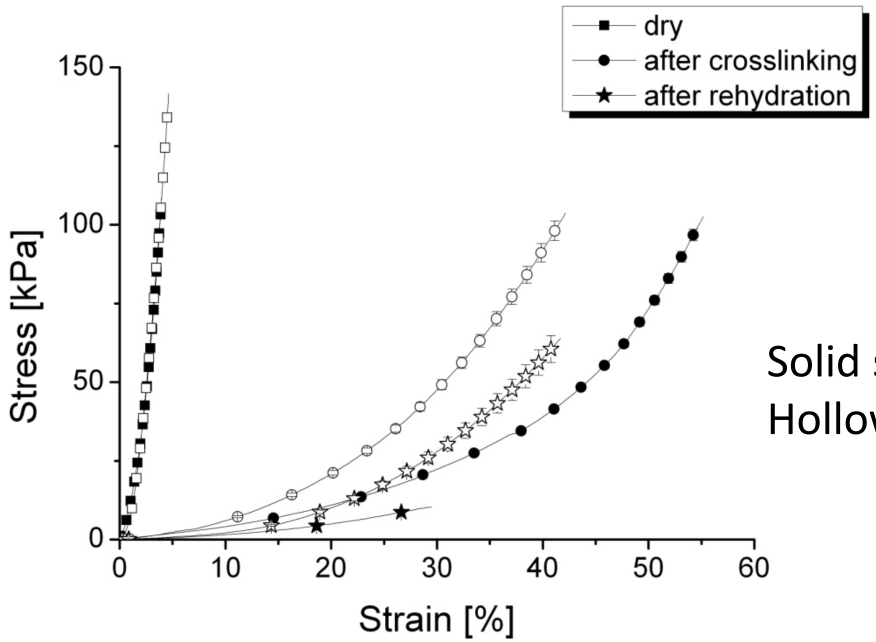


$$SR = W_s/W_d = (W_w - W_d)/W_d$$



- The amount of crosslinker T3 controls the swelling capacity of the hydrogel network.
- The swelling ratio of developed hydrogels varies from 1.5 to 5.6 which is in the range of the native nucleus ratio (1.8 to 9).

Compression of hydrogels



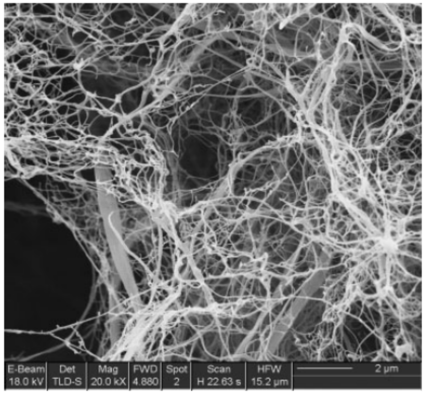
Solid symbols: T3-8
Hollow symbols: T3- 15

	E (dried samples) [kPa]	*E* (after polymerization) [kPa]	*E* (after rehydration)[kPa]
T3-8	2200	50	3
T3-15	2500	80	4

- Stiffness can be tailored mainly with PBS content.
- Modulus of native nucleus (3 to 6 kPa) achieved but ideal NP implant should be higher.

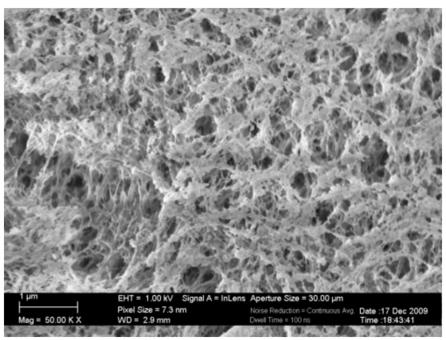
Composite hydrogels

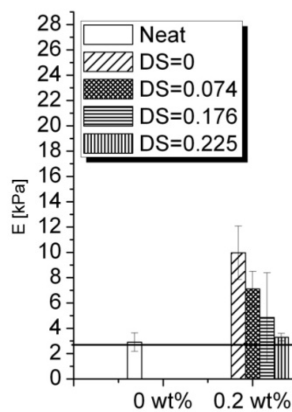
Hydrogel + Nanofibrillated Cellulose (NFC)



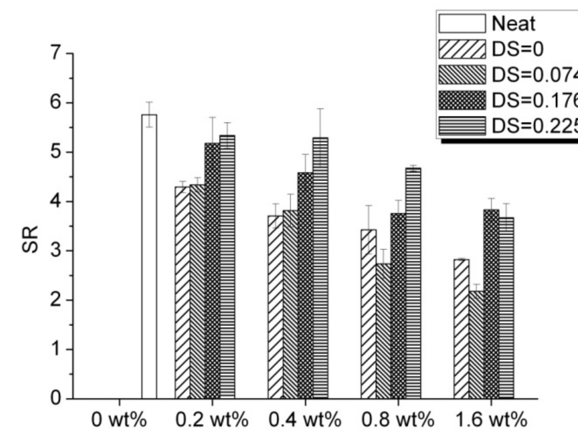
Zimmermann T, Advanced Engineering Materials. 2004;6(9):754-61

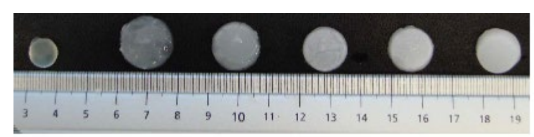
- Synthesis of injectable, UV cured polymer hydrogel
- NFC % increases E elastic modulus of 3 to 8-fold.
- Swelling behavior SR hindered by high concentrations % of neat NFC.
- Modification of fibrils hydrophilicity (DS) to tailor the swelling





$$E = \left(\frac{d\sigma}{d\varepsilon}\right)_{\varepsilon\to 0} = \alpha \cdot \beta$$





Borges, ActaBiomateriala, 2011
Eyholzer, Biomacromolecules, 2011

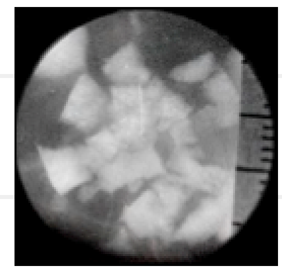
Application requirements for selecting the final materials

- Failure and fatigue performance
- Injection and UV curing
- Maintaining disk height
- *Ex and in vivo* studies

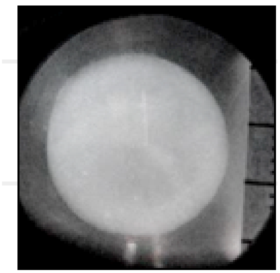
Alini, Mauro, et al. European Spine Journal (2008)

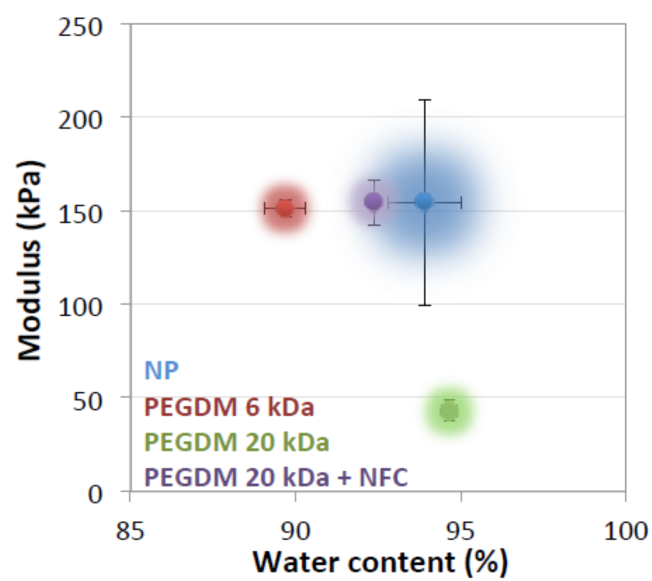
PEGDM hydrogels and cellulose fibrils

PEGDM 6 kDa at 63% compression:



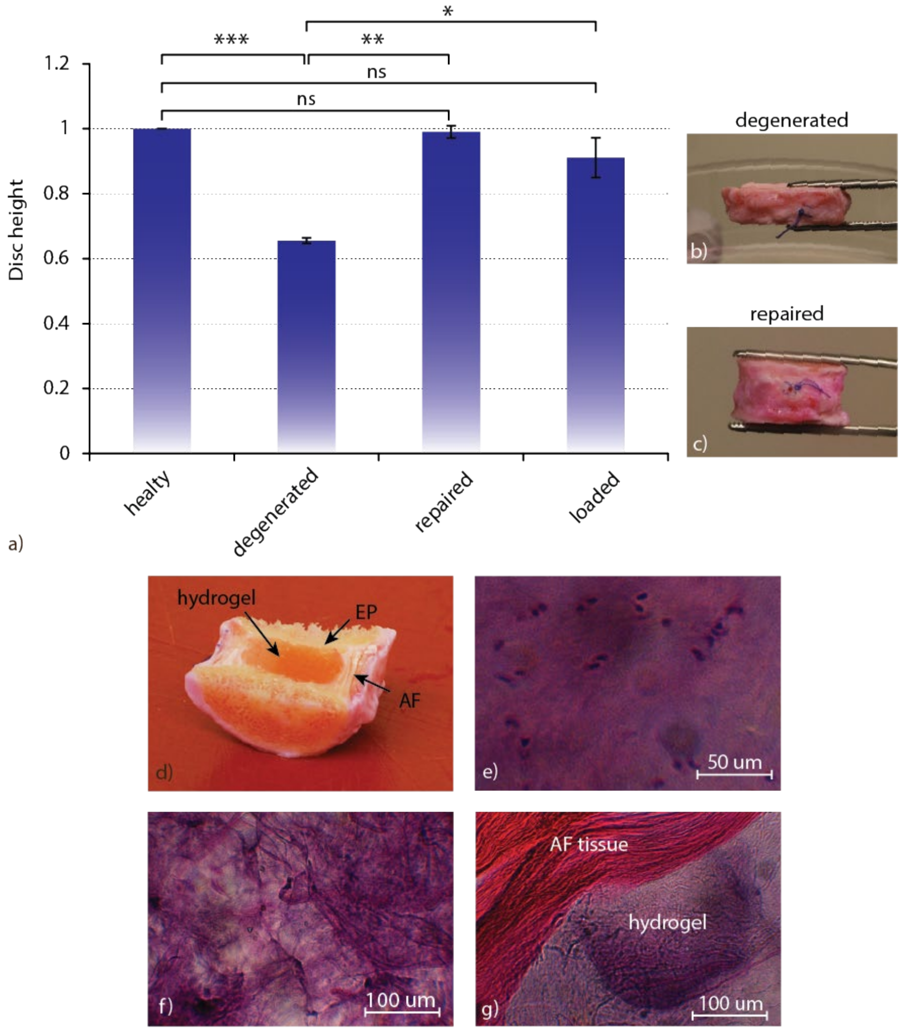
PEGDM 20 kDa reinforced with NFC at 80% compression:





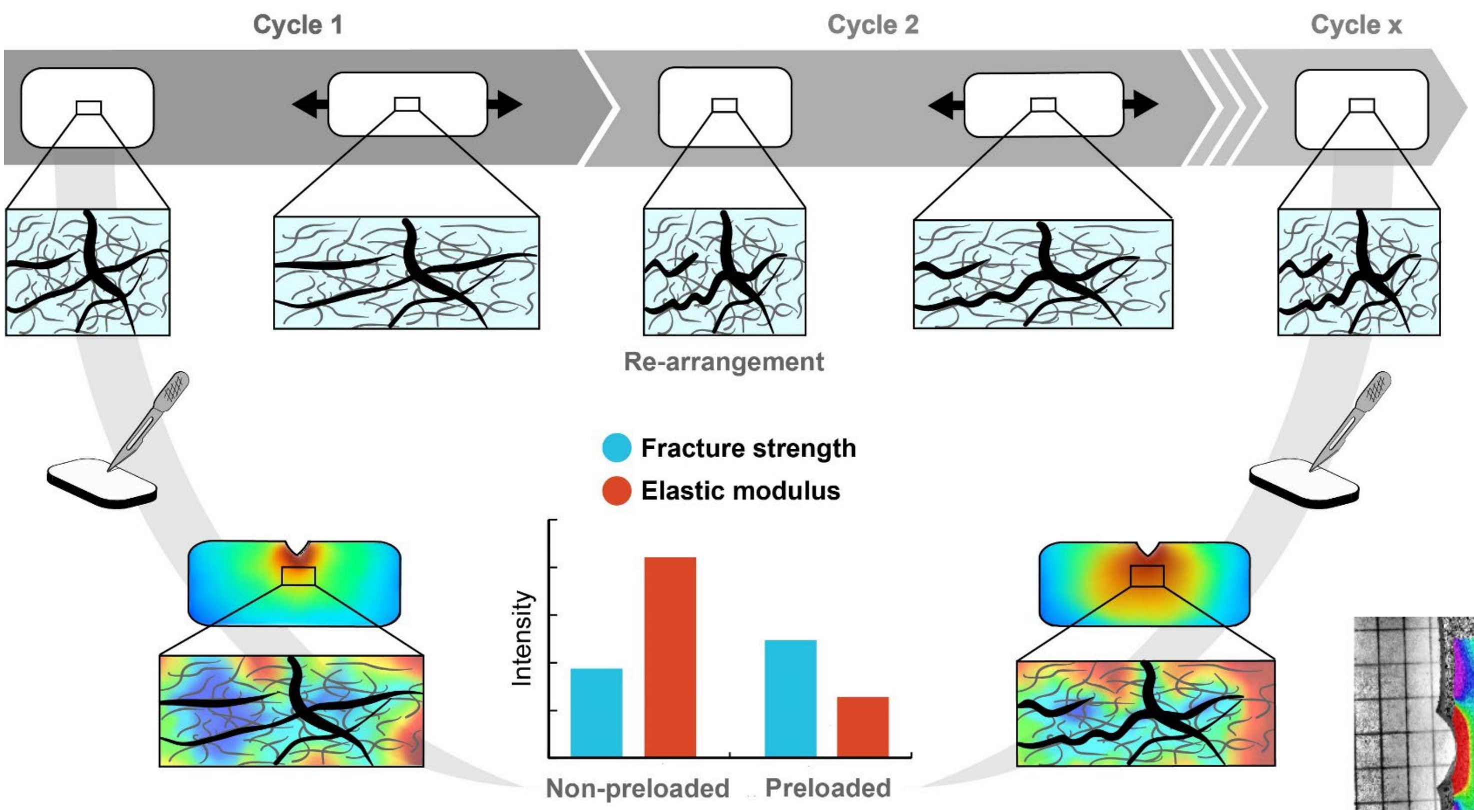
Khoushabi, CSTE, 2015

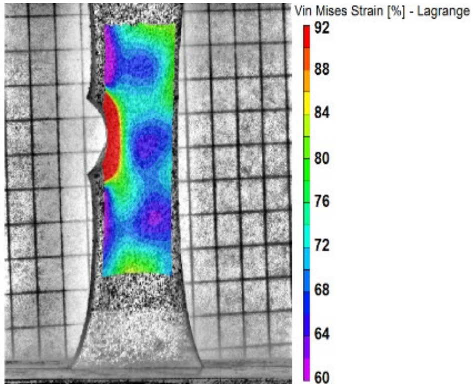
Bovine animal model



Khoushabi, Schmocker, et al 2015

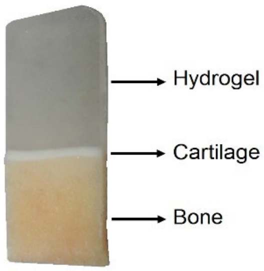
Hydrogel composites for fracture strength, dissipation, adhesion…

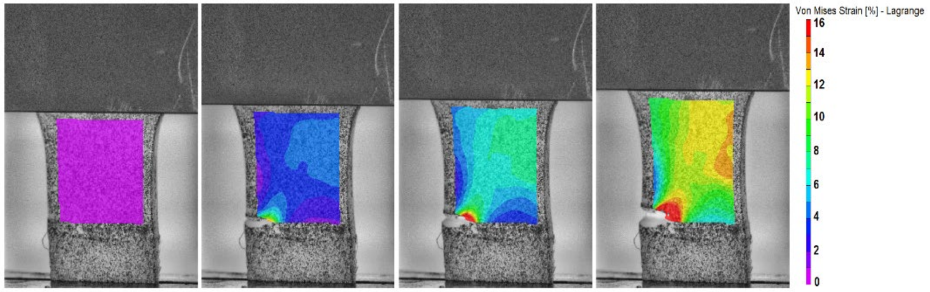


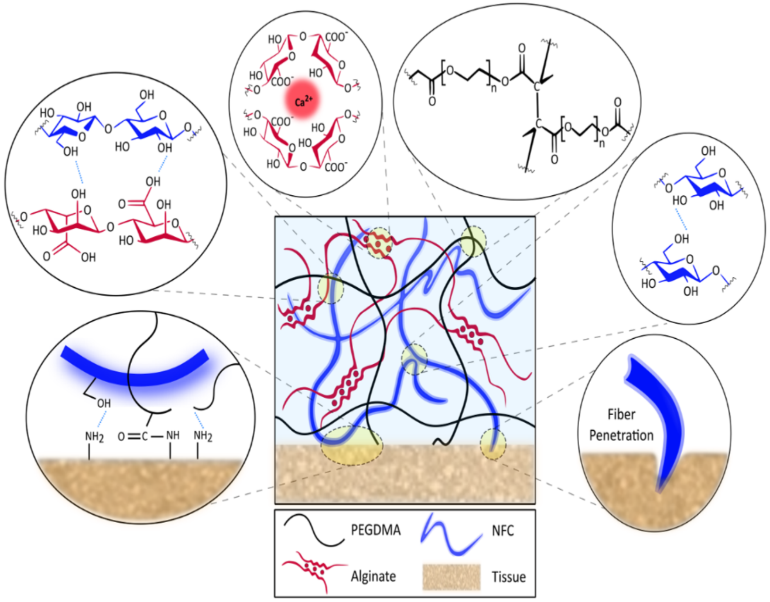


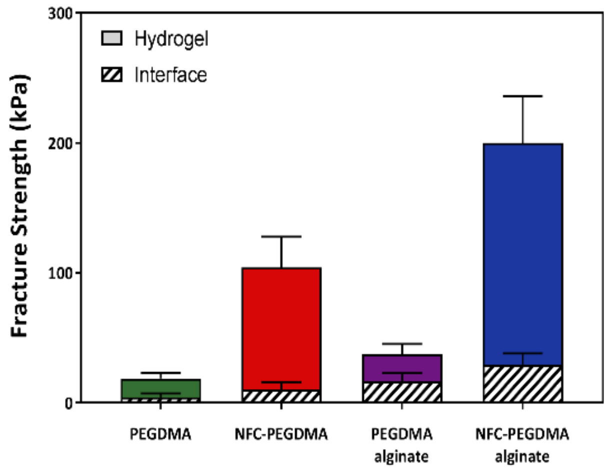
Céline Wyss et al 2018

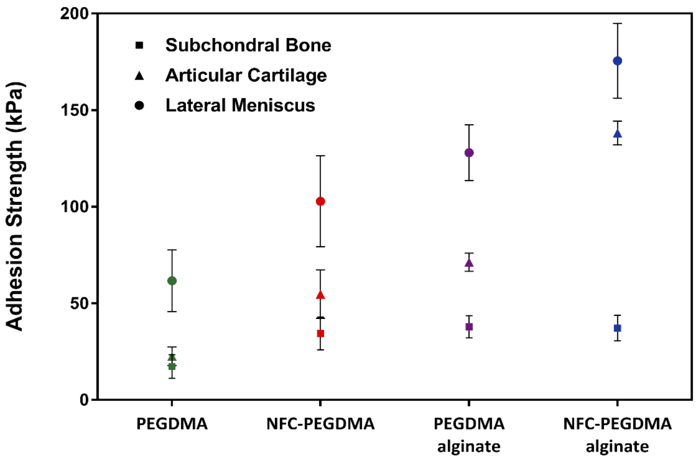
Hydrogel composites for fracture strength, dissipation, adhesion…











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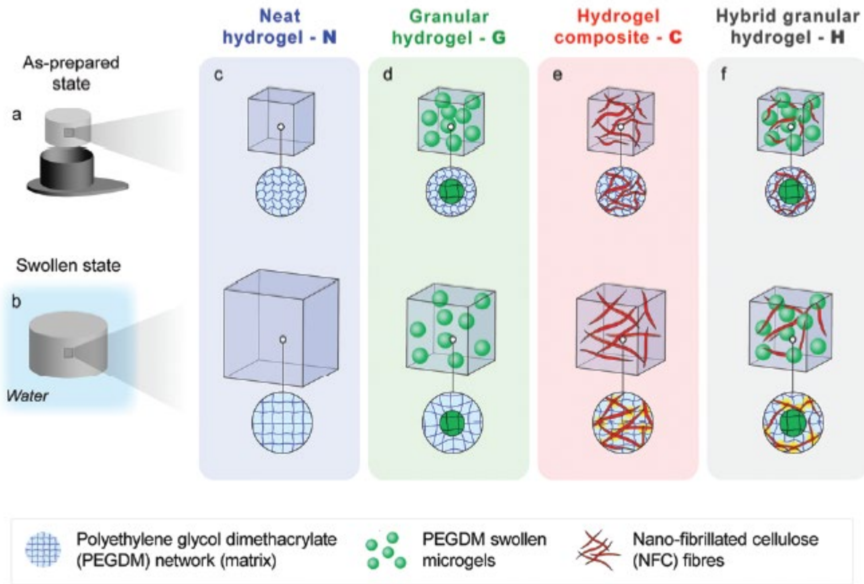
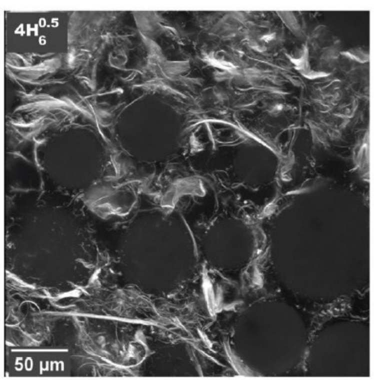
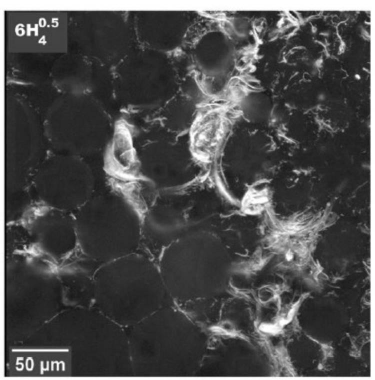
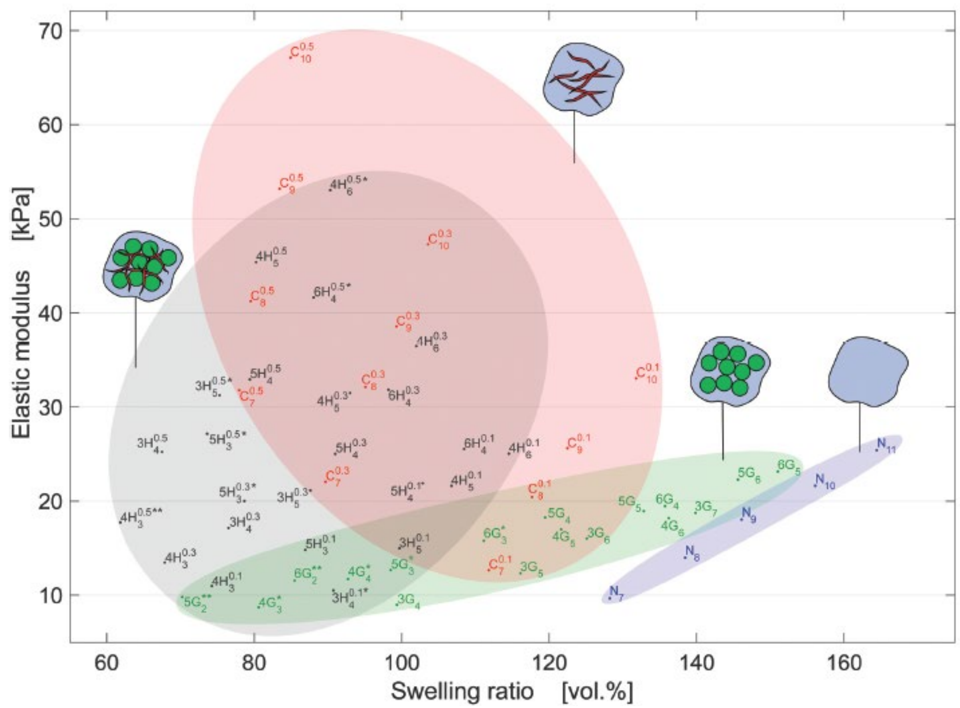
Peyman Karami, Céline Wyss et al 2018

Combining composites and microgels



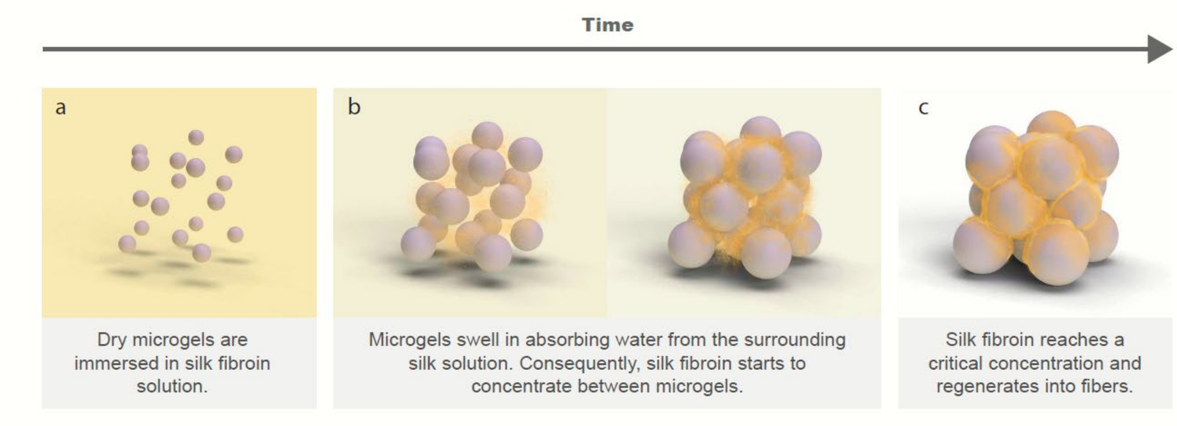


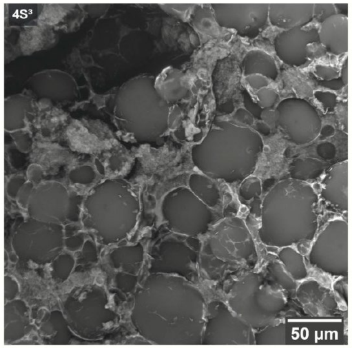


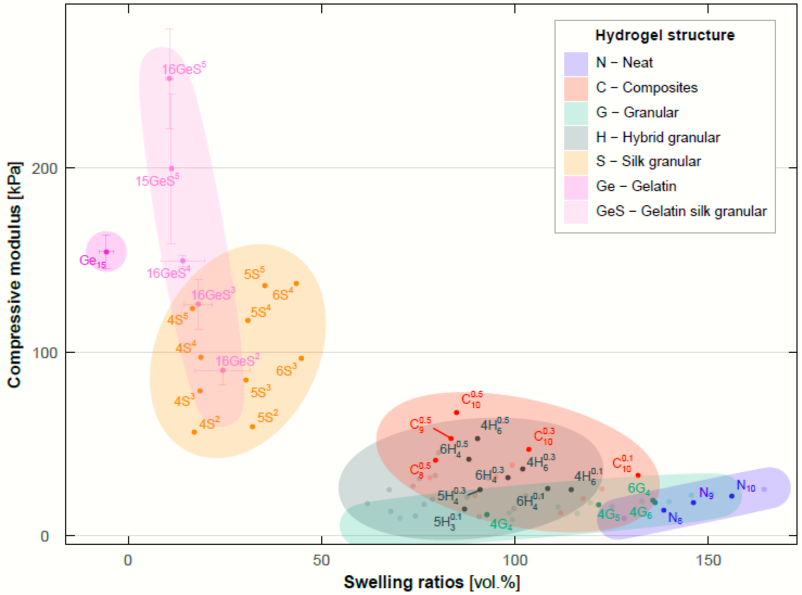


Céline Wyss et al, Soft Matter, 16,3769, 2020

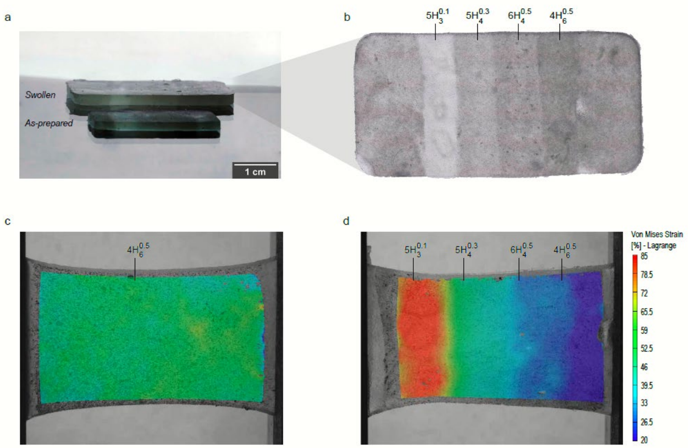
In situ self-reinforced silk hydrogel composites

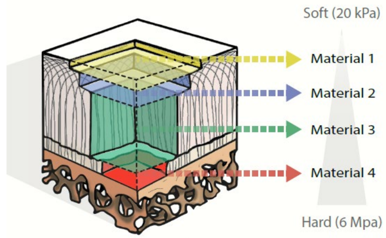






Gradient composite for soft tissues





Céline Wyss et al, Soft Matter, 2021
EPFL thesis 8128, 2021

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Biocomposites : Today & tomorrow

- Composites have recent applications in biomedical fields
- They offer the freedom to tailor structures and fonctions to tissue properties
- Cost-effective and solvent-free processes start to be available
- Biomaterials and regenerative medicine (https://ssbrm.ch/)
- Research
  - Surfaces and interfaces
  - Biomimetism
  - New polymers / fillers allowing a better control of resorption rate tailored to tissue growth and of anisotropy
  - Use biomechanical environment to foster tissue regeneration
  - Addition of bioactive factors and cells
  - Additive manufacturing

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- Karimi P., Wyss C., Khoushabi A., Schmocker A., Broome M., Moser, C., Bourban P.E., Pioletti D.P. Composite double-network hydrogels to improve adhesion on biological surfaces. ACS Applied Materials and Interfaces, 10, 38692-38699, 2018.

Outline

Polymer composites in biomedical devices

Biodegradable composites from renewable resources

Natural fibre biocomposites

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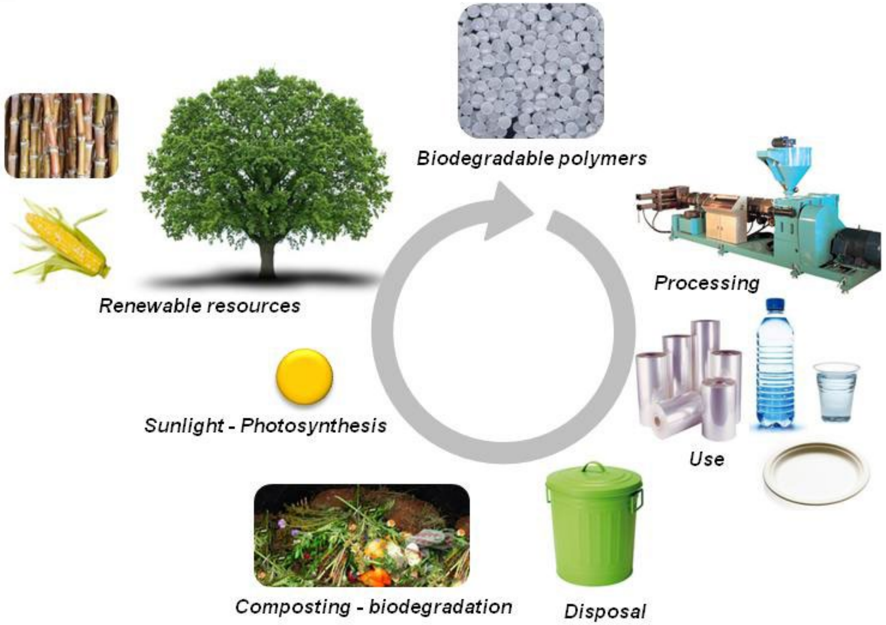
PLA/cellulose foams

SustainComp



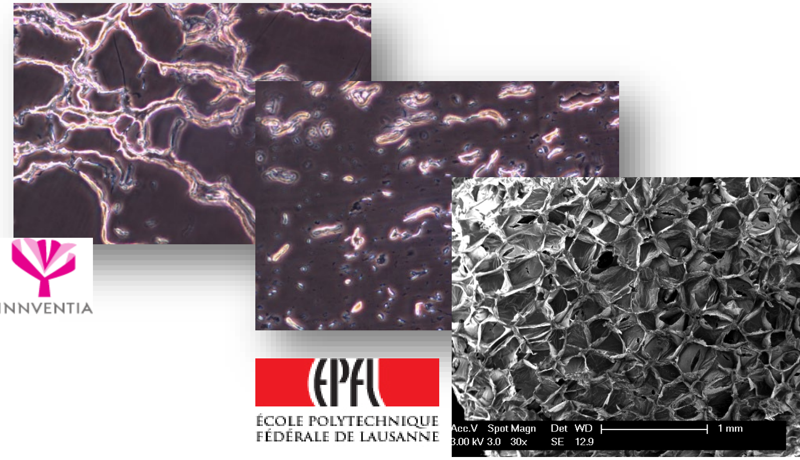
Sustainable composite foams for packaging, insulation and displays

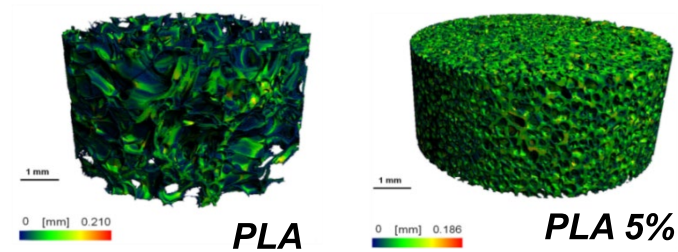
Some research highlights

- Compounding for foaming
- Foaming phenomena versus polymer rheology and degradation
- Influence of wood fibres and micro-fibrillated cellulose

(MFC) network on foam expansion and density

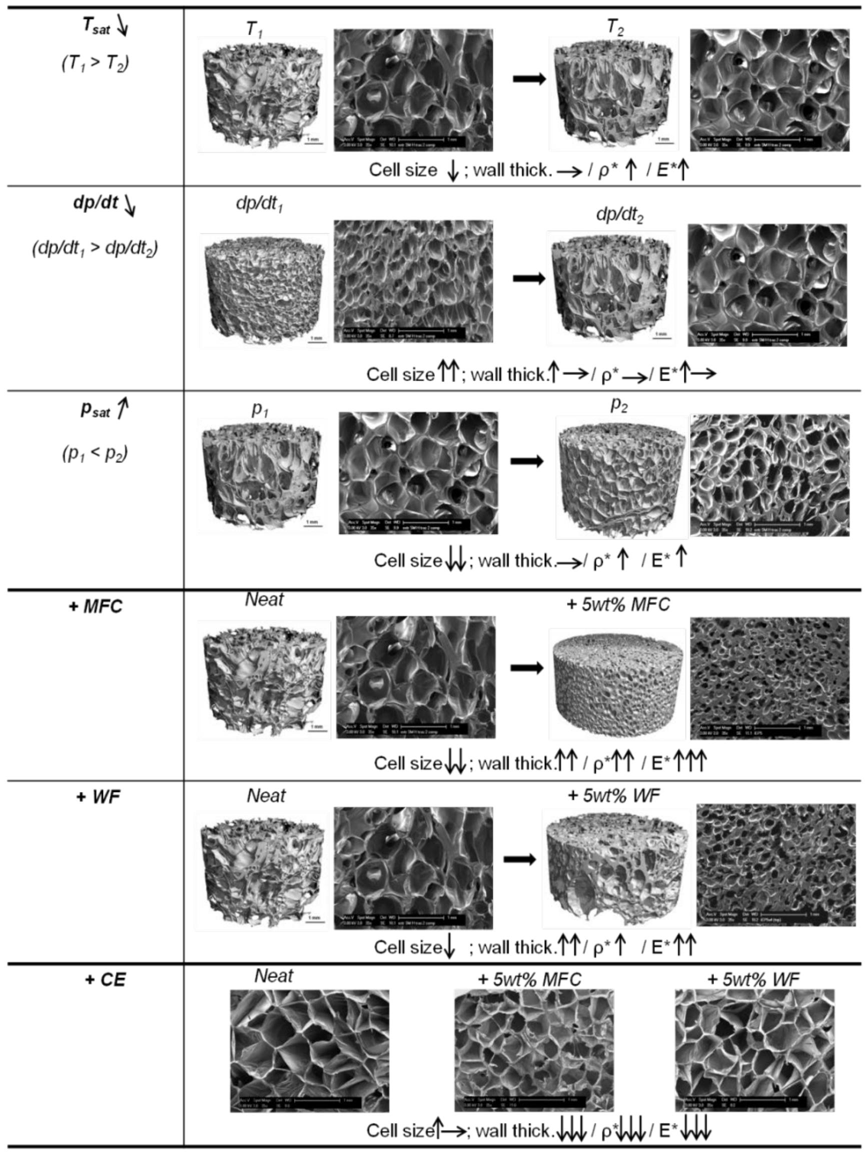
- Stable batch and continuous foaming processes





PLA ***PLA 5% MFC***

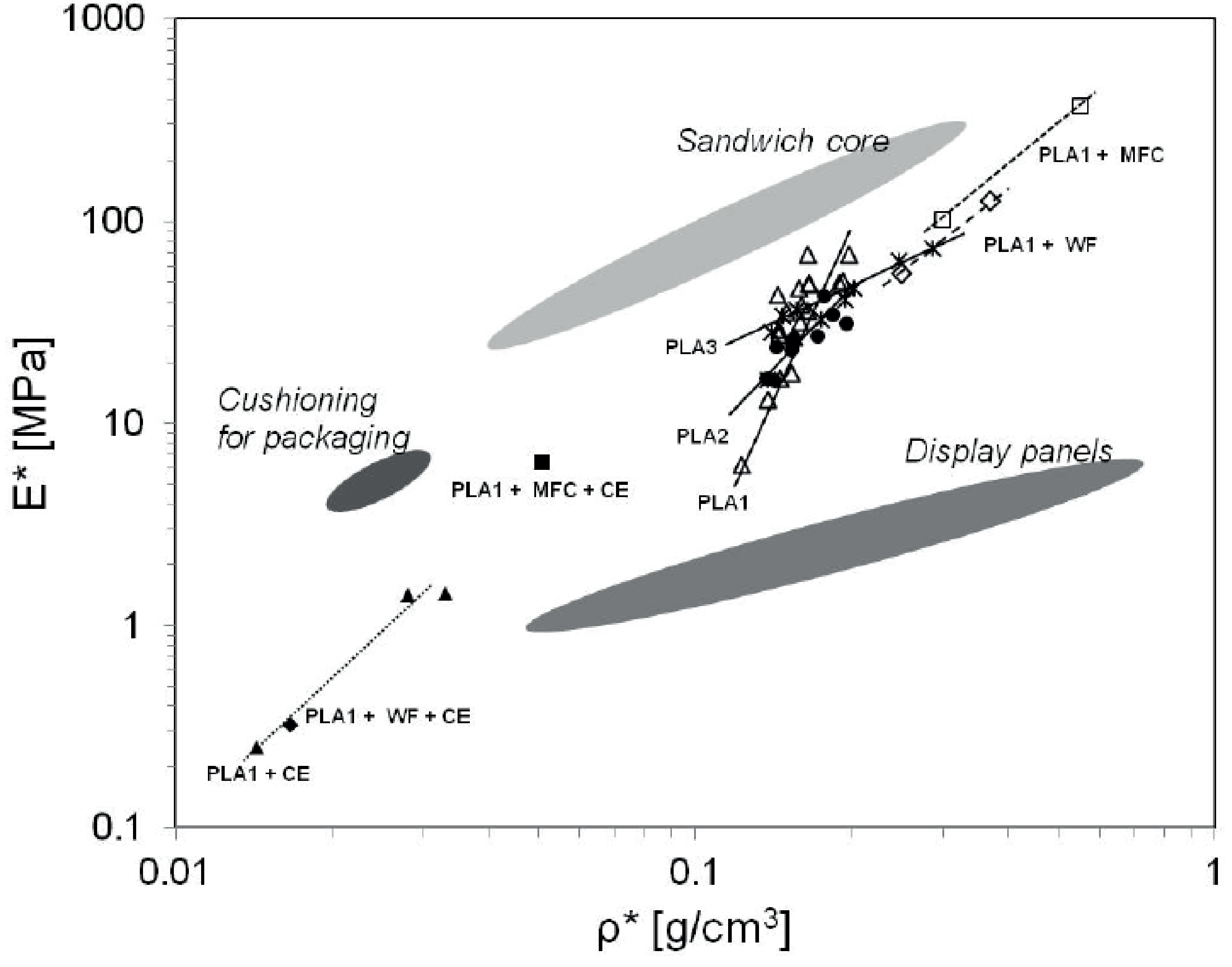
Process
Structures
Properties



SustainComp

Boissard, 2012

Process
Structures
Properties



SustainComp

Key understandings

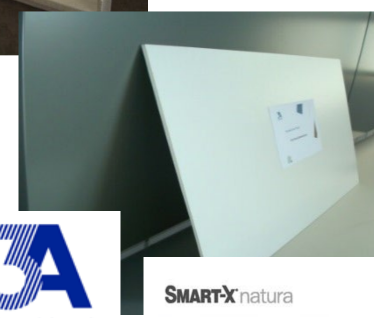
- **Compounding hydrophilic cellulose and degradable polyester for foaming**
- **Rheology of WF and MFC composites**
- **Foaming parameters for neat and composite PLAs**
- **Up-scaling of physical foaming processes**

Demonstrators

A: Materials to replace expanded polystyrene in packaging applications: **SCA PLA Cushioning**

SCA

B: Improved Mater-Bi products to replace conventional industrial protective packaging: Novamont



3A COMPOSITES

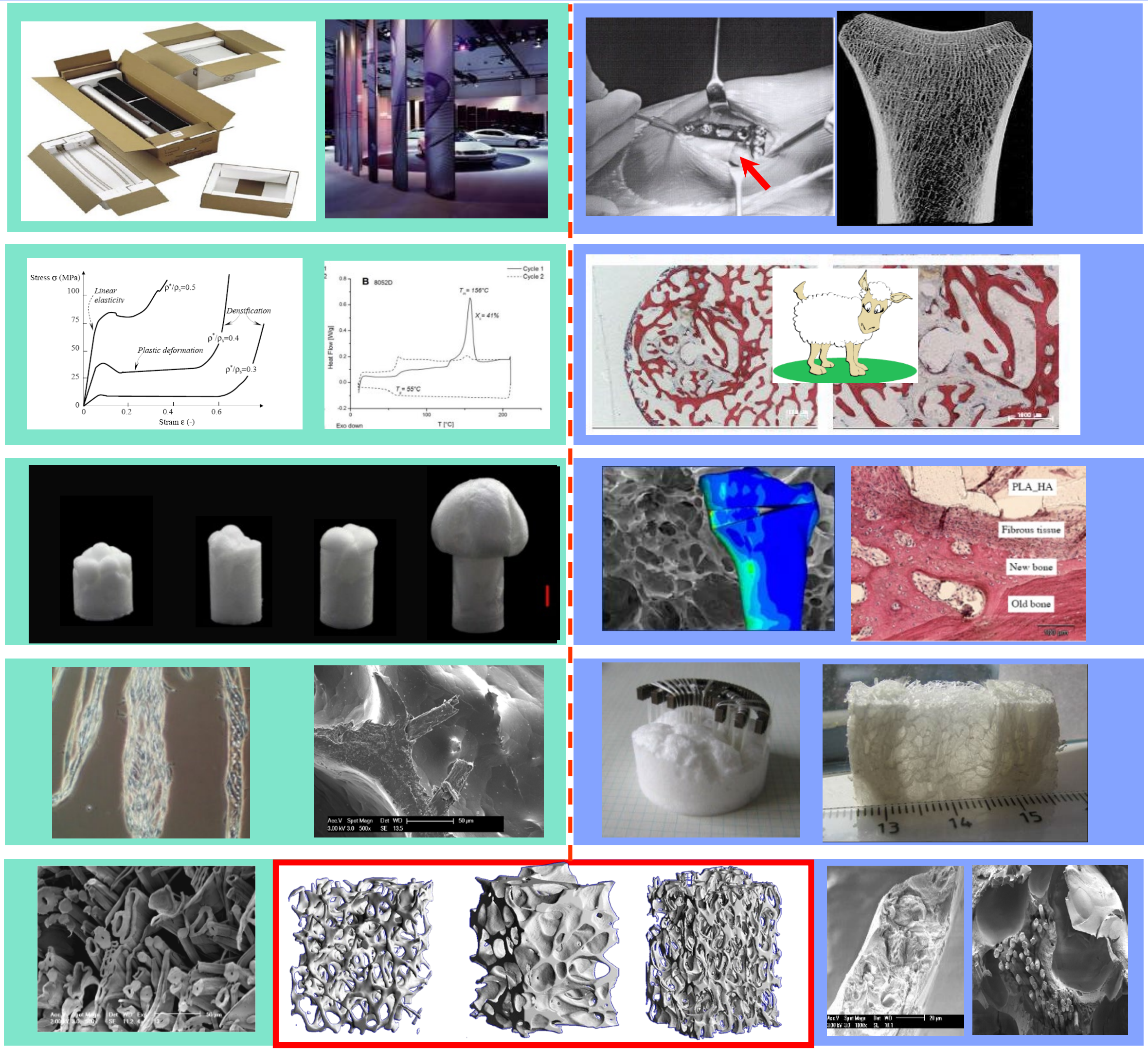
C: Sustainable' green' foam products in the display and core products portfolio: **'Display Panels from 3A Composites'**

Biodegradable
Packaging, architecture

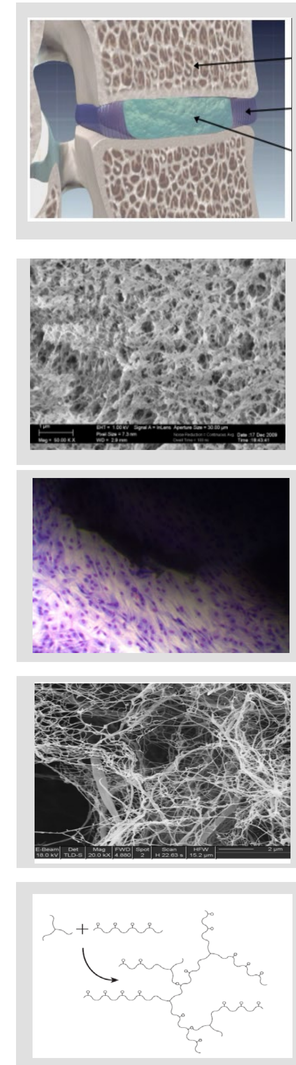
Bioresorbable
Bone implants

Biocompatible
Intervertebral disks

PLA/cellulose composite foams for light weight and cushioning applications



PLA/ceramic composite foams for bone replacement



MFC hydrogel composites for intervertebral disks

Outline

Polymer composites
in biomedical devices

Biodegradable composites
from renewable resources

Natural Fibre
bioComposites NFC

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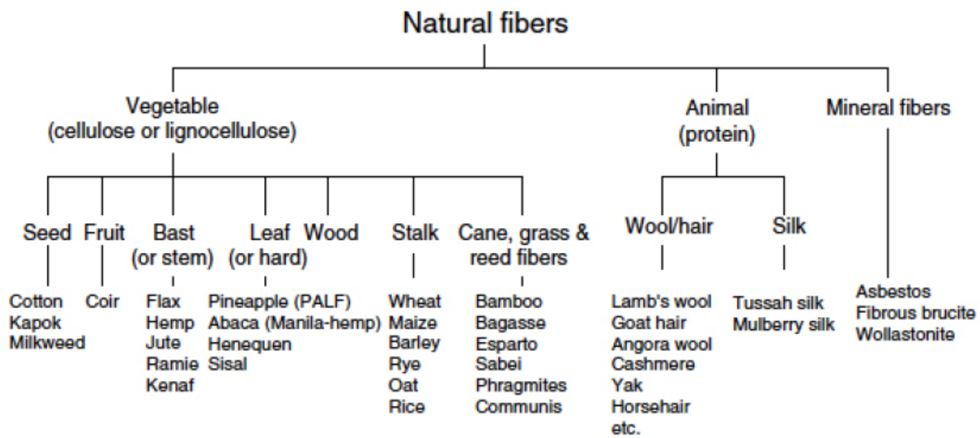
Natural Fibres for Composites



Sustainability:
- **reduction of cradle-to-gate CO_2 footprint**
- **lifecycles of final products**
- **bio-degradable**

Lightweight
Damping

Hydrophilic
Processing

Fiber	Density (g cm^{-3})	Diameter (μm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)
Flax	1.5	40–600	345–1500	27.6	2.7–3.2
Hemp	1.47	25–500	690	70	1.6
Jute	1.3–1.49	25–200	393–800	13–26.5	1.16–1.5
Kenaf			930	53	1.6
Ramie	1.55	—	400–938	61.4–128	1.2–3.8
Nettle			650	38	1.7
Sisal	1.45	50–200	468–700	9.4–22	3–7
Henequen					
PALF		20–80	413–1627	34.5–82.5	1.6
Abaca			430–760		
Oil palm EFB	0.7–1.55	150–500	248	3.2	25
Oil palm mesocarp			80	0.5	17
Cotton	1.5–1.6	12–38	287–800	5.5–12.6	7–8
Coir	1.15–1.46	100–460	131–220	4–6	15–40
E-glass	2.55	<17	3400	73	2.5
Kevlar	1.44		3000	60	2.5–3.7
Carbon	1.78	5–7	3400[a]–4800[b]	240[b]–425[a]	1.4–1.8

[a] Ultra high modulus carbon fibers.
[b] Ultra high tenacity carbon fibers.

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NFC today

Thermoset NFC

- SMC, prepreg
- UP, Epoxy, VER, Phenolic
- Jute, flax, hemp…

- Modulus E ~ 10-20 GPa
- Strength ~ 200-300 MPa
- With fibre treatment : + 15-50% E

Museeuw:
flax/carbon epoxy

Artengo: flax(5%)/
carbon epoxy

Stockli

Thermoplastic NFC

- Mainly GMT
- PP,MAPP, PET, PE
- Flax, wood…

- E ~ 6 GPa (PP), 20 GPa (PET)
- Strength ~ 100 MPa
- specific properties
  higher than GF/PP

Quadrant load floor of the Porsche Cayenne: PP reinforced with 40% kenaf, flax, wood and glass

FlexForm door panel from the Mercedes M-Class and R-class: jute(50%)/glass PP

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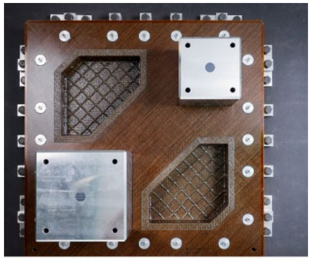
https://www.bcomp.ch/

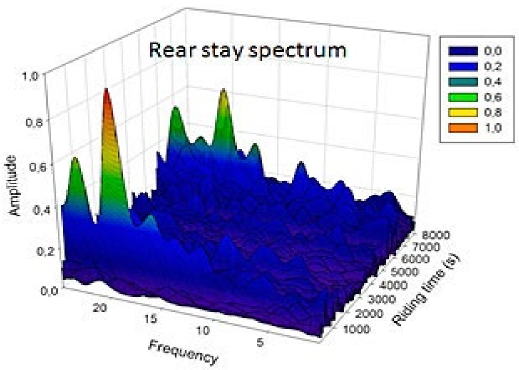
Thanks to the powerRibs™ technology, it is the first time that natural fibre composites can replace carbon fibres. ©McLaren

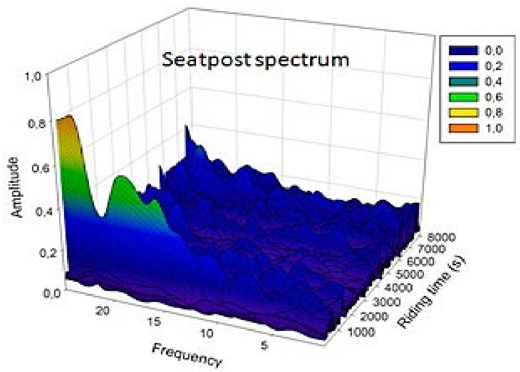


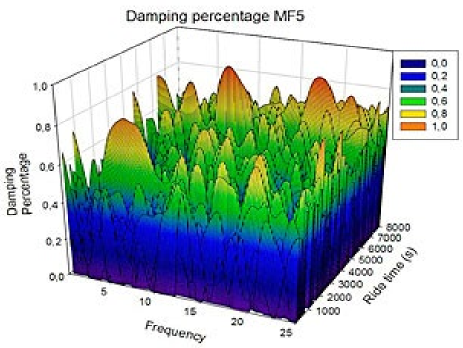
Ritsumasyl record-breaking bio-composite bridge

EPFL pierre-etienne.bourban@epfl.ch

Damping ?


Rear stay spectrum
Amplitude
Frequency
Riding time (s)
0,0
0,2
0,4
0,6
0,8
1,0


Seatpost spectrum
Amplitude
Frequency
Riding time (s)
0,0
0,2
0,4
0,6
0,8
1,0


Damping percentage MF5
Damping Percentage
Frequency
Ride time (s)
0,0
0,2
0,4
0,6
0,8
1,0

Energy absorption at different material scales

Damping phenomena

- **dampers**
- **viscoelasticity**

Materials

- **elastomeric interlayers**
- **fibre type and orientation**
- **polymer matrix**
- **interphase**

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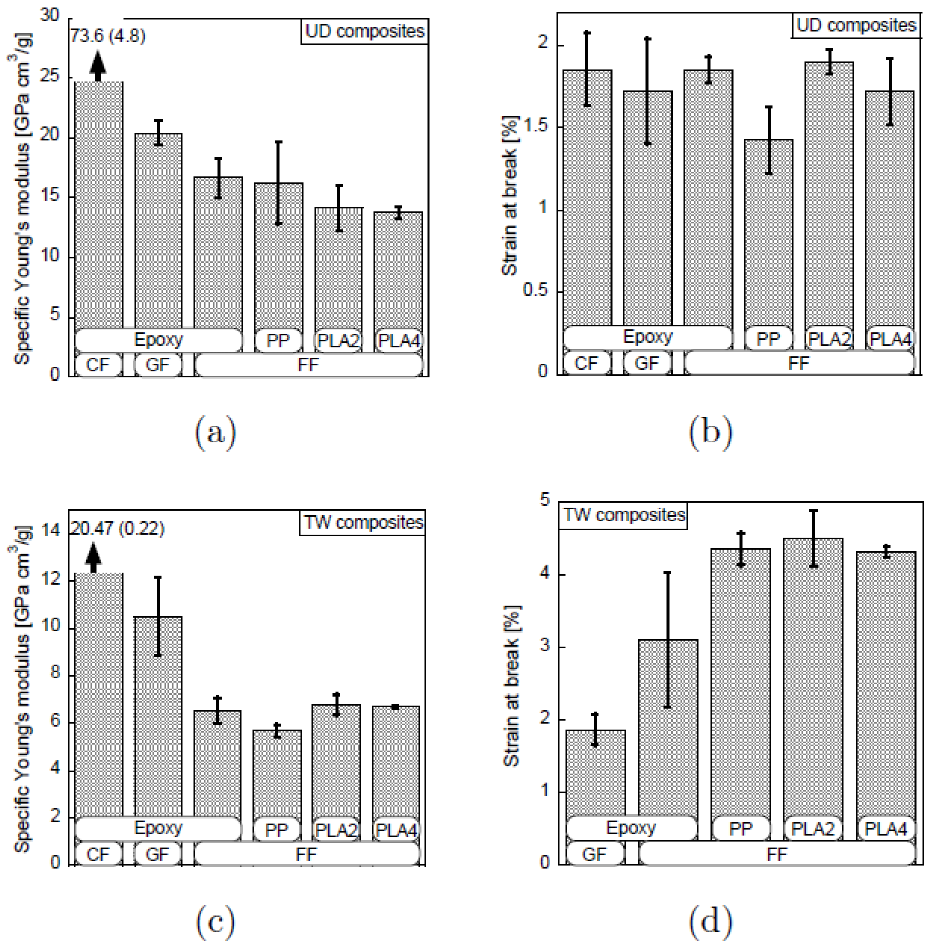
Materials and specific properties: Flax Fibre composites

Fibres	Matrices	Fabrics	Process	Abbreviations
CF	EP	UD	RTM	CF_EP_UD
CF	EP	TW	RTM	CF_EP_TW
GF	EP	UD	RTM	GF_EP_UD
GF	EP	TW	RTM	GF_EP_TW
FF	EP	UD	RTM	FF_EP_UD
FF	EP	TW	RTM	FF_EP_TW
FF	PP	UD	CM	FF_PP_UD
FF	PP	TW	CM	FF_PP_TW
FF	PLA2	UD	CM	FF_PLA2_UD
FF	PLA2	TW	CM	FF_PLA2_TW
FF	PLA4	UD	CM	FF_PLA4_UD
FF	PLA4	TW	CM	FF_PLA4_TW



(a) (b) (c) (d)

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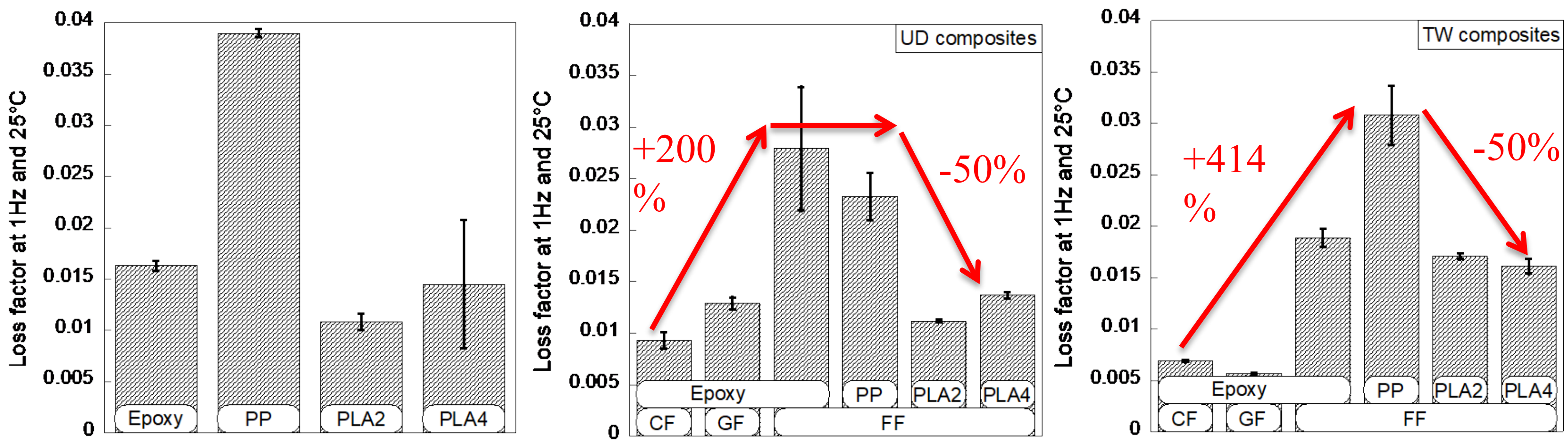
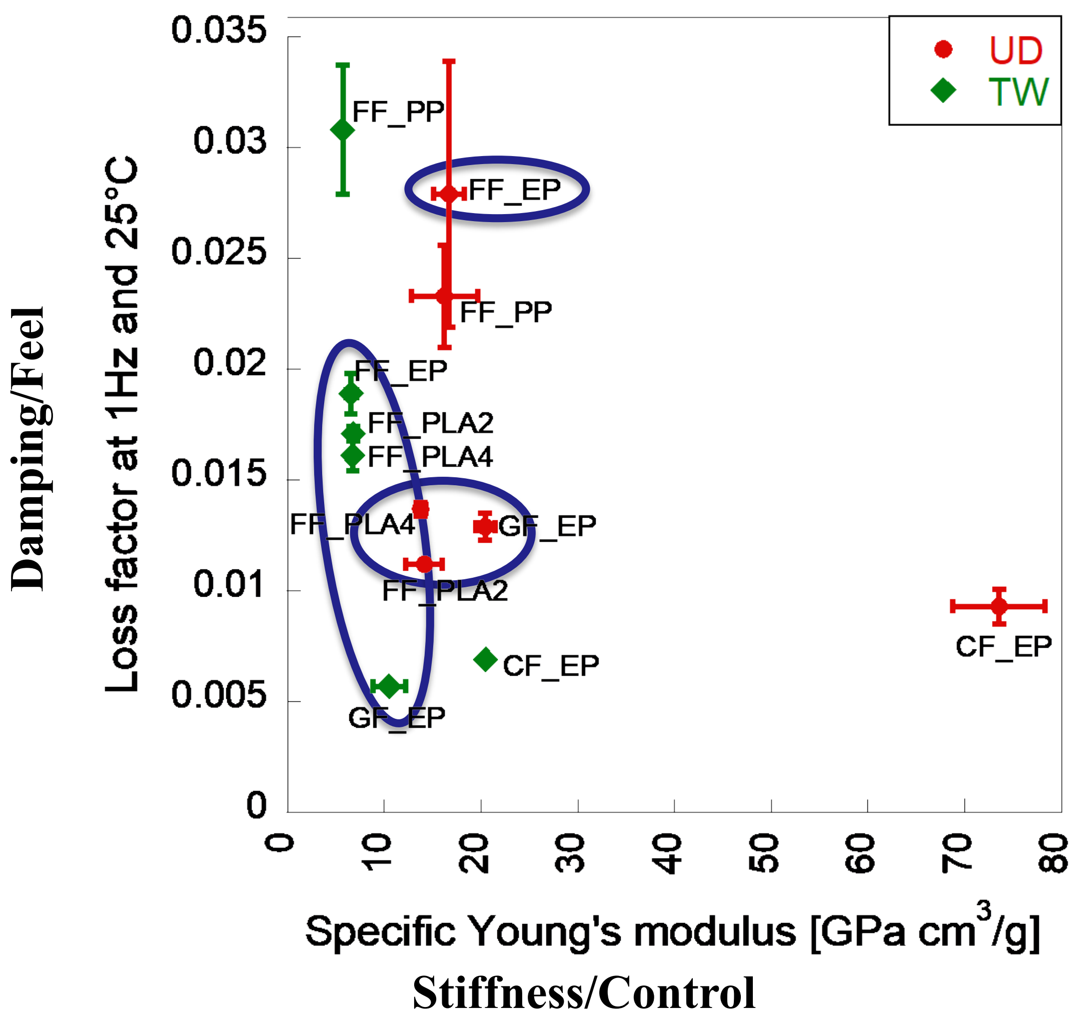
F. Duc 2014

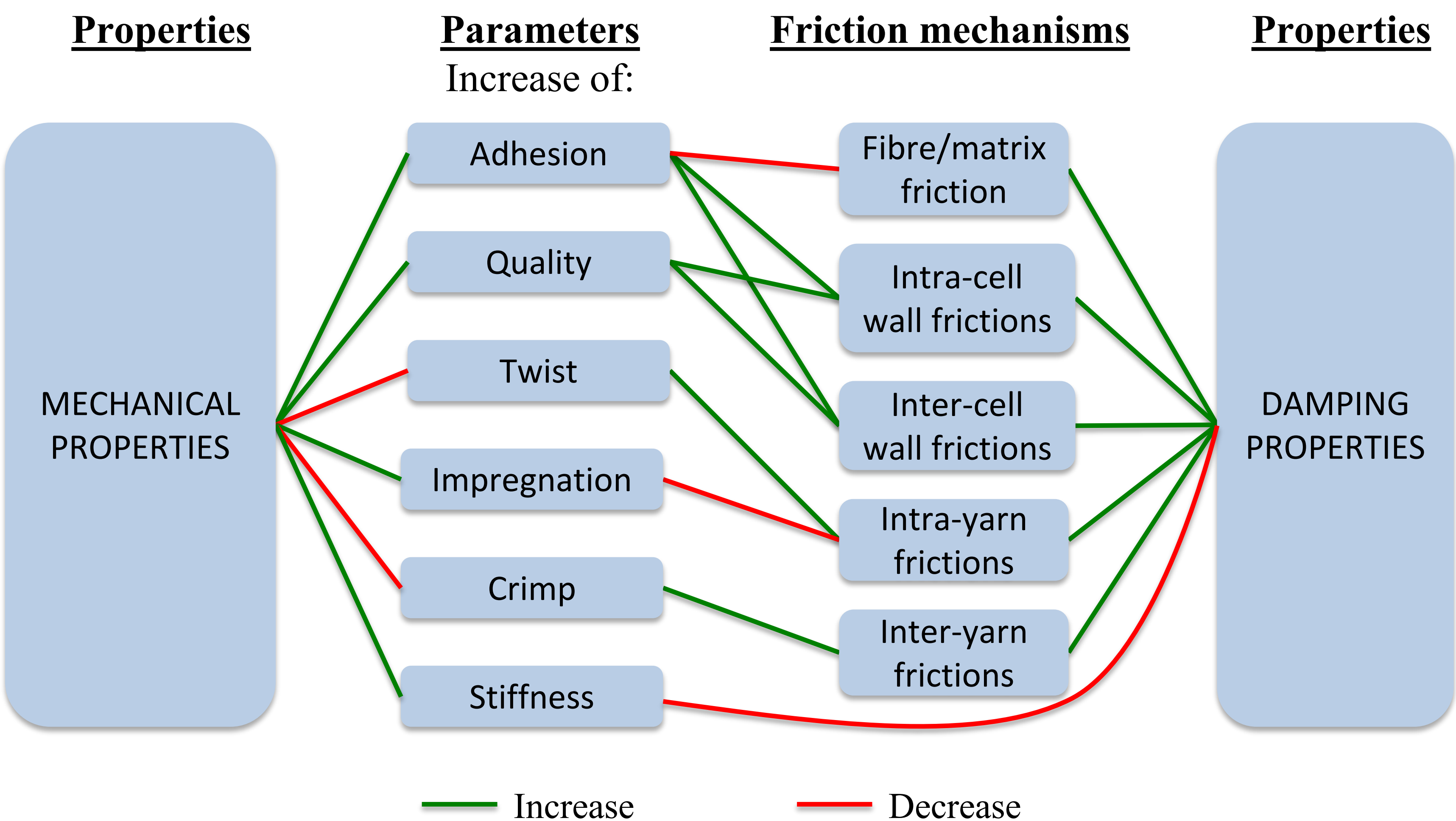
Damping properties of natural fibre composites



Stiffness versus damping properties



Coupled damping phenomena



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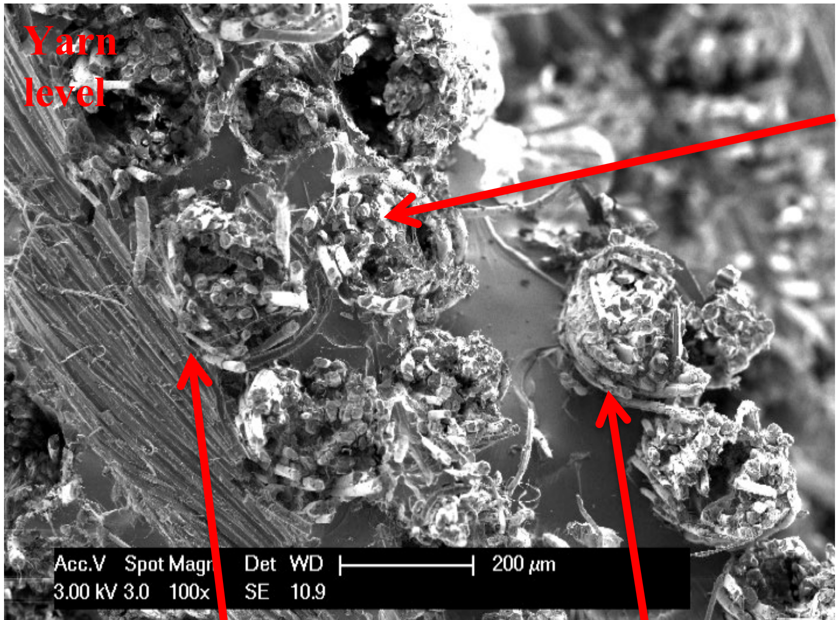
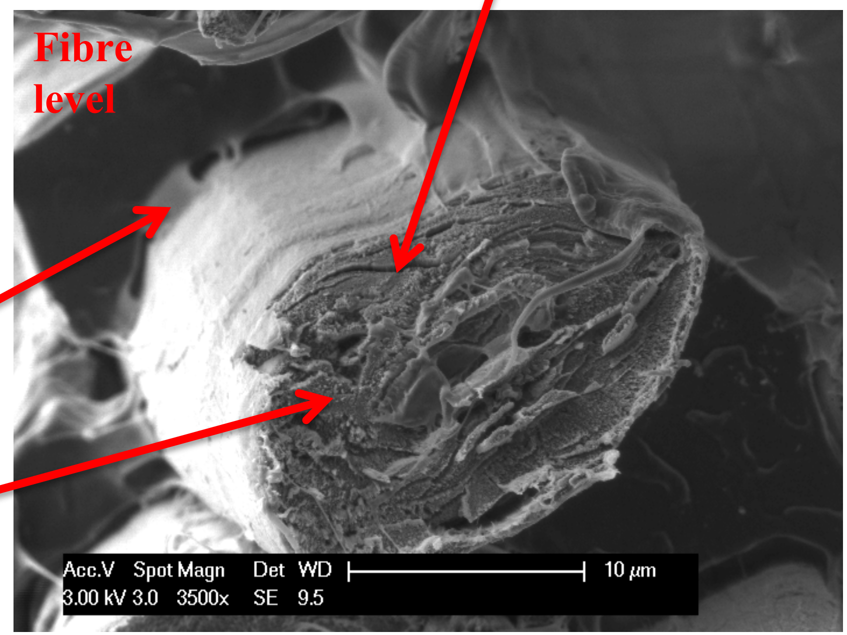
Phenomena controlling damping



2. Intra-yarn friction
Friction between the elementary fibres

3. Inter-cell wall friction
Friction between the cell walls



1. Inter-yarn friction
Friction between the yarns

Fibre (yarn)/matrix friction

4. Intra-cell wall friction
Friction between cellulose and hemicellulose

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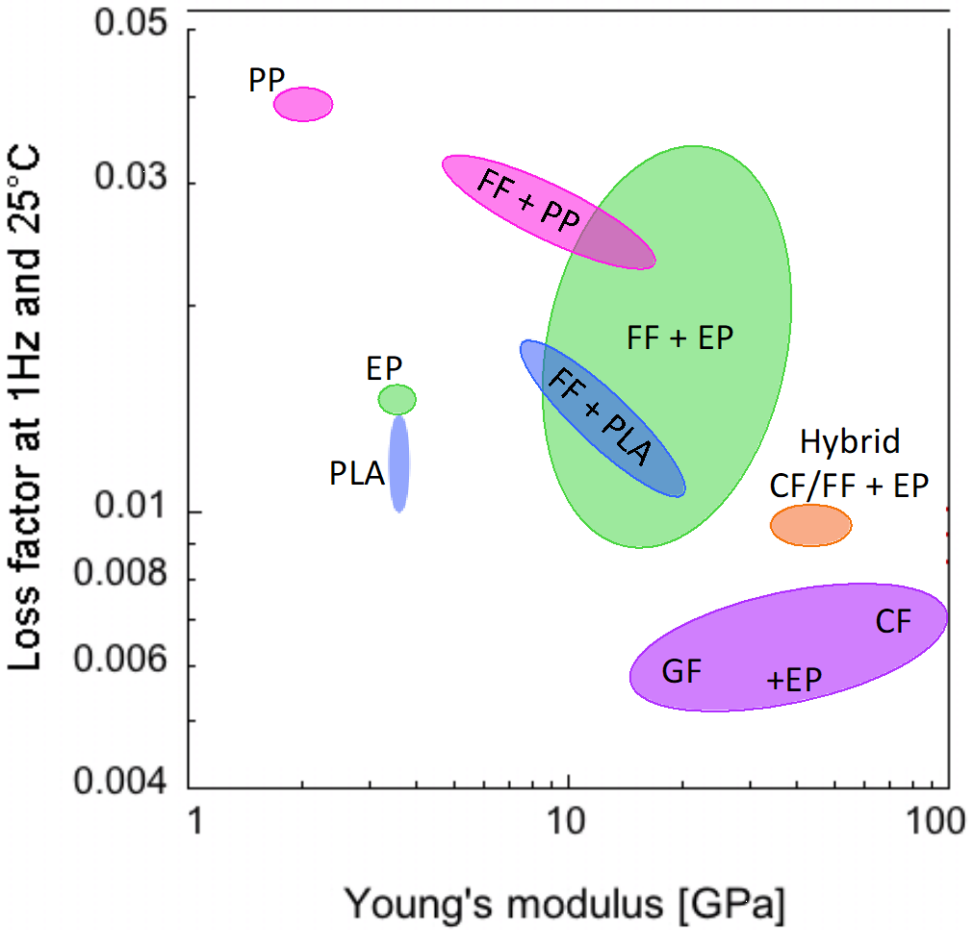
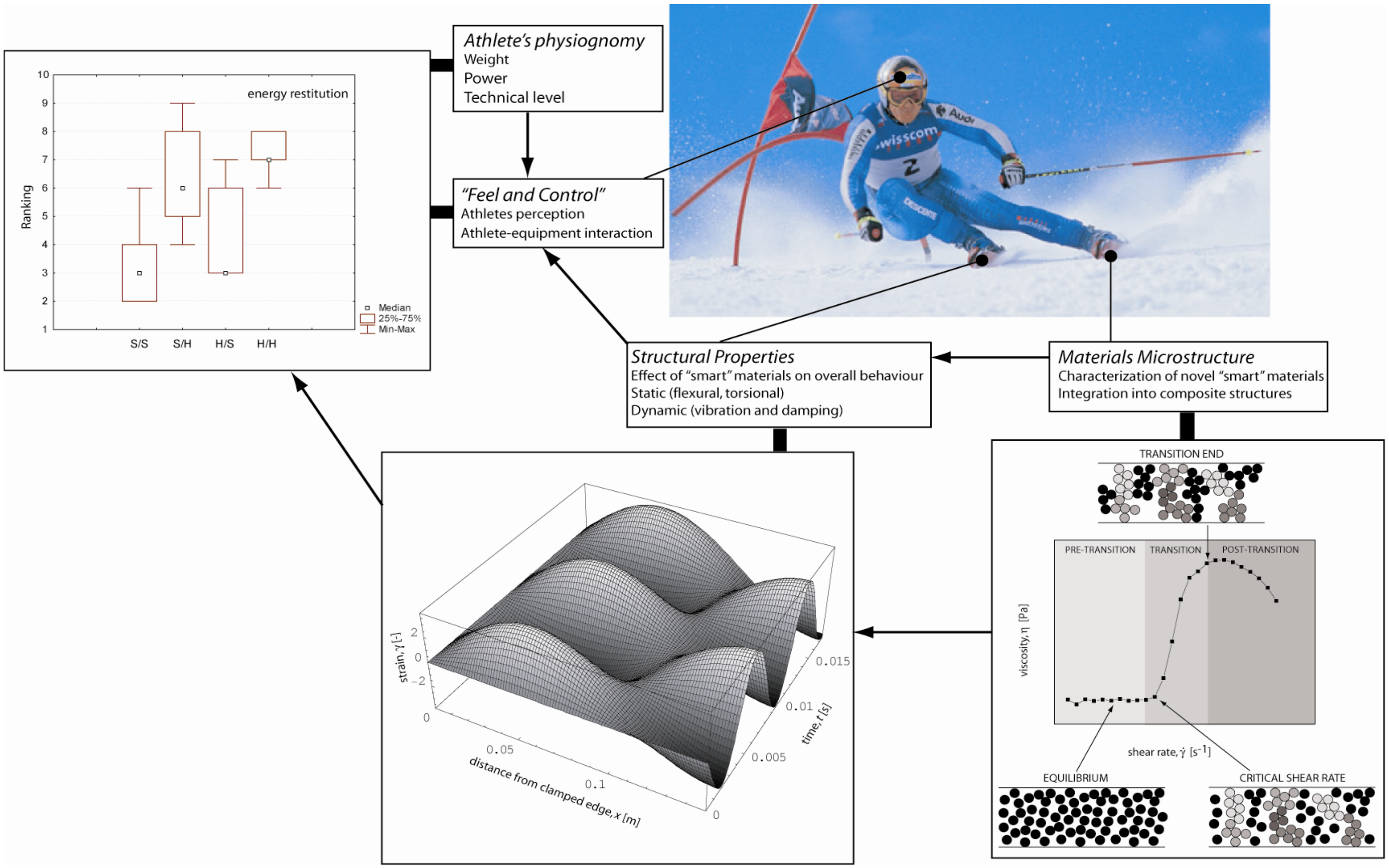
F. Duc 2014

Damping map



F. Duc 2014

Material-athlete interactions



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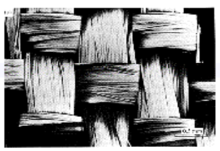
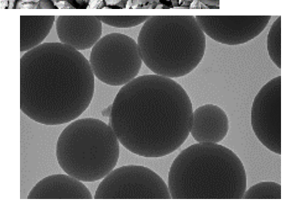
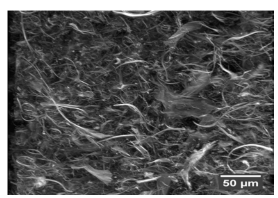
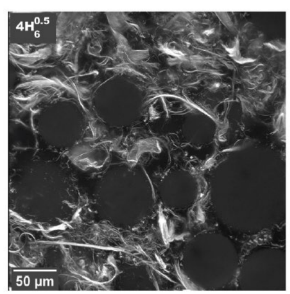
Tailored materials for controlled human-material interactions : feel and control

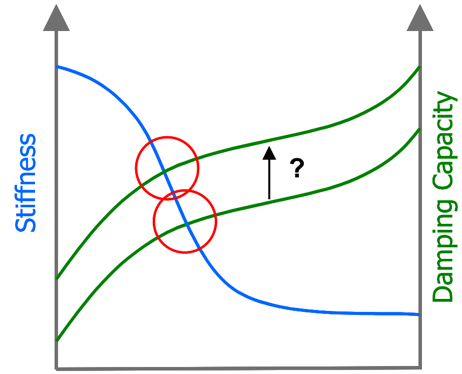
Vision: Integrate cognitive assessment in the design of novel materials and structures
Scientific topic: Embedding smart materials and sensitive devices for improving 'feel and control'.
Applications envisaged: skis, tennis raquettes, prosthesis, implants…

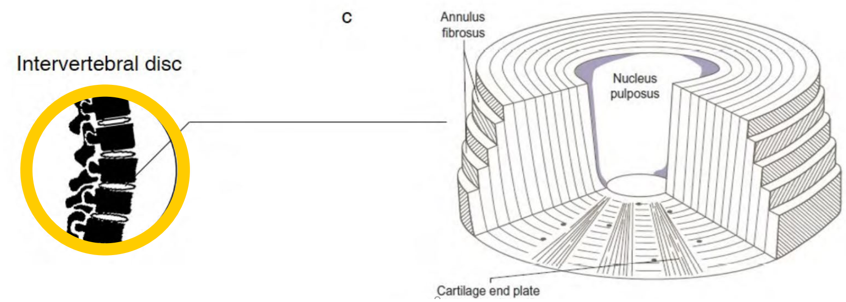


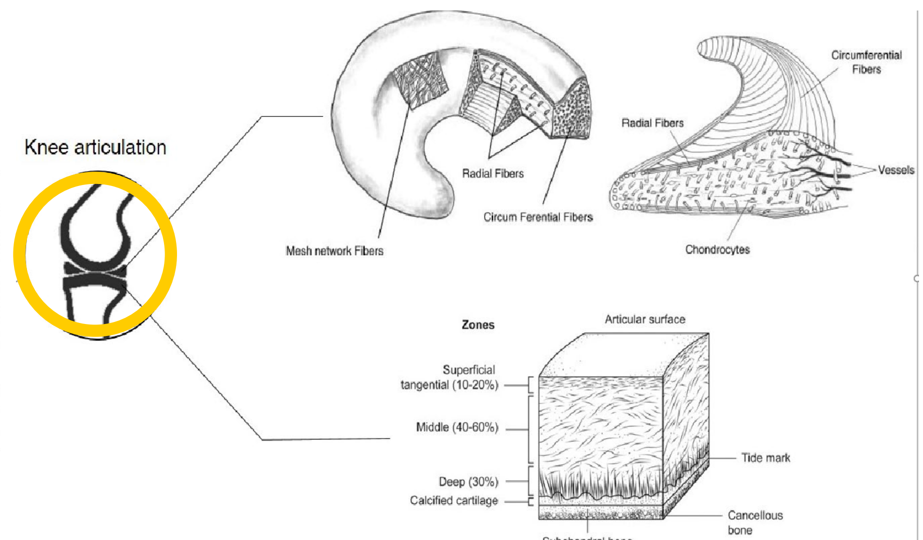












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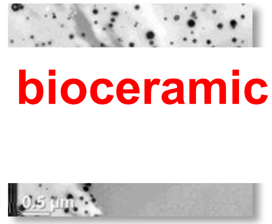
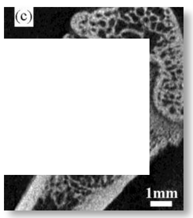
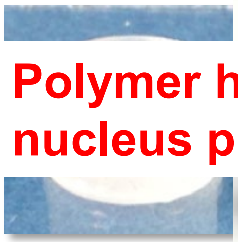
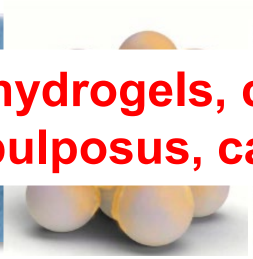
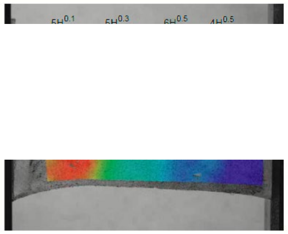
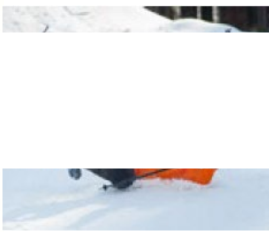
Bio^{3}composites

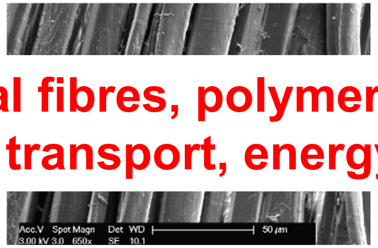
Bioresorbable polymer foams, bioceramic particles and fibres, bone replacement

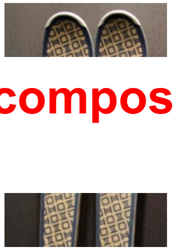



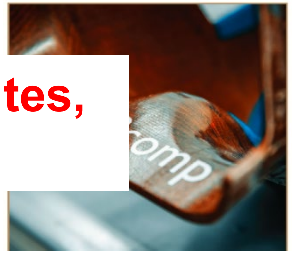

Polymer hydrogels, cellulose and silk fibres, nucleus pulposus, cartilages, helmets


Biodegradable polymers and fibres, foams, display panels, packaging



Natural fibres, polymers, sustainable composites, sport, transport, energy….



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