

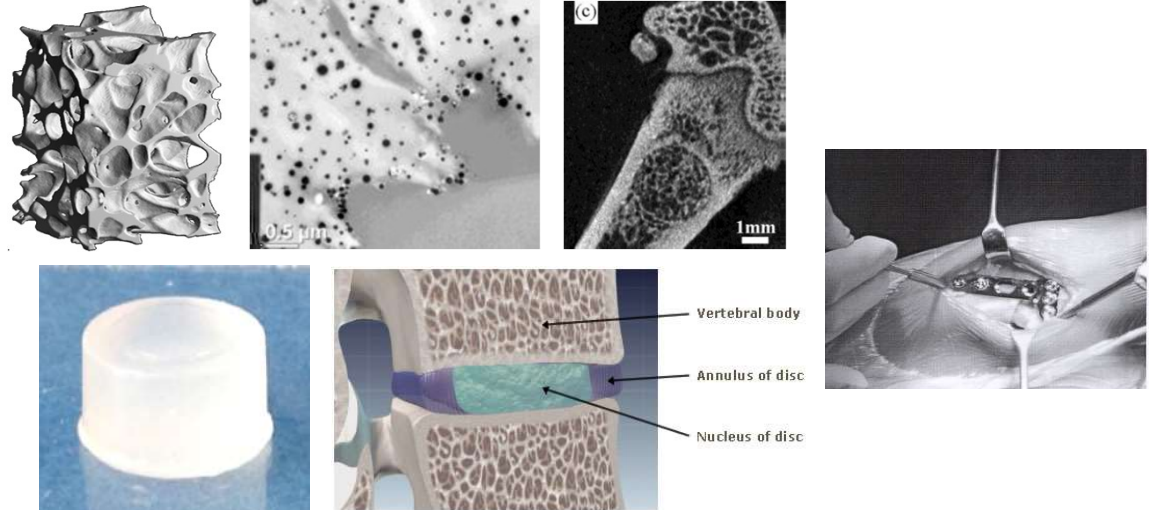
Bio³composites

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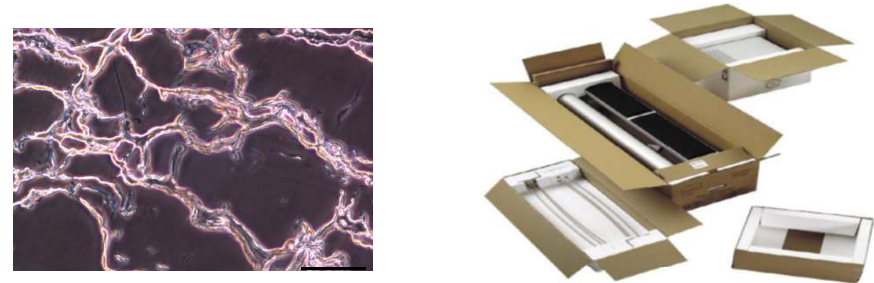
Institut des Matériaux (IMX)
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Outline

Polymer composites in **bio**medical devices



Biodegradable composites from renewable resources



Natural fibre **bio**composites



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

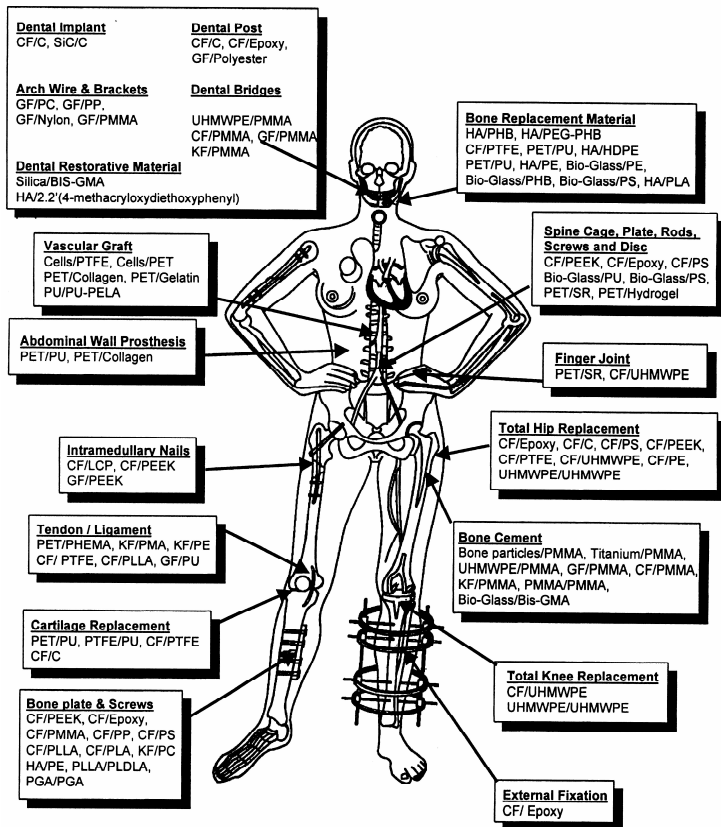


Medtronic Talent Abdominal Stent Graft



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

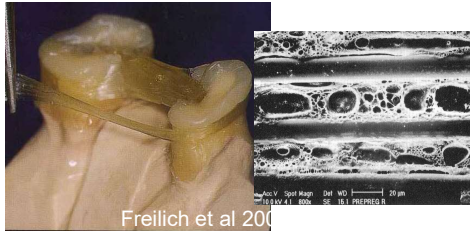
- Dental filling:** Acrylate resin +33-78 wt% (quartz,baryum glass,colloidal silica)



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



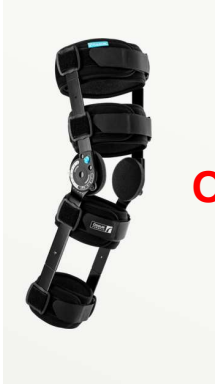
Fibers	vol%	$\sigma_{\text{transverse}}$ (MPa)
UHMWPE	48	188
glass	33	265

Challenges : impregnation, interfaces, shrinkage, conversion degree...



Orthoses and prostheses

Orthoses

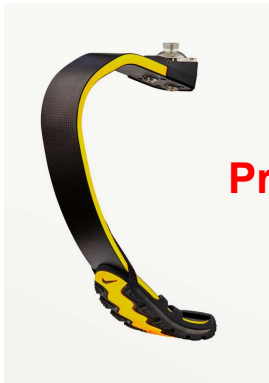


<https://www.ossur.com>



<https://www.ottobock.ch>

Prostheses



Prostheses for sports



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



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

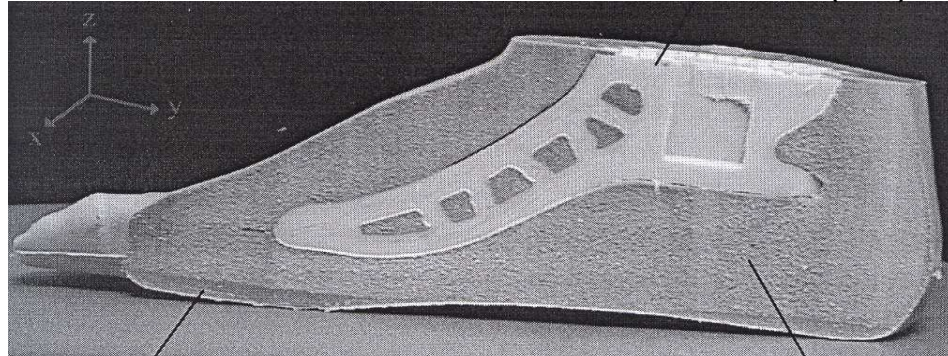
Preimpregnated carbon-epoxy

- (+) • 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

Affordable Prostheses

Minimal cost and maximal life time: feet for ICCR

Center rib (PP)



Sole (PU)

Foot core (PU foam)



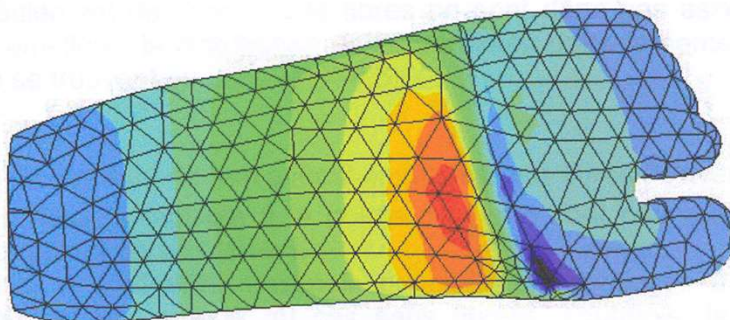
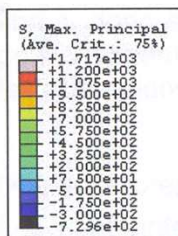
ICRC



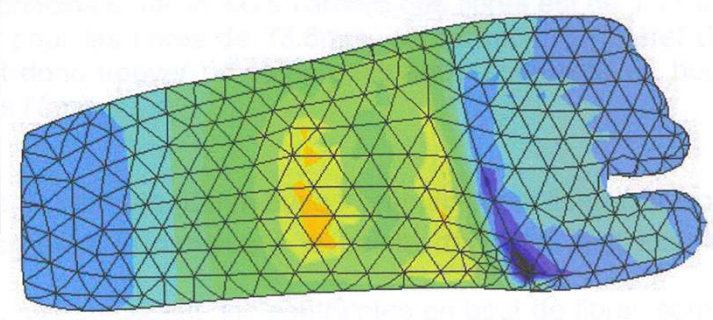
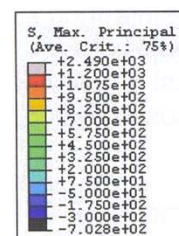
CR ÉQUIPEMENTS SA



Challenge: fatigue cracks at the top of the center rib



Without additional reinforcement $\sigma_{\max} = 1.2 \text{ MPa}$



With UD glass fibers $\sigma_{\max} = 0.85 \text{ MPa}$

Affordable all-terrain feet: ICRC's Agilis prostheses

5 May 2019, Health care / New technologies



<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

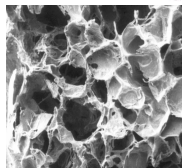
Sutures



Dental membranes



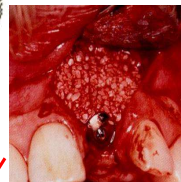
Matrices for tissue engineering



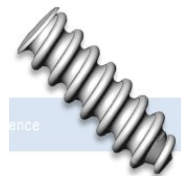
Vertebral cages



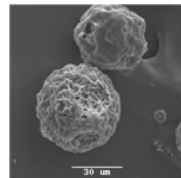
Fixation elements for maxillofacial surgery



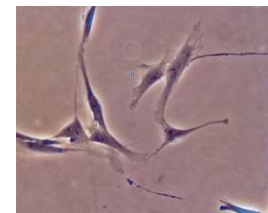
Biomaterials for bone augmentation



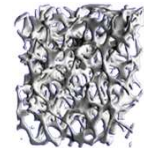
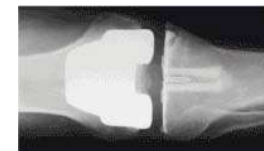
Bioresorbable screws (fixation)



Drug release

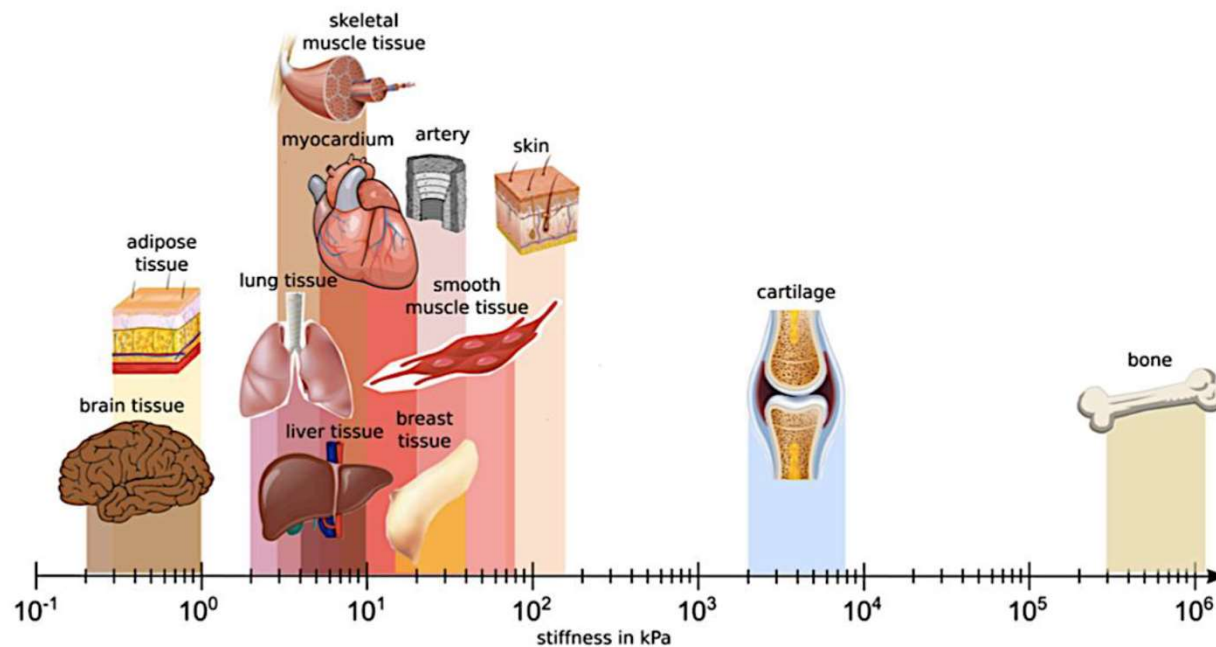


Biologists



➡ **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

- **Woven 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**

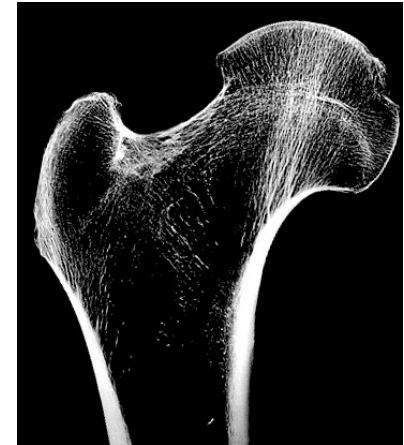
- Low mechanical resistance
- High porosity > 95%, but not controlled
- Large specific surface



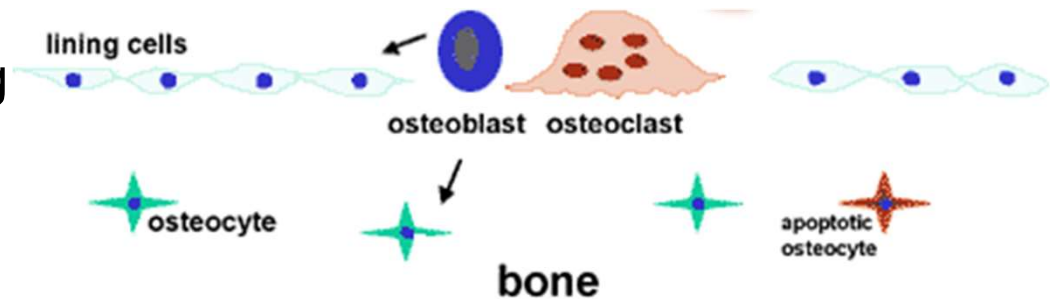
<https://www.innovationintextiles.com/biofelt-absorbable-scaffold-for-implant-devices/>

Bone

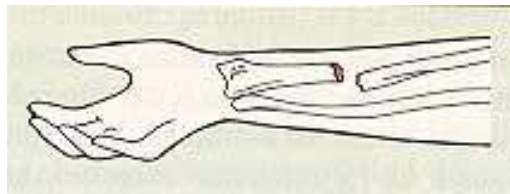
- Bone is a mineralized structure, with 3 functionalities
 - Mechanical
 - Protective
 - Metabolic



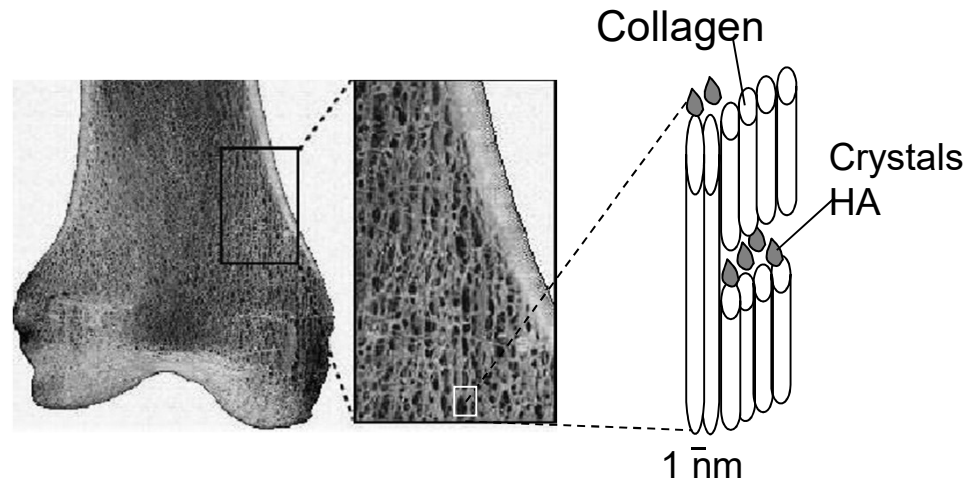
- Bone is a living material, going through remodeling



- 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 $\varnothing$ 200-400 μm
 - Mechanical resistance

Foams

	Porosity (%)	Ø pore (µm)	Mechanical property	Advantage	Drawback
Solvent casting / particulate leaching (SC/PL)	90-95	100-180	$E_c \sim 160 \text{ kPa}$	- Open pores - + short fibers	- <i>Organic solvent</i> - Residual particles - Sensitive to person and material - Thin membranes
Gas foaming (GF)	90-95	~100	$E_c \sim 300 \text{ kPa}$	- 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 - <i>Organic solvent</i> - Sensitive to person and material
Thermally induced phase separation (TIPS)	80-95	20-100 (< 500)	$E_c \sim 6 \text{ MPa}$ $\sigma_c = 0.23 \text{ MPa}$	- Open pores - Many parameters to adjust pore diameter - + short fibers	- <i>Organic solvent</i>

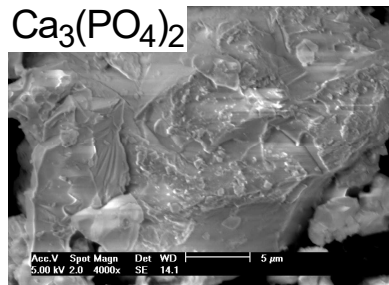
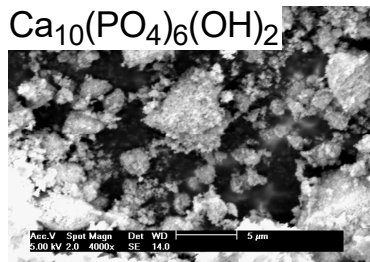
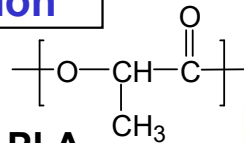
Development of a biocomposite foam

Materials

Compounding

↳ **Homogeneous reinforcement dispersion**

- Bioresorbable polymers
Poly (L-lactic acid) **PLA**
IV=1.6-1.8 dL/g; $T_m=181.7^\circ\text{C}$
- Bioceramics: reinforcement, resorption control, osteoconductivity
Hydroxyapatite **HA**
nanometric size; 50 m²/g
Tricalcium phosphate **β -TCP**
micrometric size; 1-2 m²/g



Twin- screw extruder

Foaming process

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

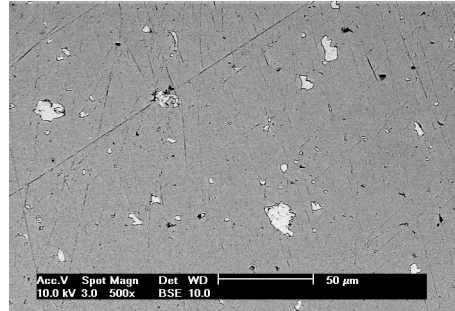


Autoclave scCO₂, P_{max} 300 bar, T_{max} 300 ° C

Mixing ceramic into PLA

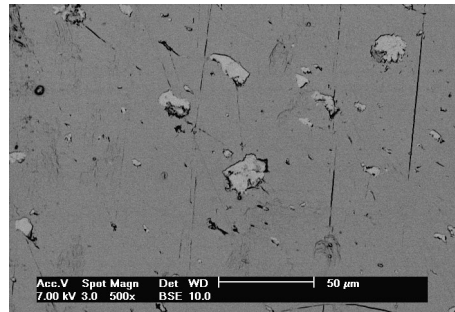
Extrusion

⇒ Homogeneous dispersion



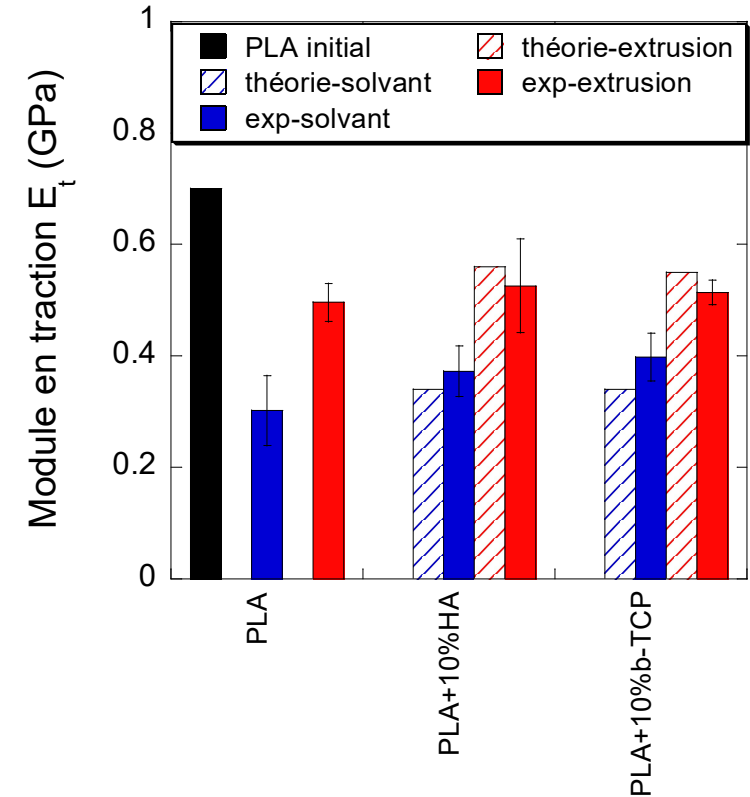
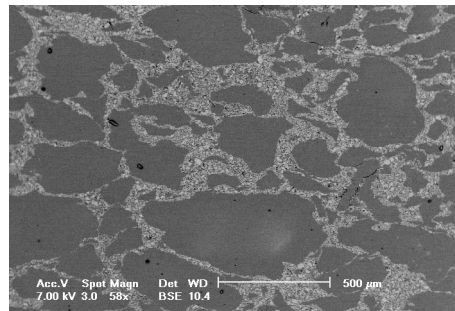
Solvent phase dispersion

⇒ Homogeneous dispersion, but solvent traces



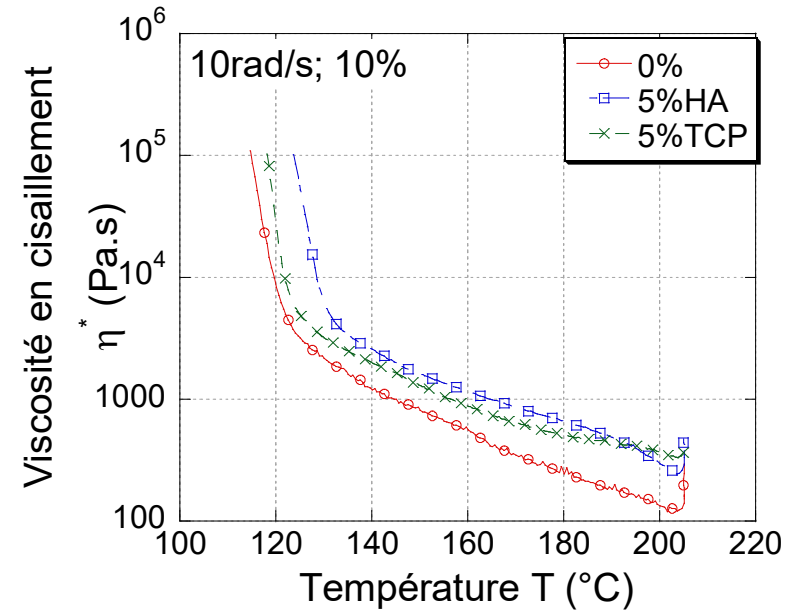
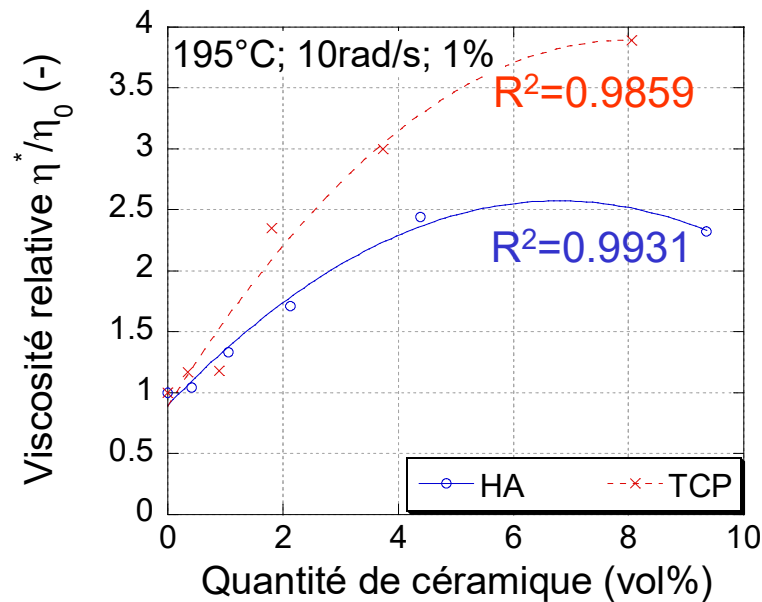
Dry powder mixing

⇒ Ceramic rich zones



⇒ Extrusion mixing is the chosen method

Viscosity of filled PLA



- Semi-diluted suspensions

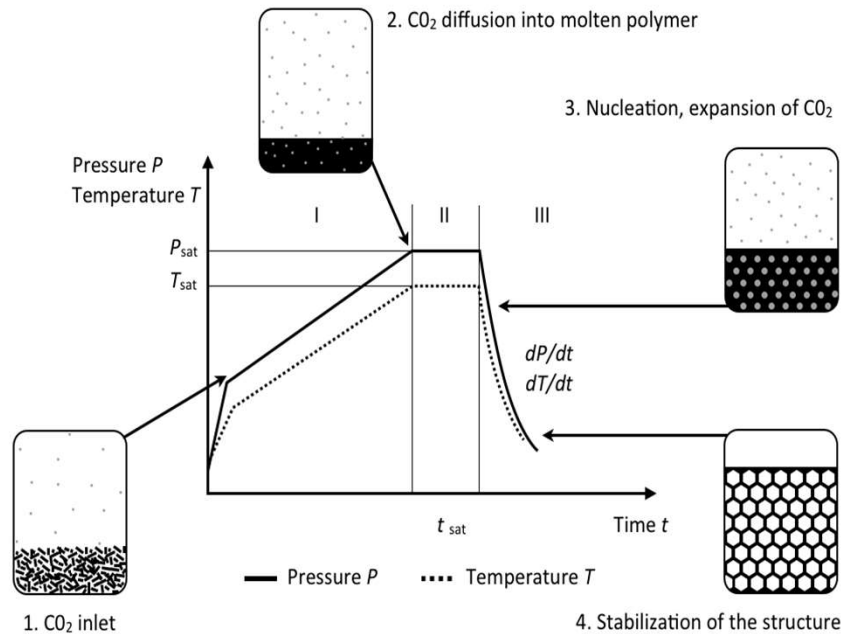
$$\frac{\eta^*}{\eta_0} = 1 + \frac{5}{2}\Phi + k_2\Phi^2$$

- Filler amount $\nearrow$ from 0 to 8 %
 $\Rightarrow \eta^* \nearrow$ by a factor of 2.5-4

- $T \searrow$ by 80 °C $\Rightarrow \eta^* \nearrow$ by a factor 10^3
- $\text{CO}_2 \searrow$ by 6 % $\Rightarrow \eta^* \nearrow$ by a factor 2-4

$\Rightarrow T$ = main parameter affecting viscosity

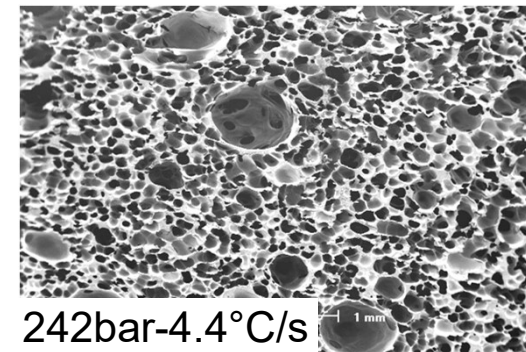
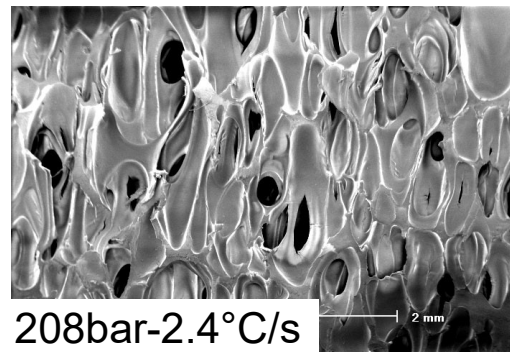
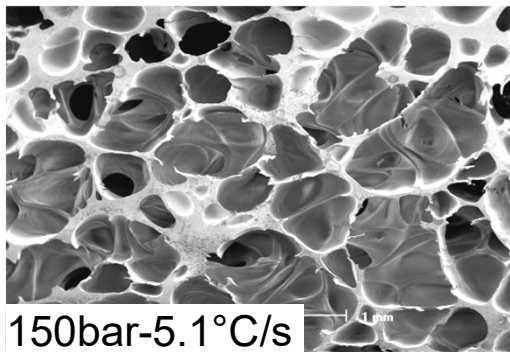
Supercritical CO₂ foaming



Factors affecting foaming

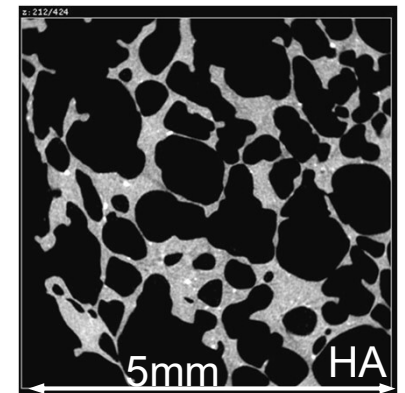
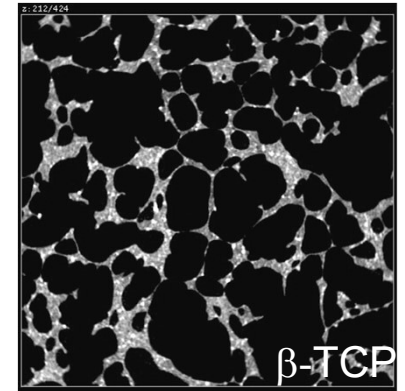
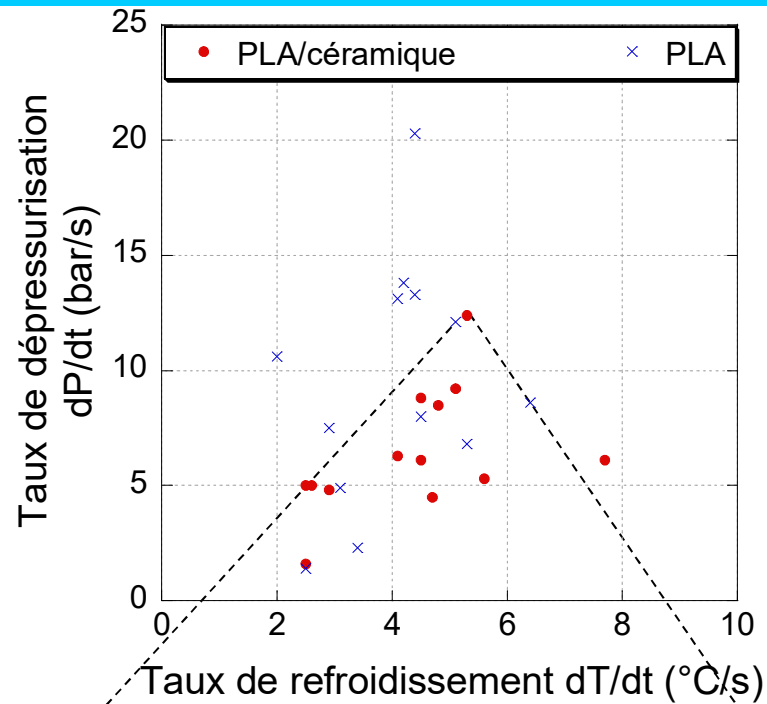
- External parameters
 - Saturation P_{sat} , T_{sat} , t_{sat}
 - Gas release rate dP/dt vs cooling rate dT/dt
- Polymer / CO₂ interactions : *Diffusion*
Concentration: C_{CO_2}
- Elongational viscosity μ

$$\mu = f(\text{polymer}, T, C_{CO_2})$$

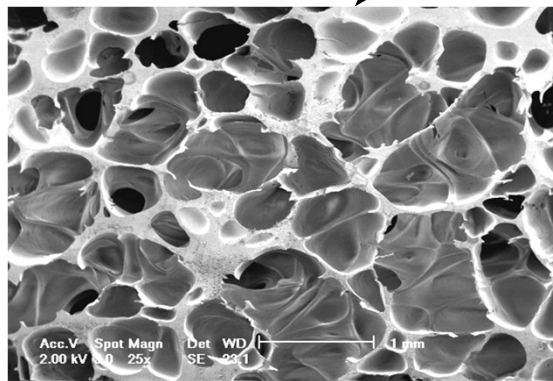


- ↳ Higher saturation pressure $\Rightarrow$ smaller pores, higher porosity
- ↳ Slower cooling rate $\Rightarrow$ more open porosity

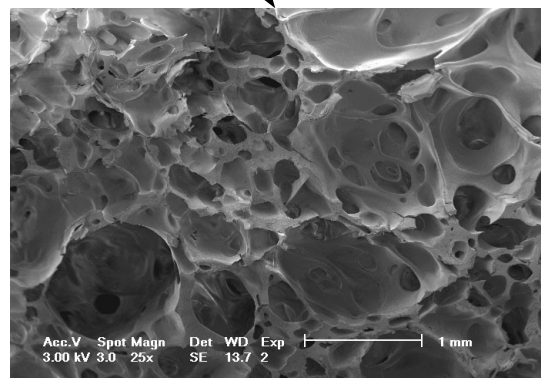
Foaming biocomposite PLA



Homogeneous dispersion of fillers in pore walls



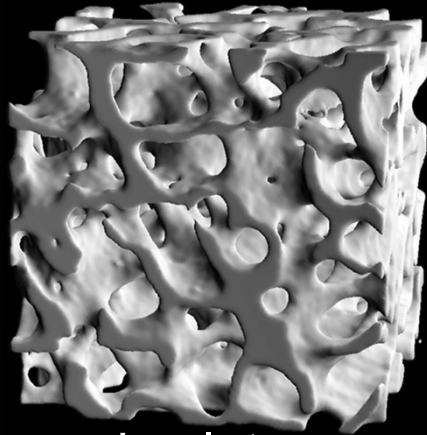
PLA



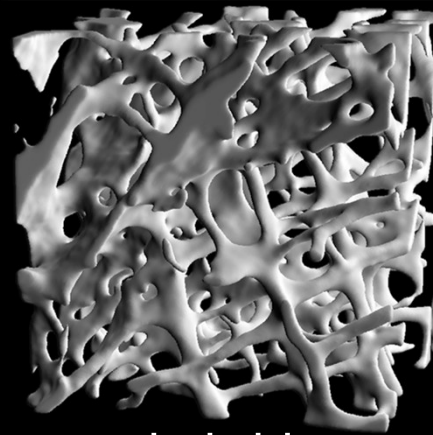
PLA + 5 wt% HA

Trabecular bone and composite foams

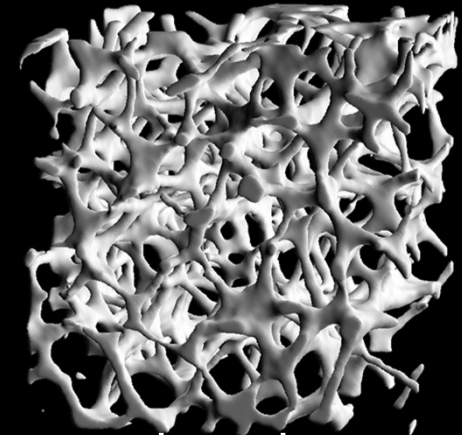
BONE



in plates

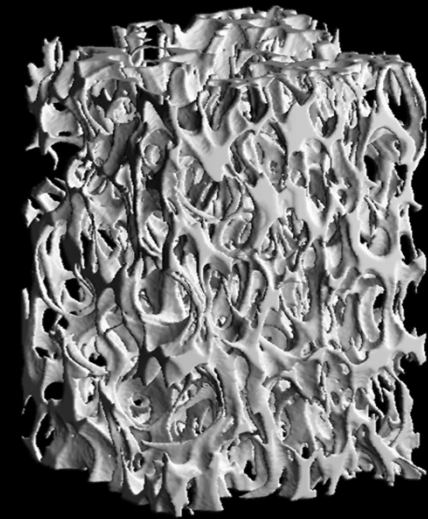
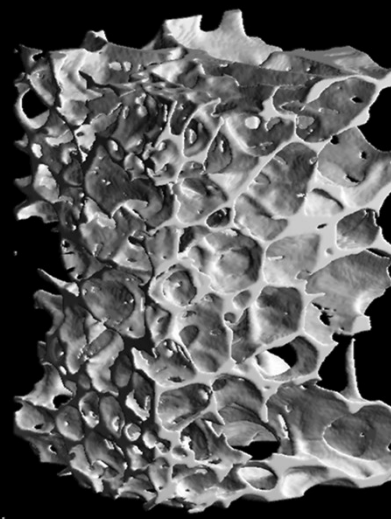
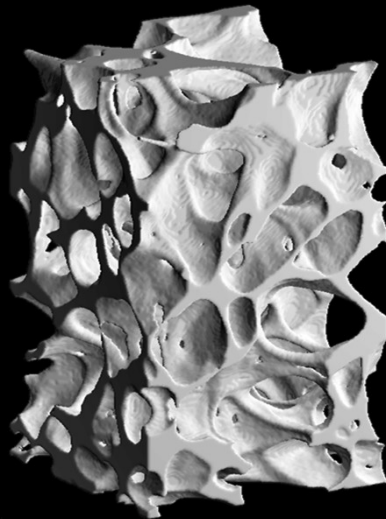


hybrid

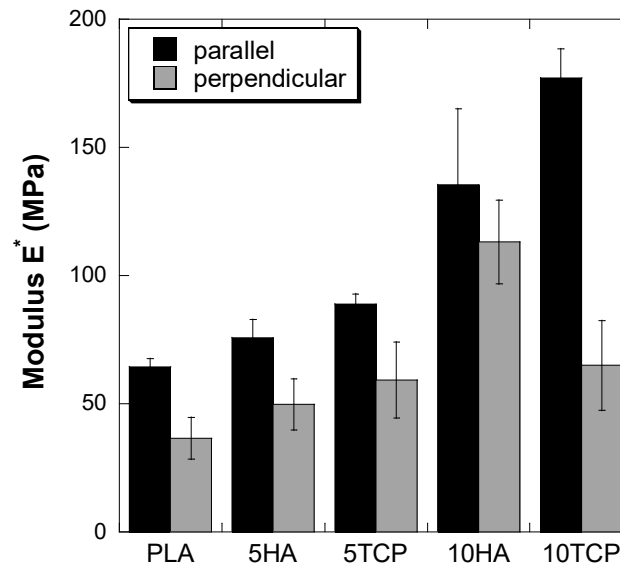


in rods

BIOCOMPOSITE



Mechanical behavior



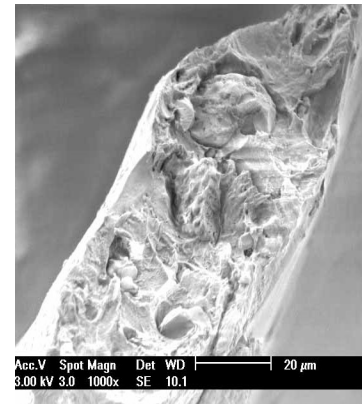
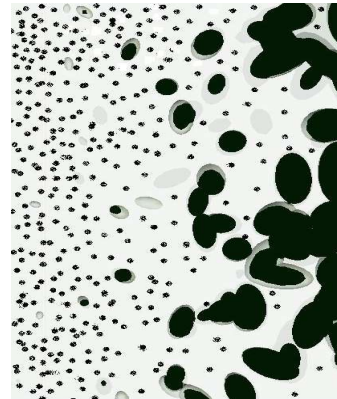
- Filler volume ↗
 - ⇒ modulus E^* and yield stress σ^* ↗
 - ⇒ improvement of foam mechanical resistance

- E^* up to 250 MPa
- σ^* up to 6 MPa

} Suitable for trabecular bone regeneration

Cellular composites with long fibres

...with fillers

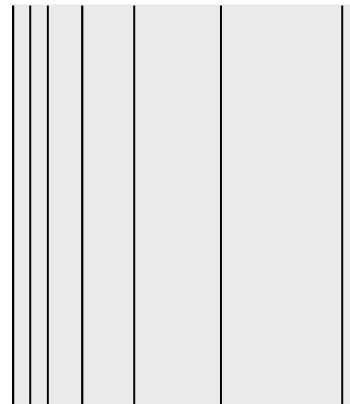


...MPa

Porosity Gradient

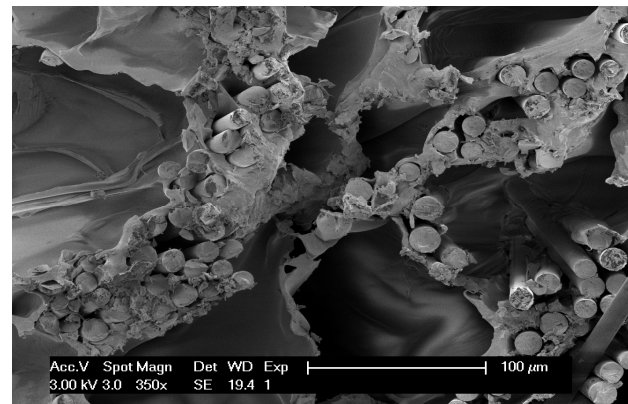
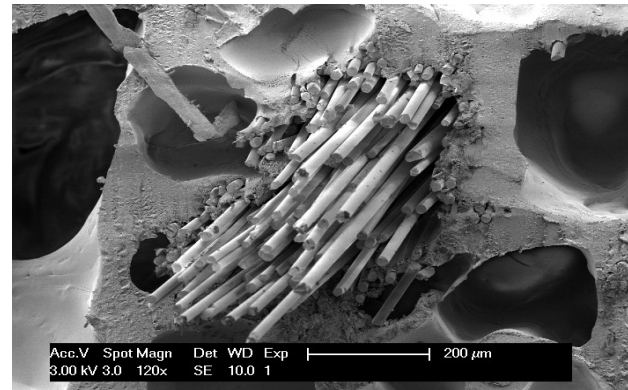


+ gradient of fibres

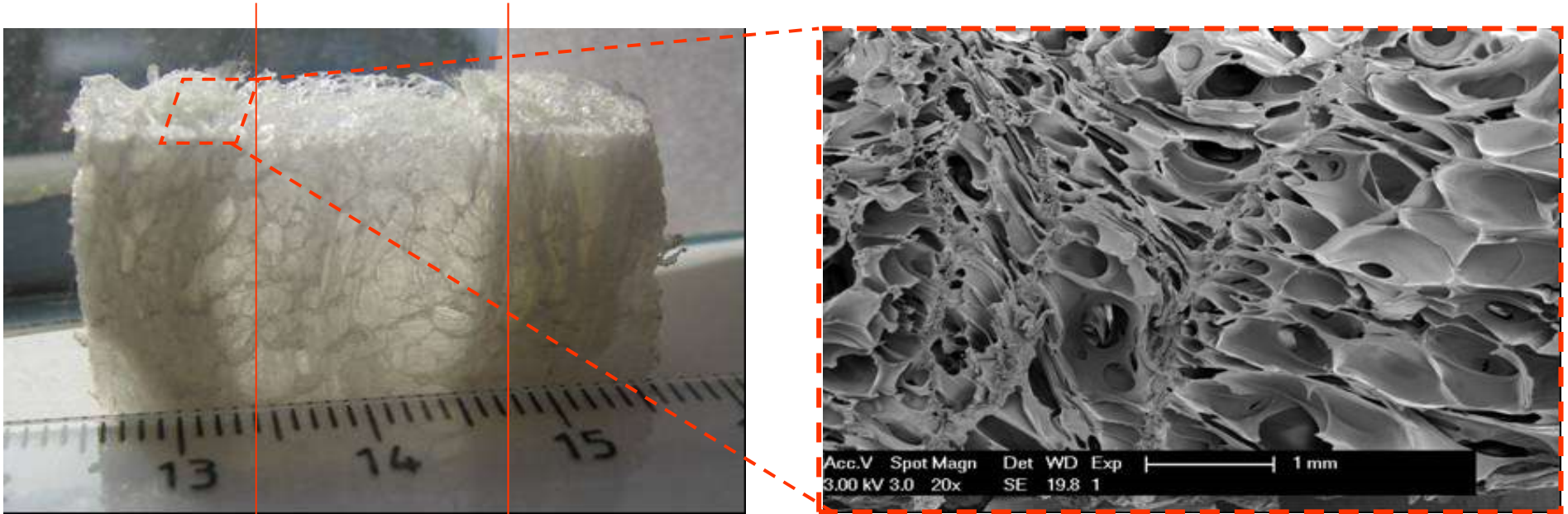


...GPa

Foaming biocomposites with continuous fibres



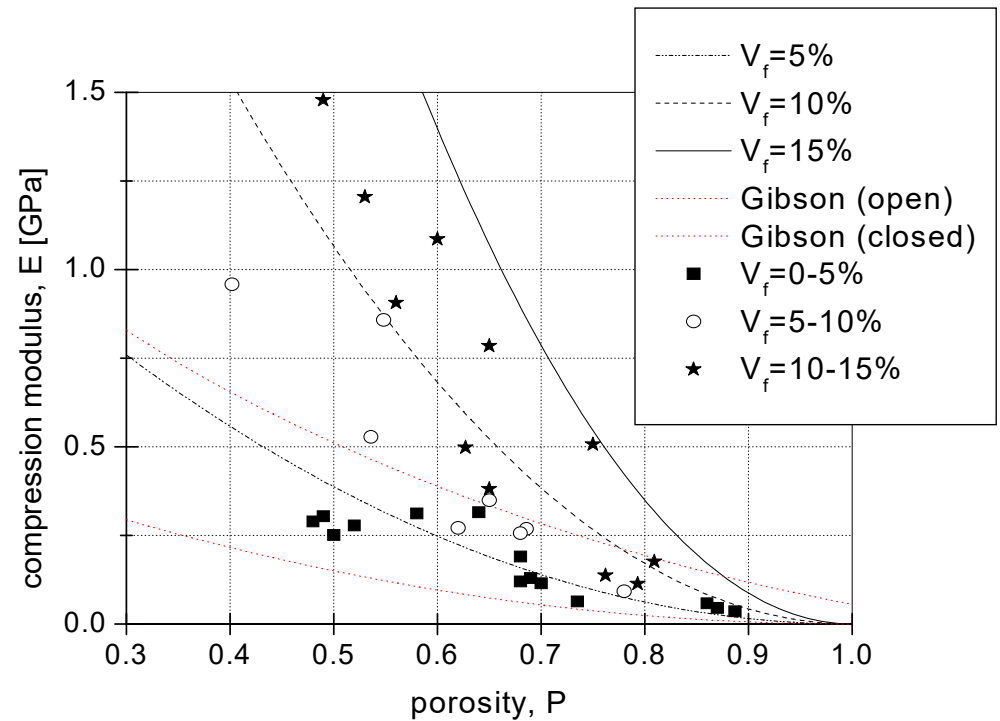
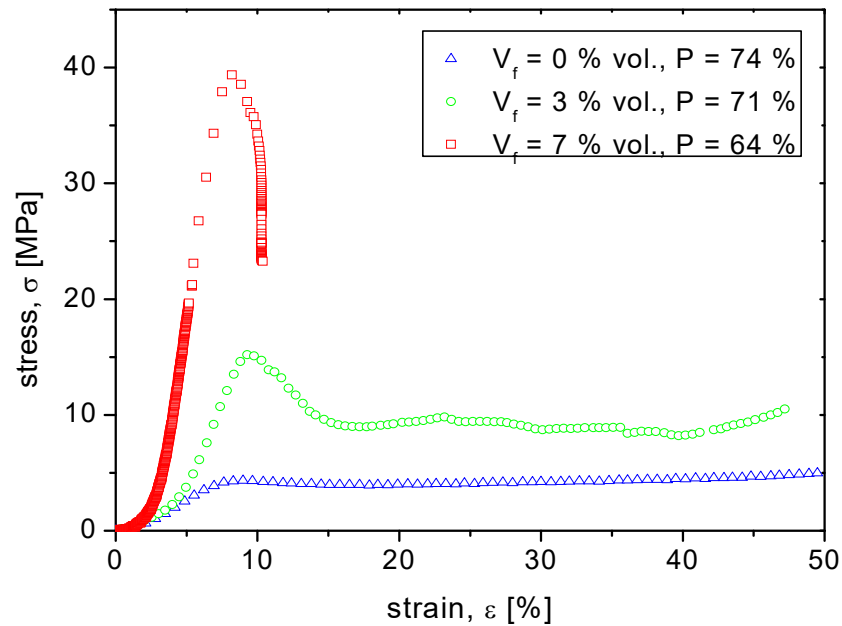
Gradients in fibre & porosity fraction



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

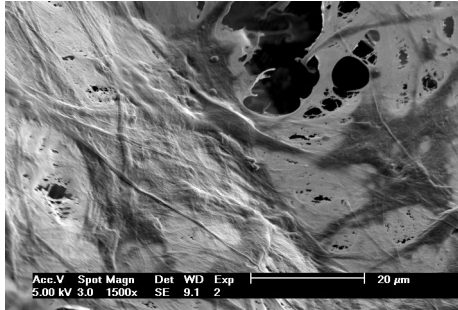
A smooth transition of the composites architecture from skin to core entails an advantageous distribution of internal stresses.

Fibres for mechanical performance

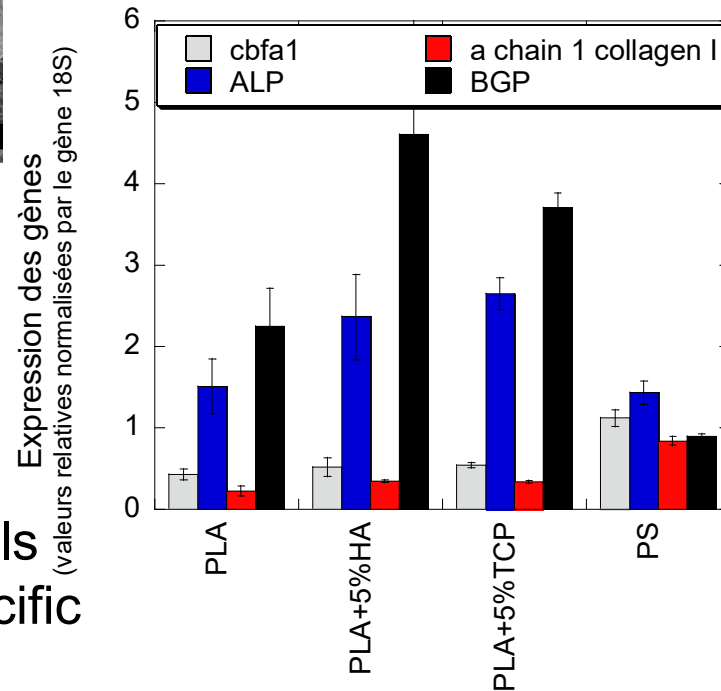


Even little fibre content stiffens the cellular composites.

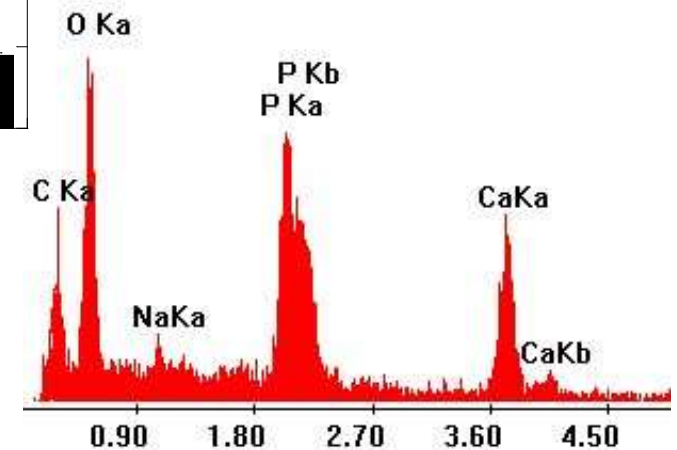
In vitro biocompatibility



- *Proliferation*: cells spread on the support



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

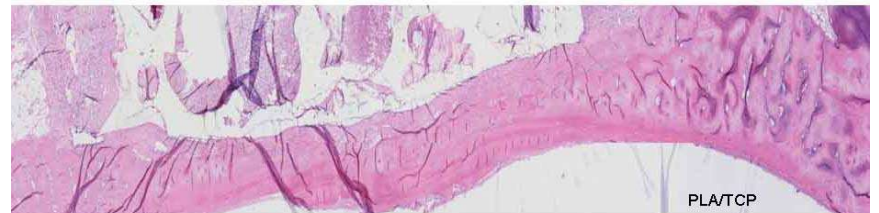
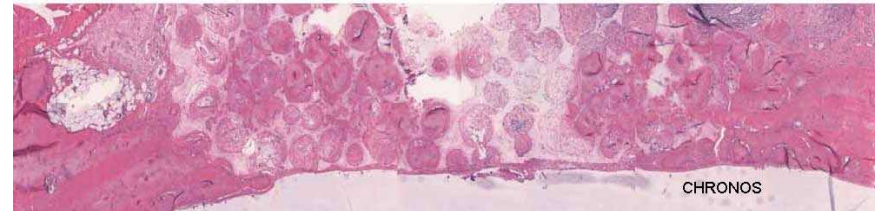


- *Differentiation*: cells express genes specific of osteoblastic phenotype

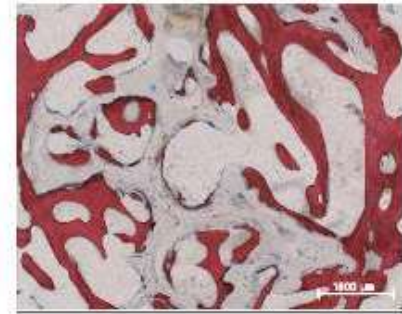
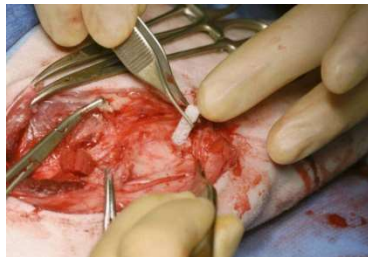
➡ Biocomposite scaffolds are biocompatible with bone fetal cells

In vivo biocompatibility

- **Rats:** cranial critical size defect



- **Sheep :** Femoral and tibial defects



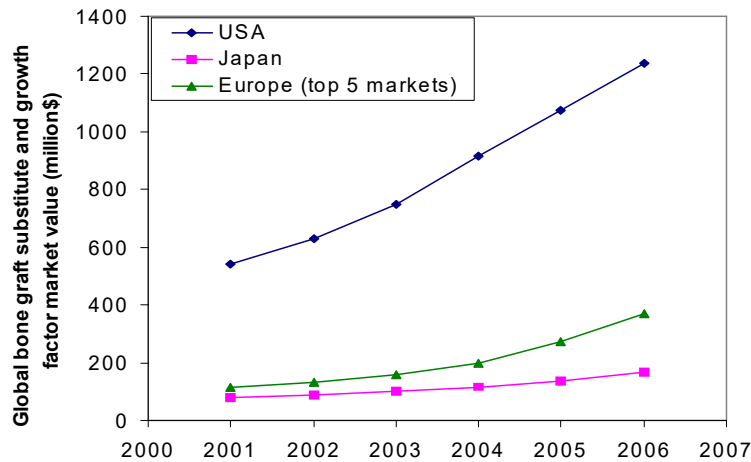
⇒ no inflammation, ossification

- **Human**



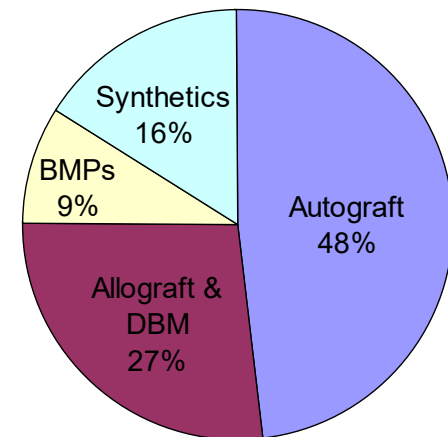
Bone grafts market

- Worldwide: 1'350'000 /year



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

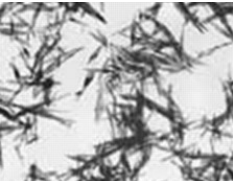
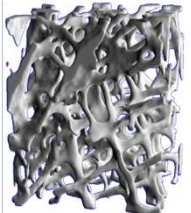
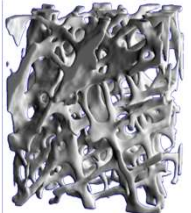
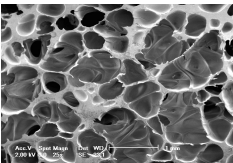
- Bone graft distribution



↪ Search for a synthetic substitute which favors bone regeneration

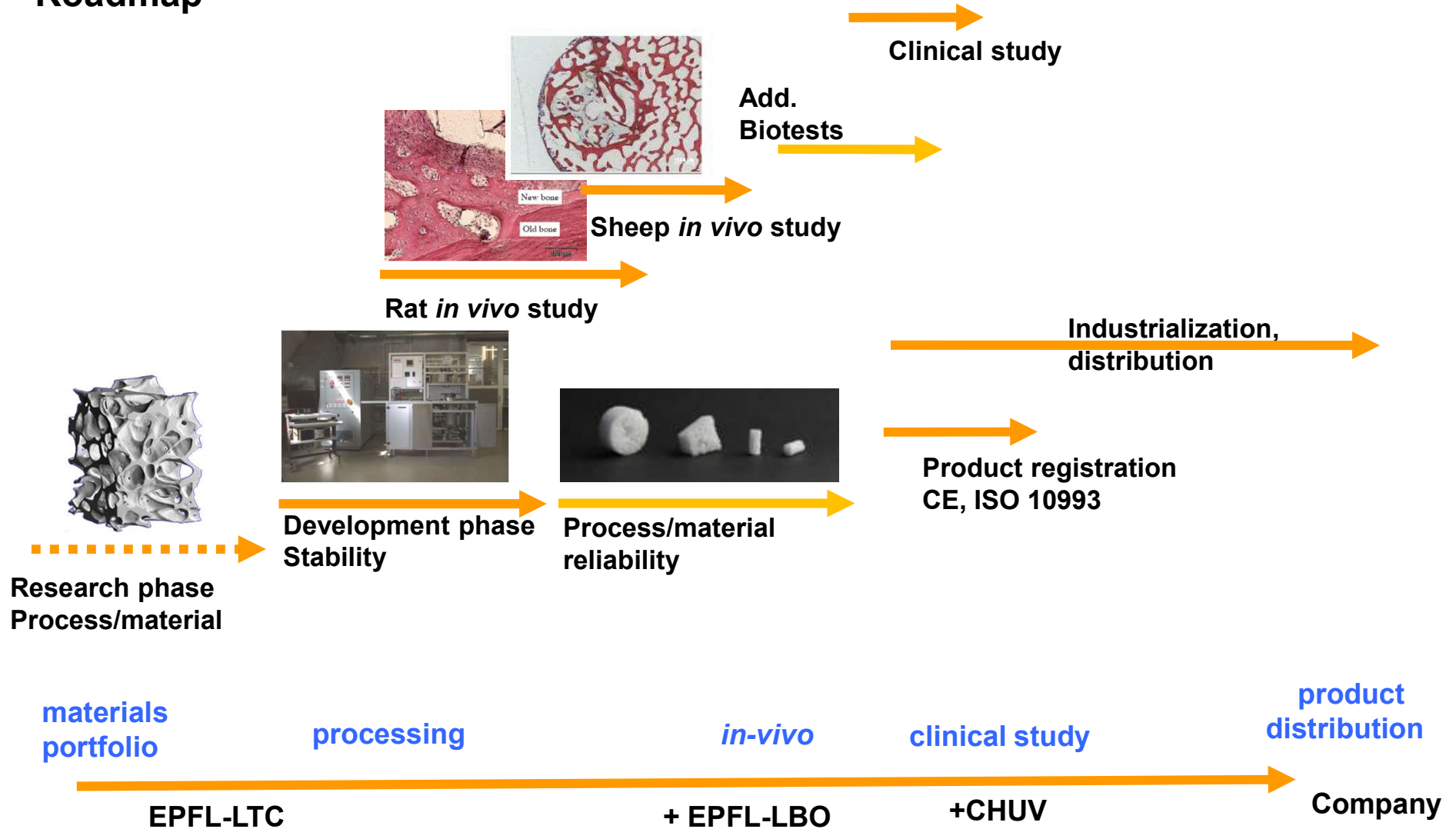
- Highly competitive & fragmented market
- A new product must demonstrate
 - Its unique selling proposition
 - Be customer oriented

Comparison with existing products

	Autografts <i>gold-standard</i>	Allografts <i>Osteotech</i>	 Ceramics <i>Synthes</i>	 Polymers <i>Macropore</i>	 Gels <i>Ostim Medical</i>	Proteins <i>Stryker OP-1</i>	 EPFL Composite
Osteoconductive	+++	+++	++	+	++	+++	++
Osteoinductive	+++	+	0	0	+	+++	0
Qty available	---	-	+++	+++	+++	+++	+++
Shapability	+	+	-	+	n.a.	n.a.	+++
Mech. resistance (compare to bone)	=	= 	>>> (brittle)	<< 	no	n.a.	= 

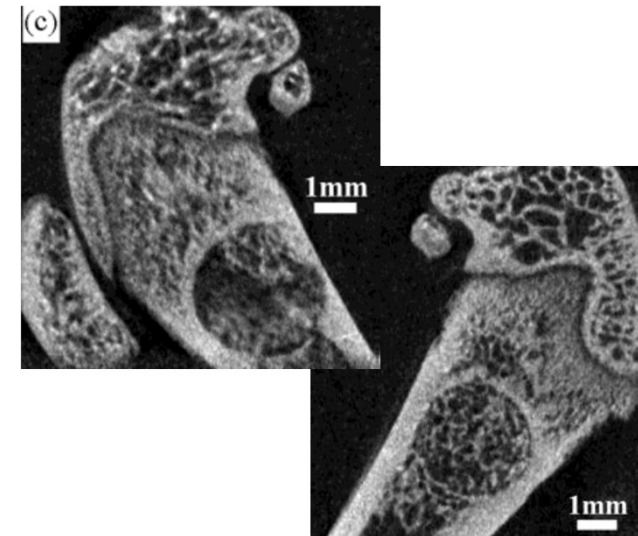
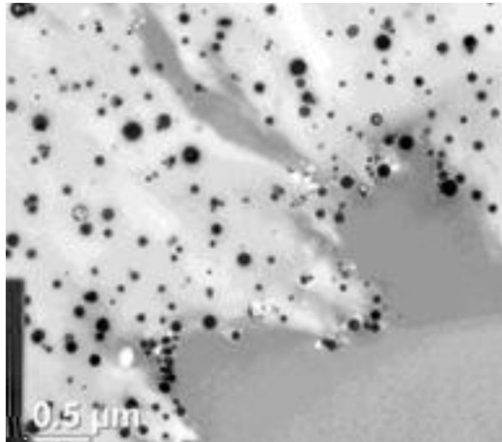
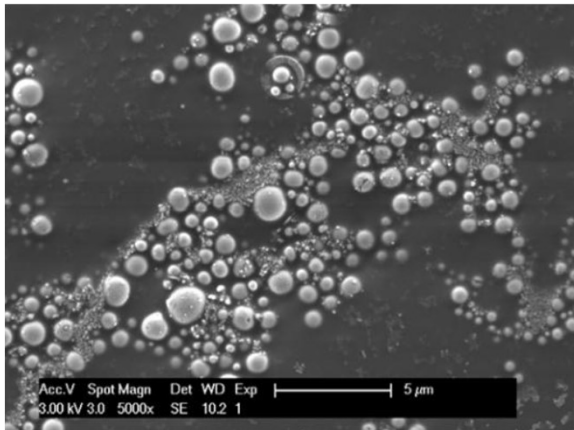
Biocomposite A: shape your scaffold

Roadmap



Biocomposite B : more osteoconductive

cellular nano composite



Biocomposite A

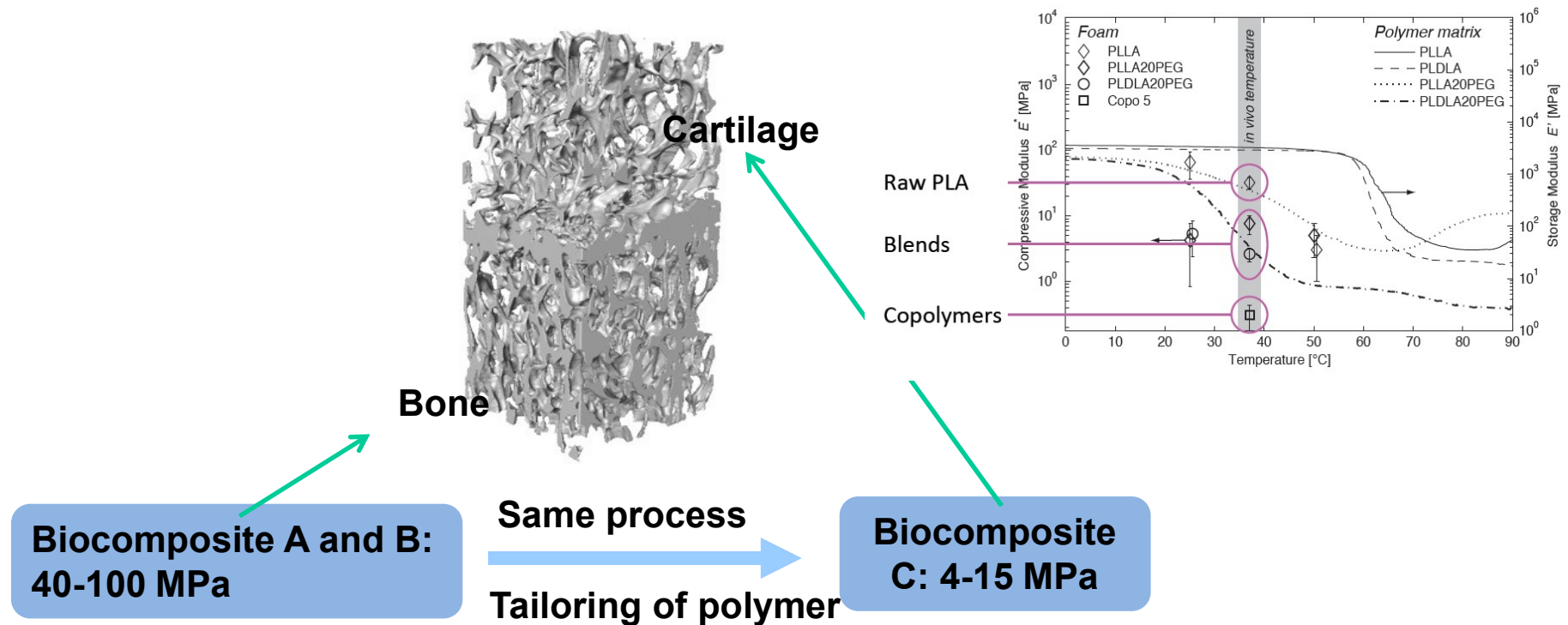
Same PLLA polymer
Same process

New nano filler

Biocomposite B

Biocomposite C : Softer cellular scaffold

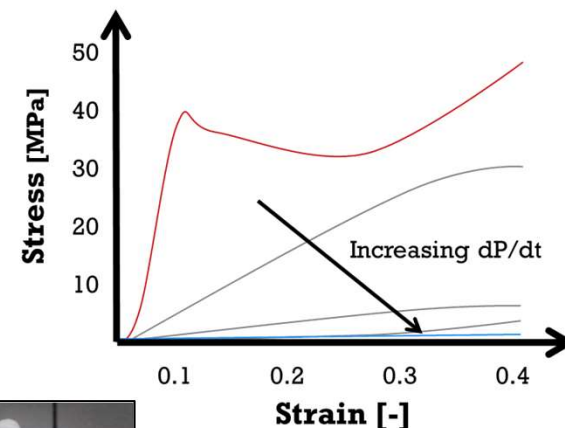
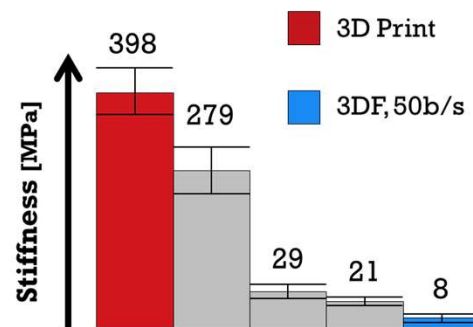
PLLA blends and copolymers



Cuénoud, 2012

Biocomposite D : 3D printed scaffolds

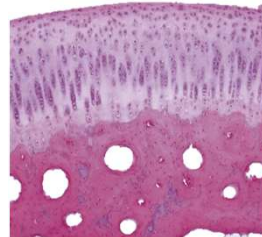
- Custom-made 3D structures
 - Reproduce geometry of body parts, surgeon support, replica of in vivo milieu
- In vitro platforms to study cell response and drug screening
 - scaffold pore size, geometry, wettability, adhesion, mechanical loading on cells behavior
- Templates/scaffolds for tissue regeneration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



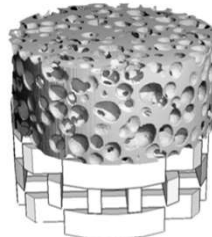
Matteo Marascio

FDM of different PLA based structures

Human cartilage



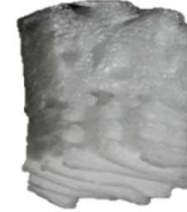
Model



3D Printed

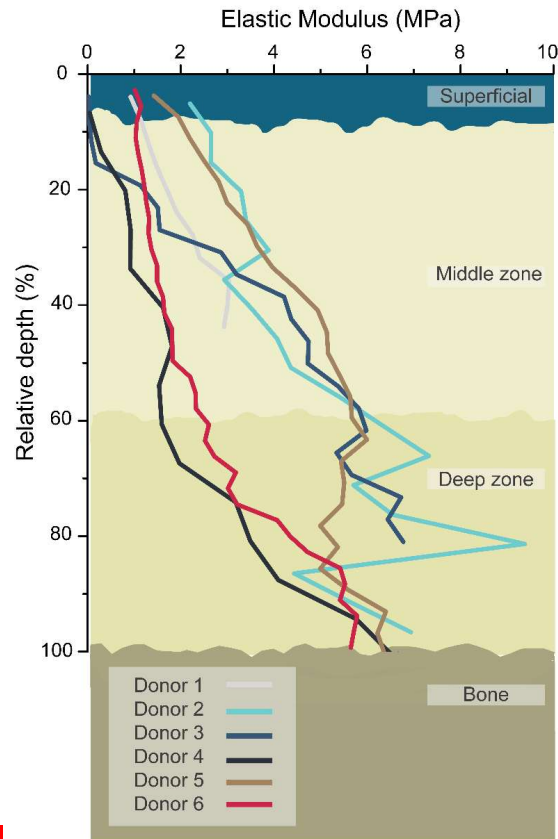


Foamed

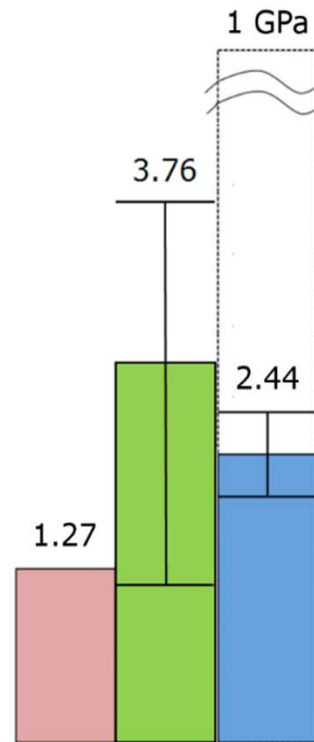


— PLAPCL

— PLABTCP



Aggregate modulus (MPa)



- PLAPCL raw
- Articular cartilage (literature)
- Articular cartilage (Chapter 4)
- Multi material foam PLAPCL - PLABTCP

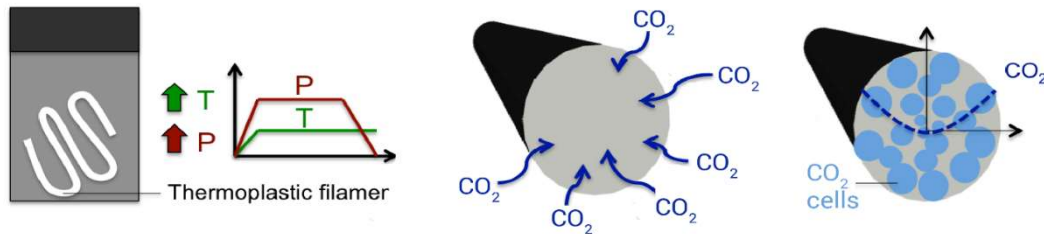
Direct 3D Foam Printing

Phase 1: Filament saturation

Material saturation

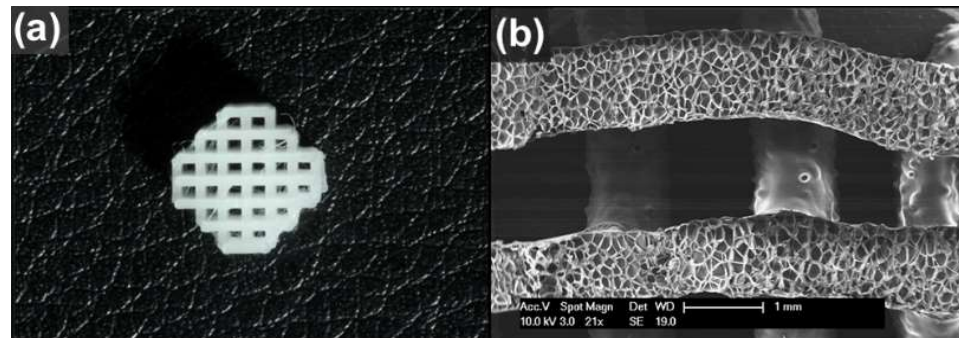
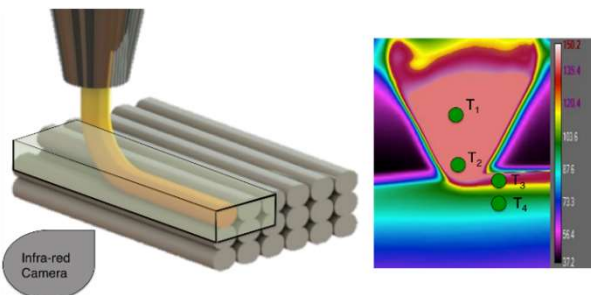
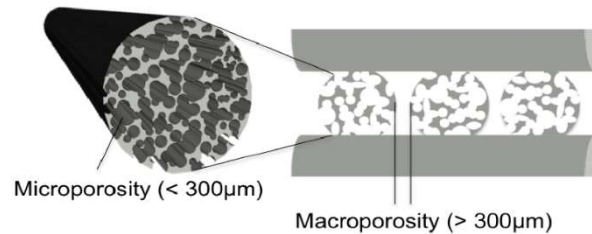
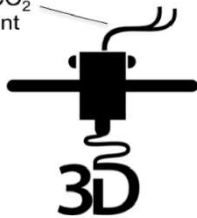
CO₂ diffusion

CO₂ saturation profile

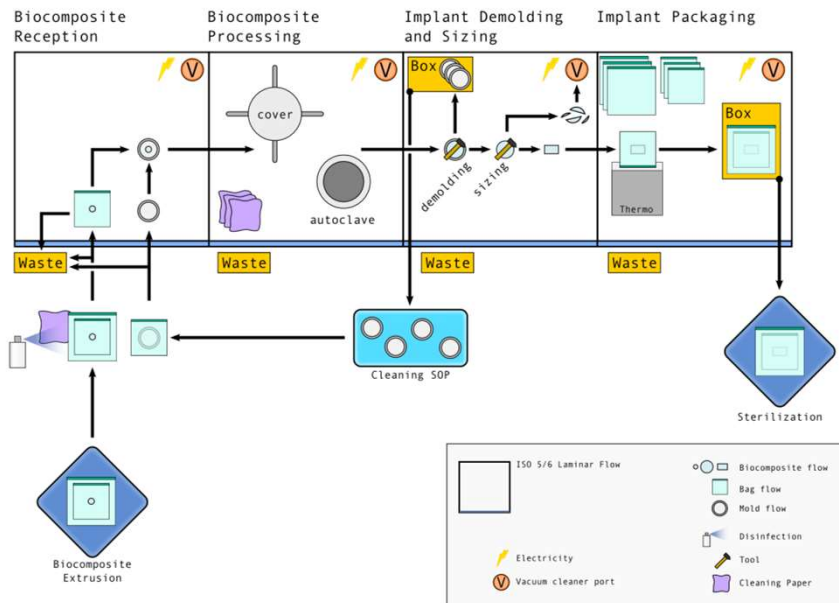


Phase 2: Fused Deposition Modeling printing

Thermoplastic CO₂ saturated filament



Processing for medical devices



- **Additional phenomena to control**

- **Degradation during processing**
 - Drying
 - Molecular weight drop
- **Contamination**
 - Environment
 - Tools
- **Sterilization**
 - EtOH
 - Gamma



Biocomposite D : 3D printed devices

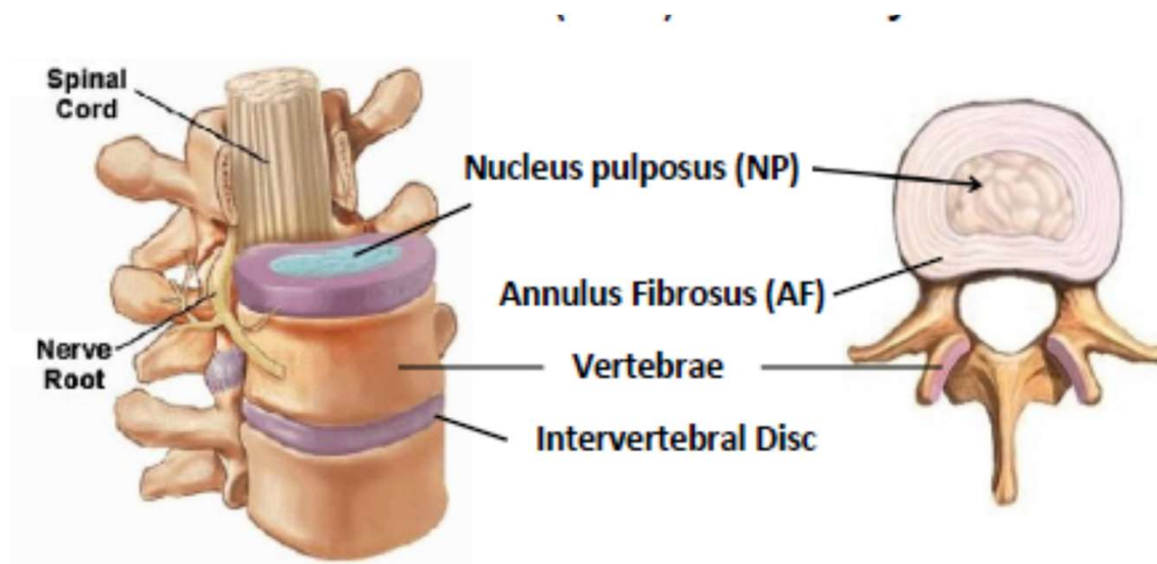


OUTLINE

- 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	$6 \times 10^{-16} \text{ m}^4/\text{Ns}$ – $15 \times 10^{-16} \text{ m}^4/\text{Ns}$ (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	$\pm 10\%$ (max $\pm 25\%$) (Tsantrizos 2005)

^afrequency: 1-100 rad·s⁻¹

Some examples of other types of tissue for comparison:

- Compact bone: $|G^*| = 4\text{GPa}$ $\tan(\delta) = 0.01$ (Lakes 1979)
- Spinal motion segment: $|G^*| = 45\text{MPa}$ $\tan(\delta) = 0.1$ (Ohshima 1989)
- Meniscus: $|G^*| = 100\text{kPa}$ $\tan(\delta) = 0.40$ (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

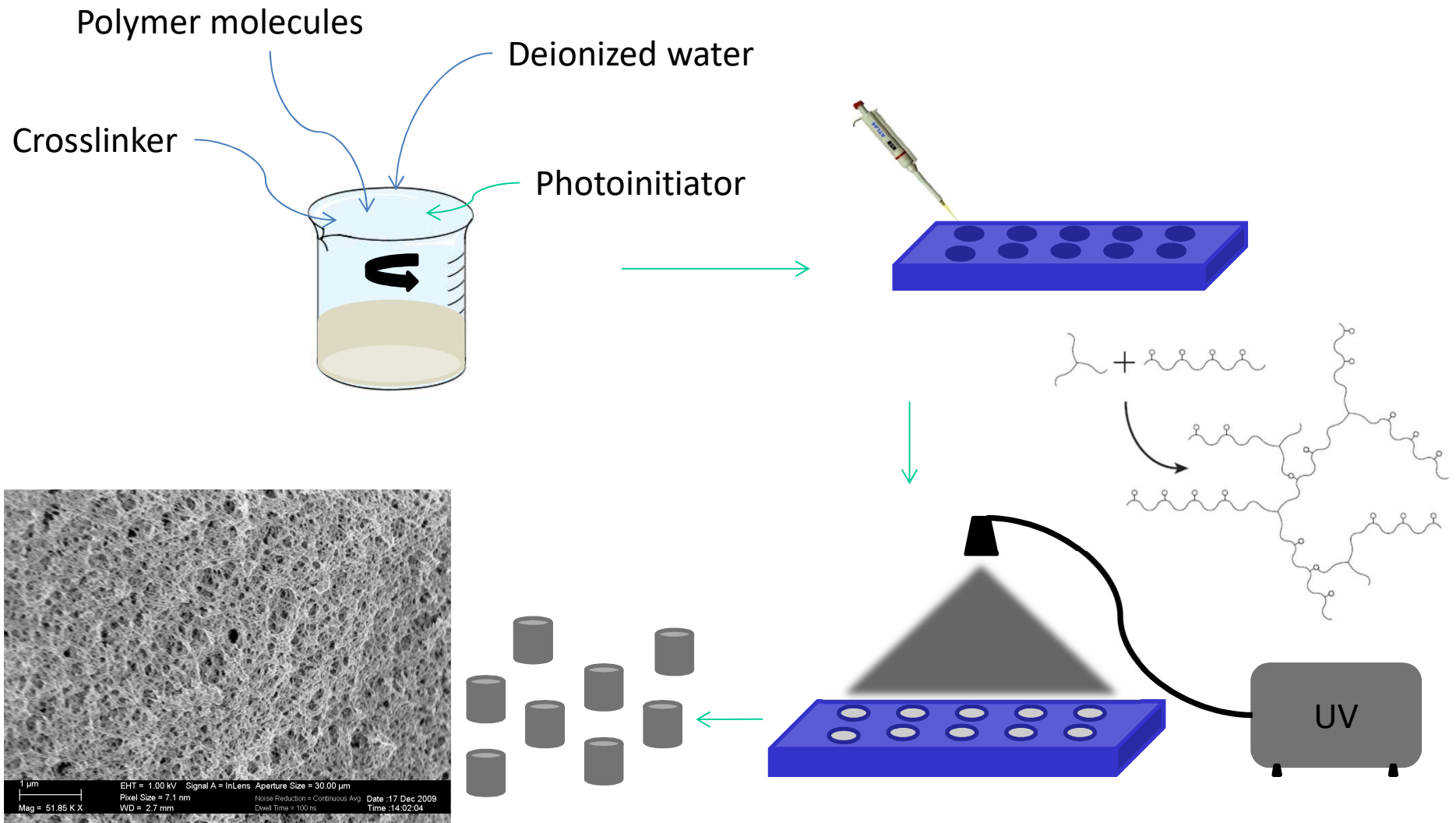
Injectable, in situ curing

New material system, UV curing

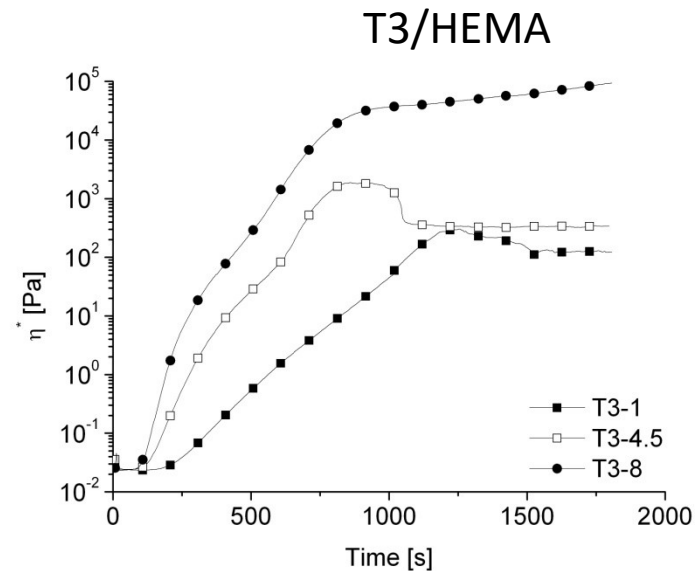
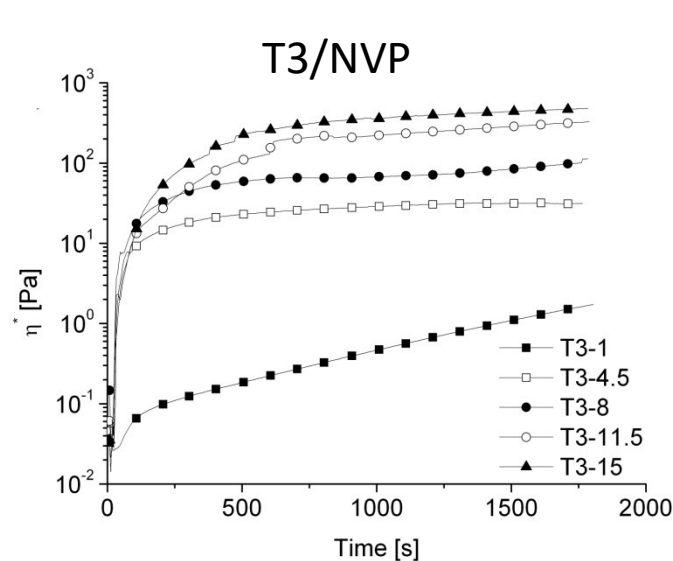
Hydrogel, composite hydrogel

Easy to synthesize molecules

Synthesis and Curing kinetics

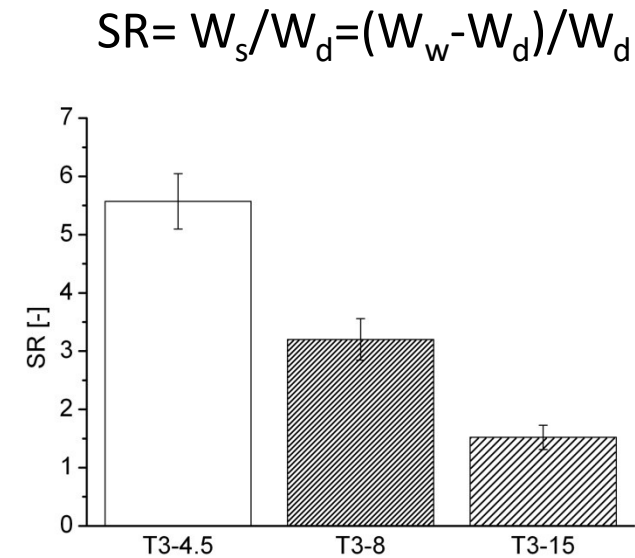
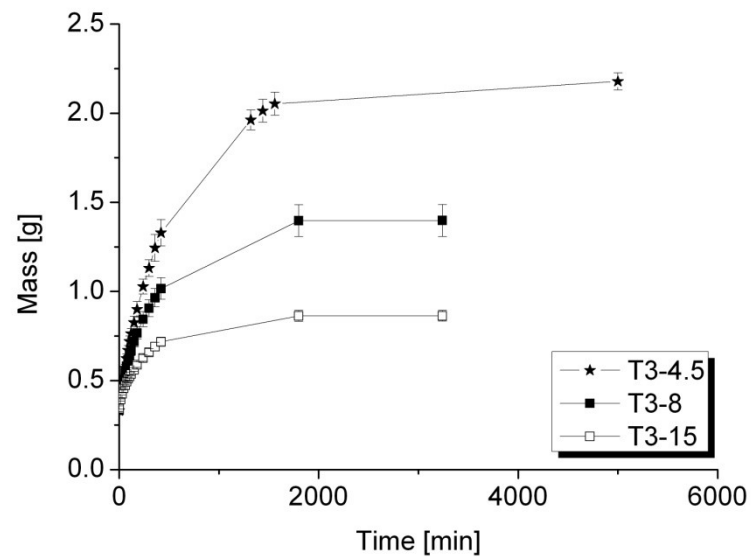


Influence of the crosslinker (T3) concentration



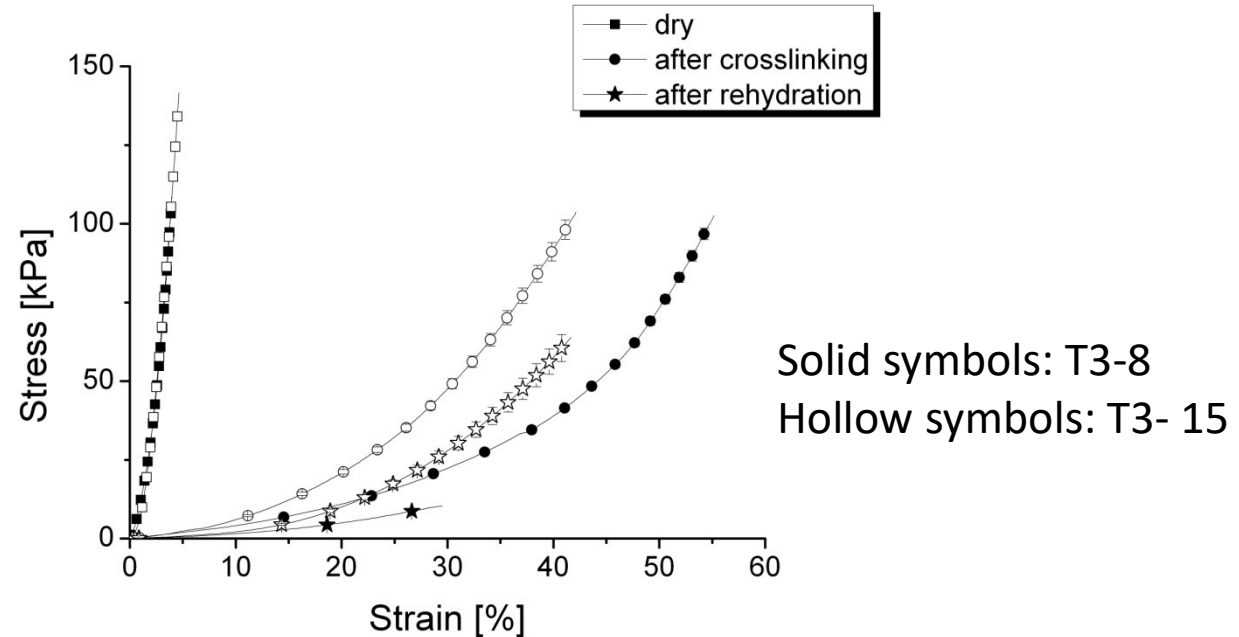
- Plateau indicates end of polymerization.
 - η^* increases with T3 concentration $\rightarrow$ stiffer network.
 - T3/HEMA hydrogels stiffer than T3/NVP hydrogels.
 - Curing time longer for T3/HEMA hydrogels.
-
- Stiffness of network defined by T3 concentration.
 - Short curing times induce low stiffness of hydrogel network.

Swelling behavior



- 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

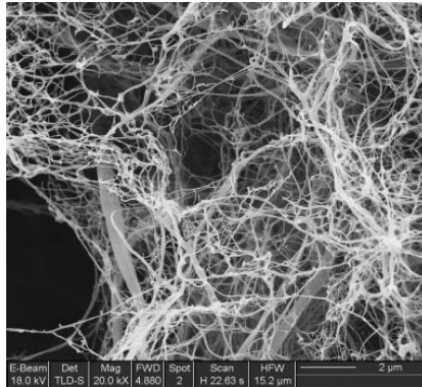


	E (dried samples) [kPa]	E (after polymerization) [kPa]	E (after rehydration)[kPa]
T3-8	2200	50	3
T3-15	2500	80	4

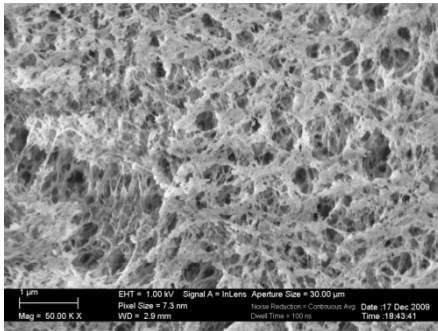
- Stiffness can be tailored mainly with PBS content.
- Modulus of native nucleus (3 to 6 kPa) achieved but ideal NP implant should be higher.

Composite hydrogels

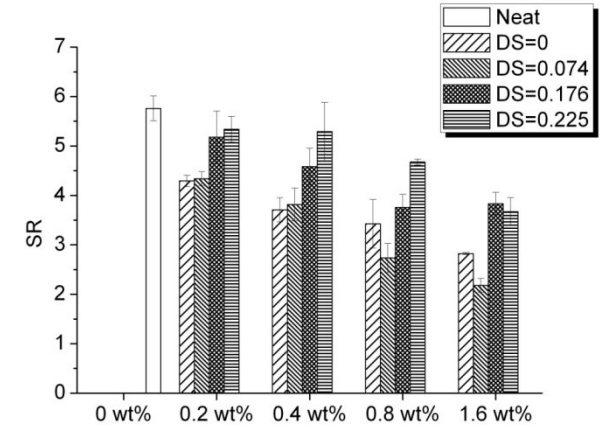
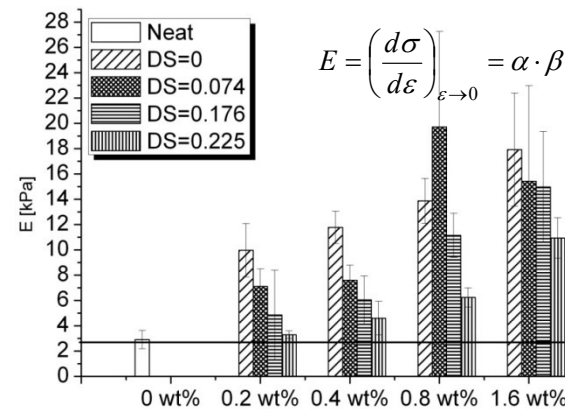
Hydrogel + Nanofibrillated Cellulose (NFC)



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



Borges, ActaBiomaterialia, 2011
Eyholzer, Biomacromolecules, 2011

Application requirements for selecting the final materials

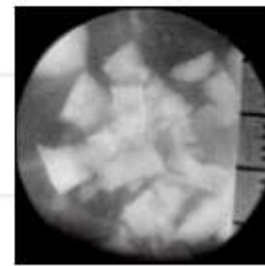
- Failure and fatigue performance
- Injection and UV curing
- Maintaining disk height
- *Ex and in vivo* studies



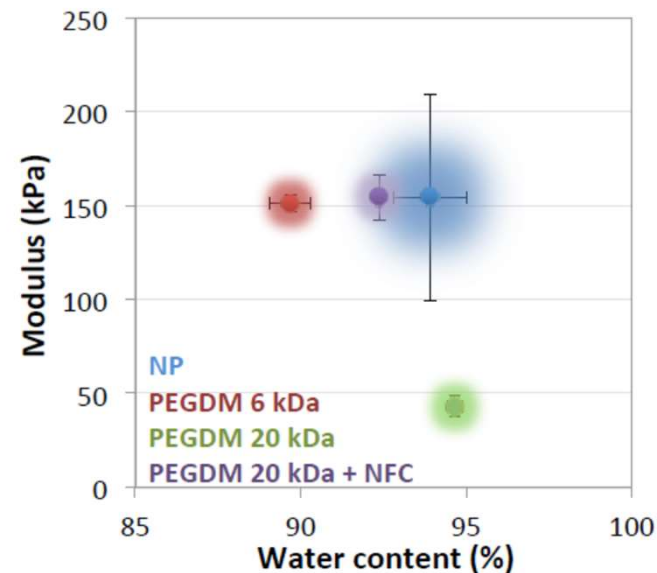
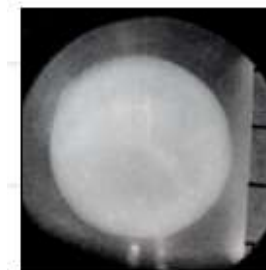
Alini, Mauro, et al. European Spine Journal (2008)

PEGDM hydrogels and cellulose fibrils

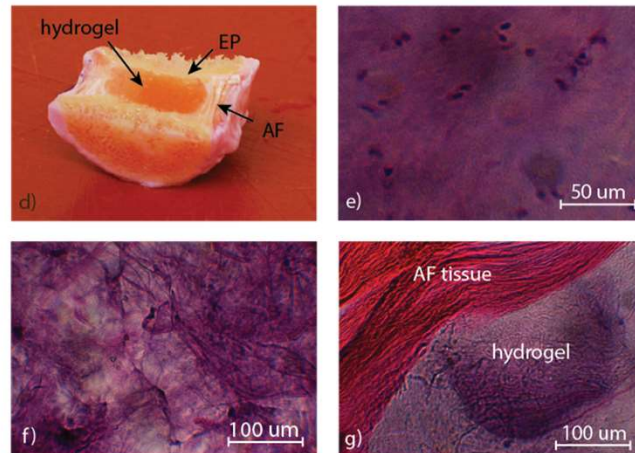
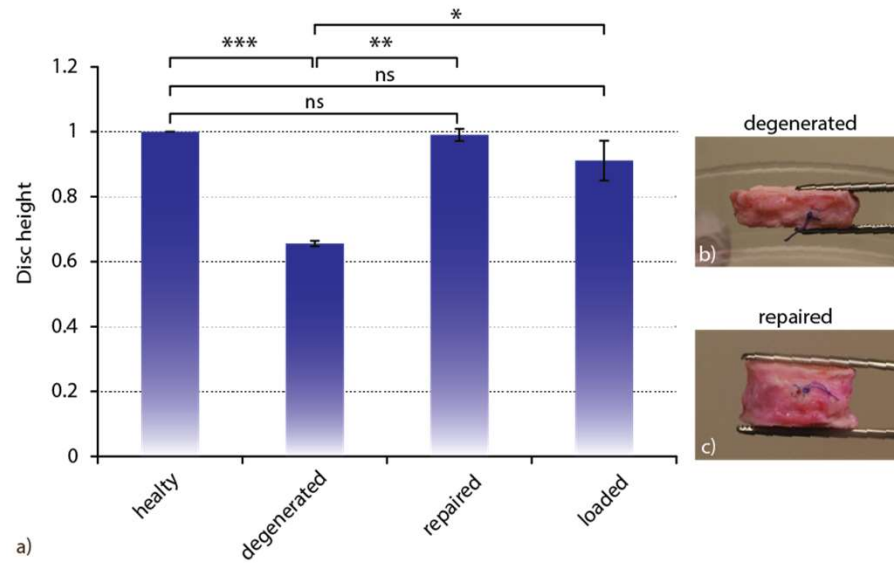
PEGDM 6 kDa
at 63% compression:



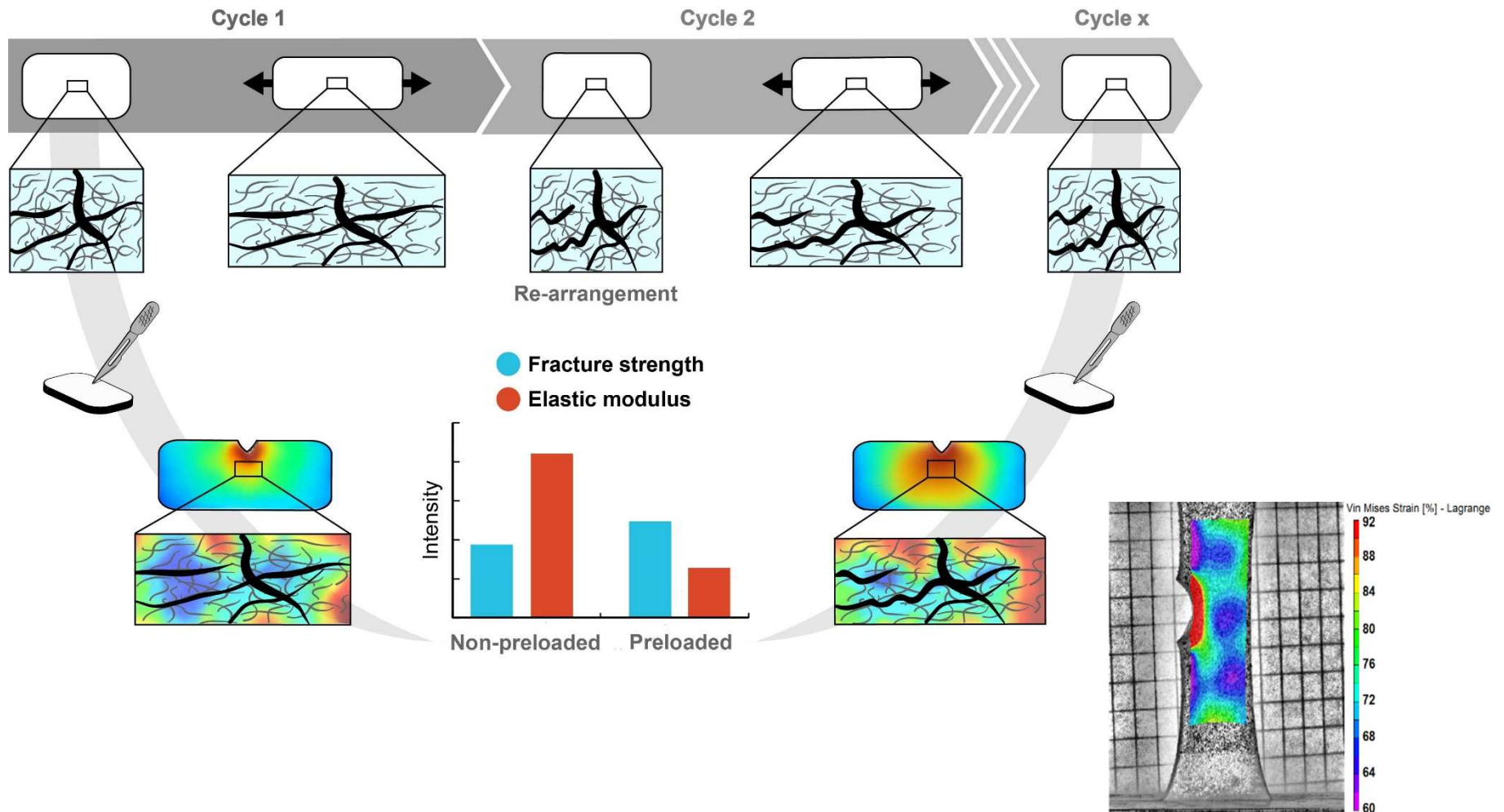
PEGDM 20 kDa reinforced with NFC
at 80% compression:



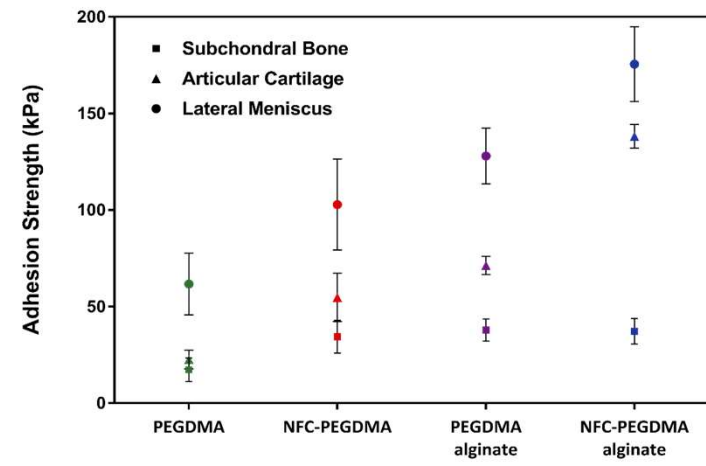
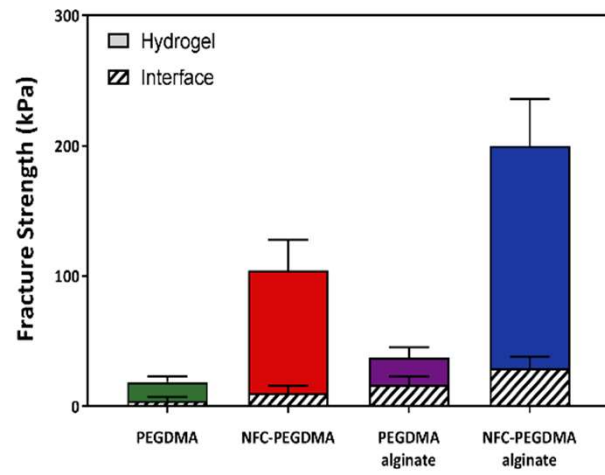
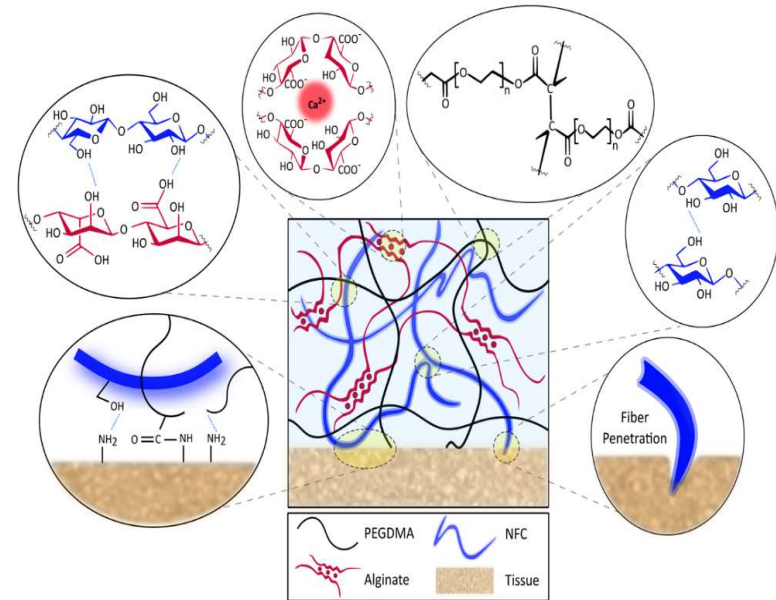
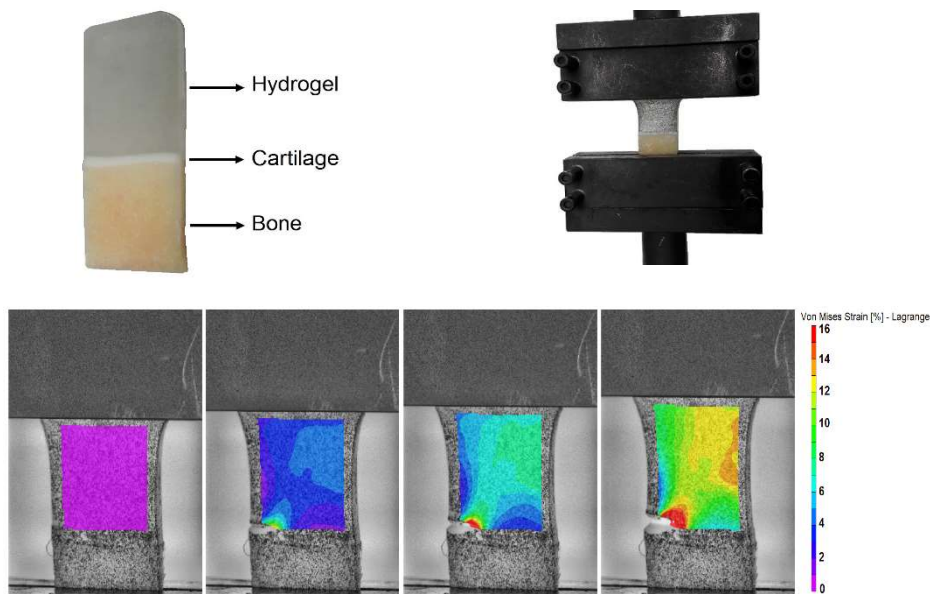
Bovine animal model



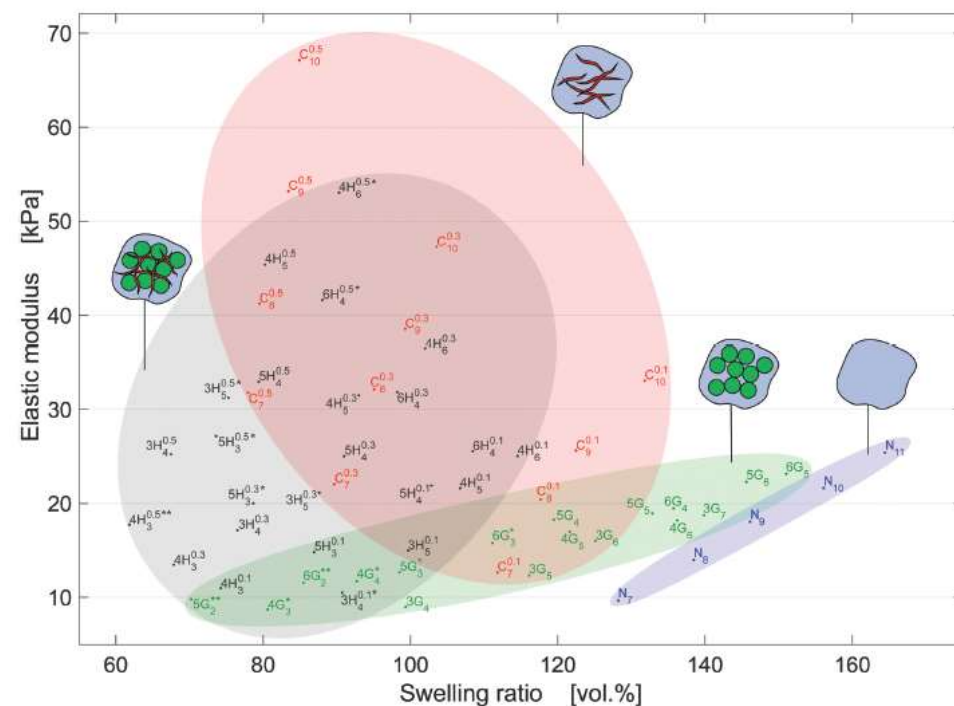
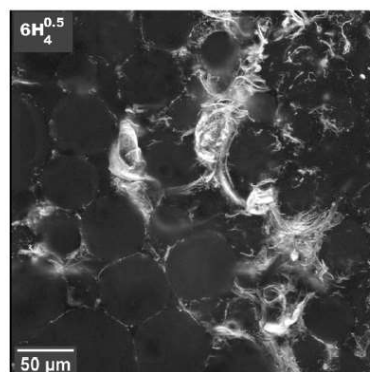
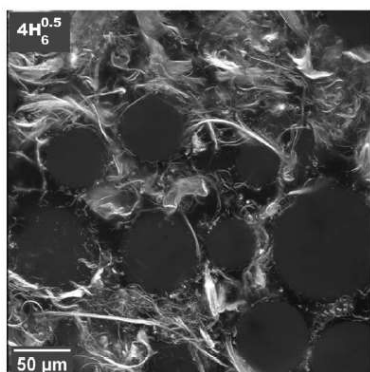
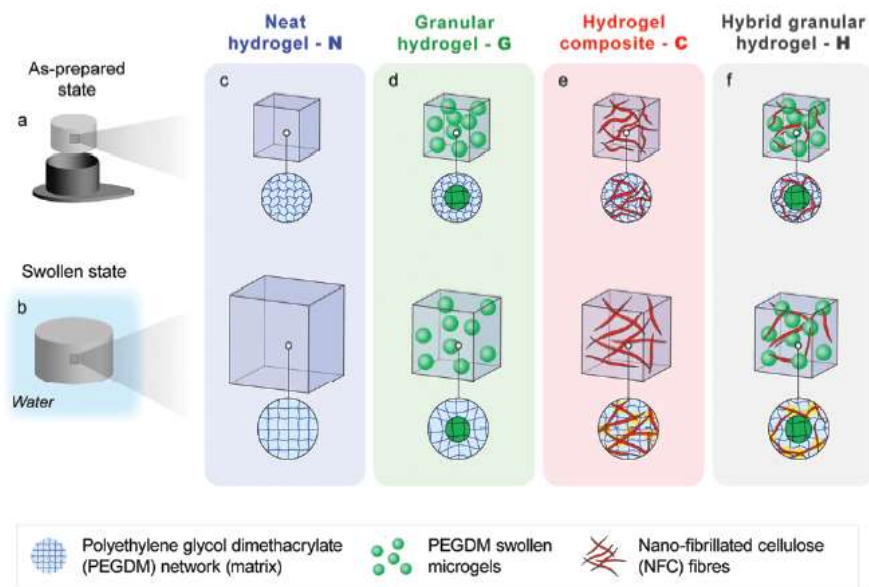
Hydrogel composites for fracture strength, dissipation, adhesion...



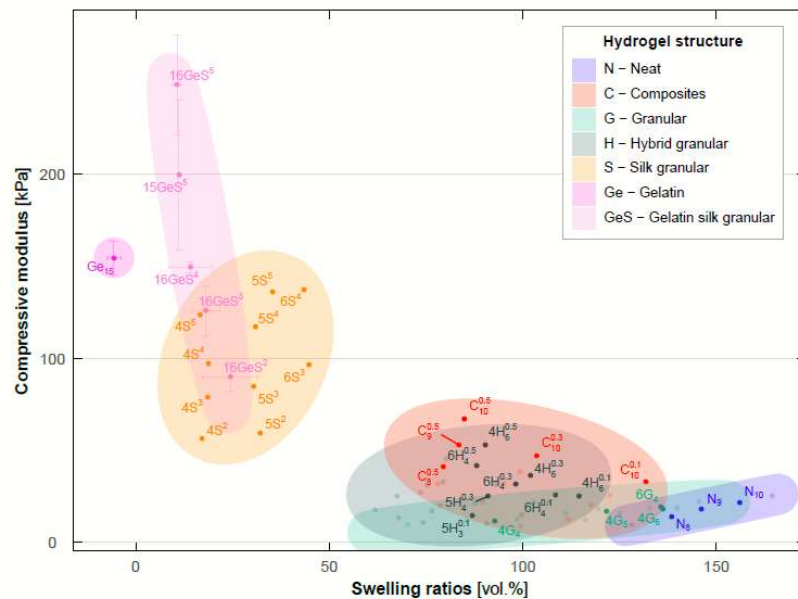
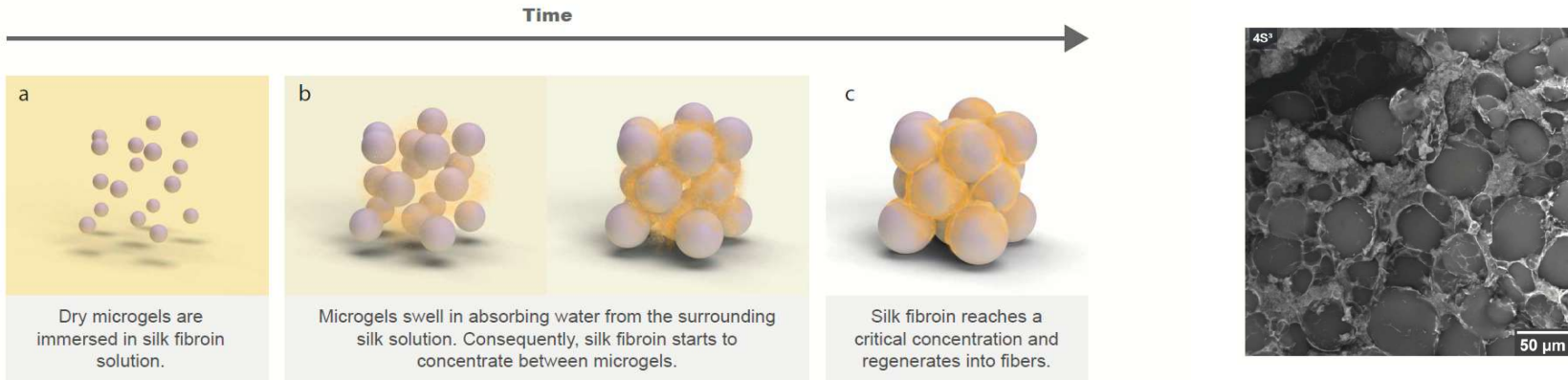
Hydrogel composites for fracture strength, dissipation, adhesion...



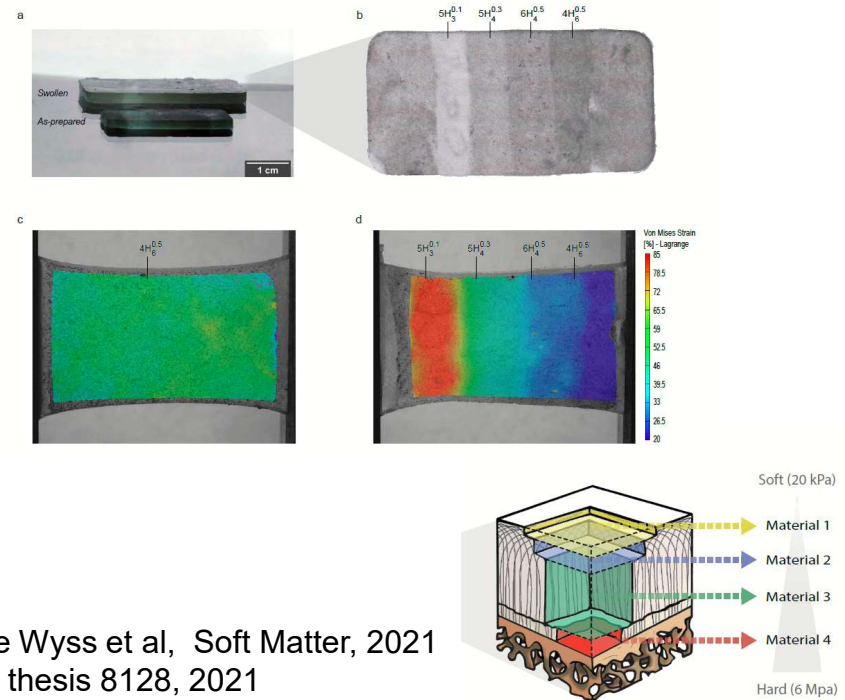
Combining composites and microgels



In situ self-reinforced silk hydrogel composites



Gradient composite for soft tissues



Biocomposites : Today & tomorrow

- Composites have recent applications in biomedical fields
- They offer the freedom to tailor structures and functions 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

Biblio

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- Frost & Sullivan, 2004
- EPFL Diplomas V Gulgoz 2002, J Rion 2004
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- Bioresorbable composites prepared by supercritical fluid foaming. *Journal of Biomedical Materials Research*, 2005;75A:89-97
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- Cellular thermoplastic composites with microstructural gradients of fibres and porosity, *Composites Science and Technology*, 2008
- Curing kinetics and mechanical properties of a composite hydrogel for the replacement of the nucleus pulposus, *Composites Science and Technology*, 2010
- Antons J., Marascio M., Nohava J., Martin R., Laurent-Applegate L., Bourban P.E., Pioletti D.P. Depth-dependent mechanical properties of human articular cartilage obtained by indentation measurements. *J Mat Sc Mat Med*, 29, 57, 2018.
- M. G. M. Marascio, J. Antons, D. P. Pioletti, et P.-E. Bourban, 3D Printing of Polymers with Hierarchical Continuous Porosity, *Advanced Materials Technologies*, vol. 2, n° 11, p. 1700145, 2017.
- A. Khoushabi, C. S. Wyss, B. Caglar, D. Pioletti, et P.-E. Bourban, Tailoring swelling to control softening mechanisms during cyclic loading of PEG/cellulose hydrogel composites, *Composites Science and Technology*, vol. 168, p. 88-95, 2018.
- C. S. Wyss, P. Karami, P.-E. Bourban, et D. P. Pioletti, Cyclic loading of a cellulose/hydrogel composite increases its fracture strength, *Extreme Mechanics Letters*, vol. 24, p. 66-74, 2018.
- 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.

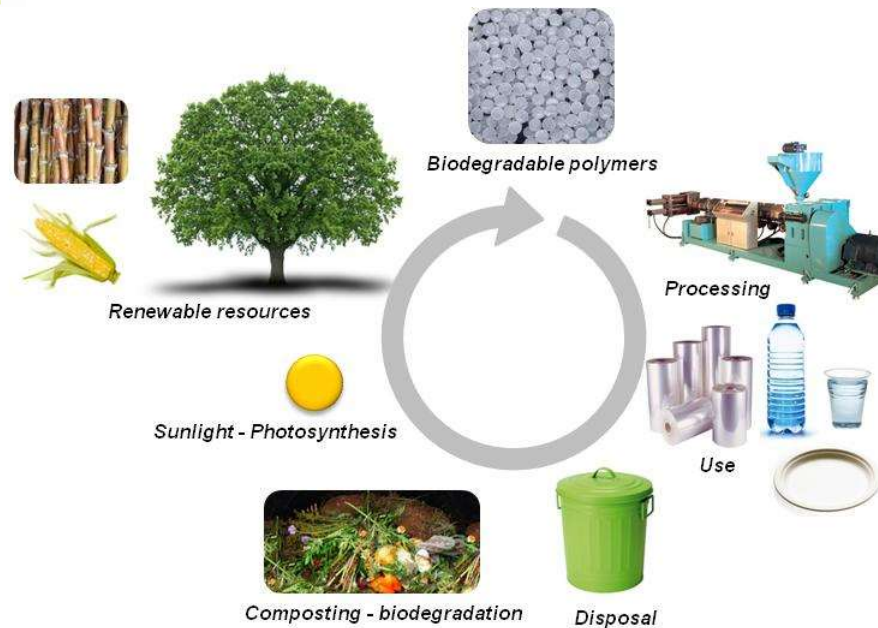
Outline

Polymer composites
in biomedical devices

Biodegradable composites
from renewable resources

Natural fibre
biocomposites

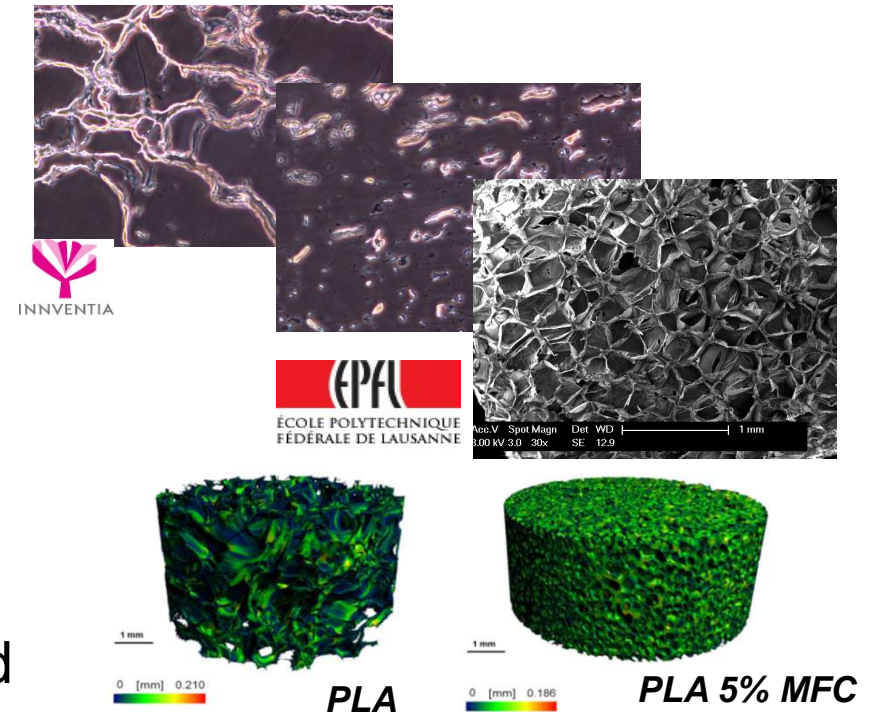
PLA/cellulose foams



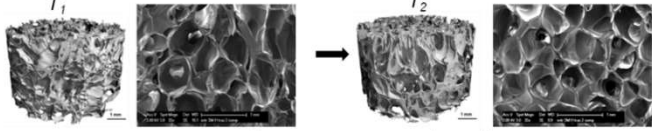
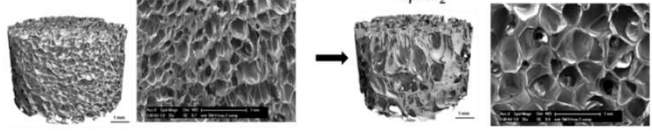
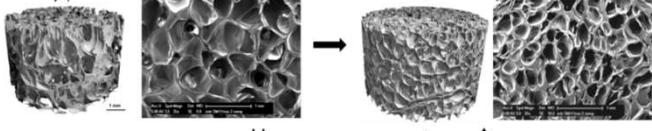
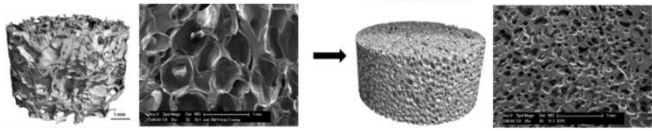
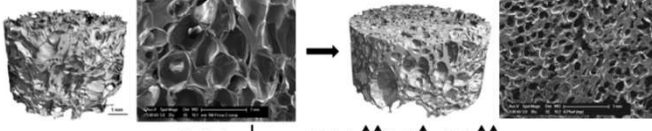
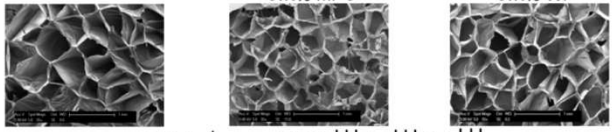
Sustainable composite foams for packaging, insulation and displays

Some research highlights

- Compounding for foaming
- Foaming phenomena versus polymer rheology and degradation
- Influence of wood fibres and microfibrillated cellulose (MFC) network on foam expansion and density
- Stable batch and continuous foaming processes

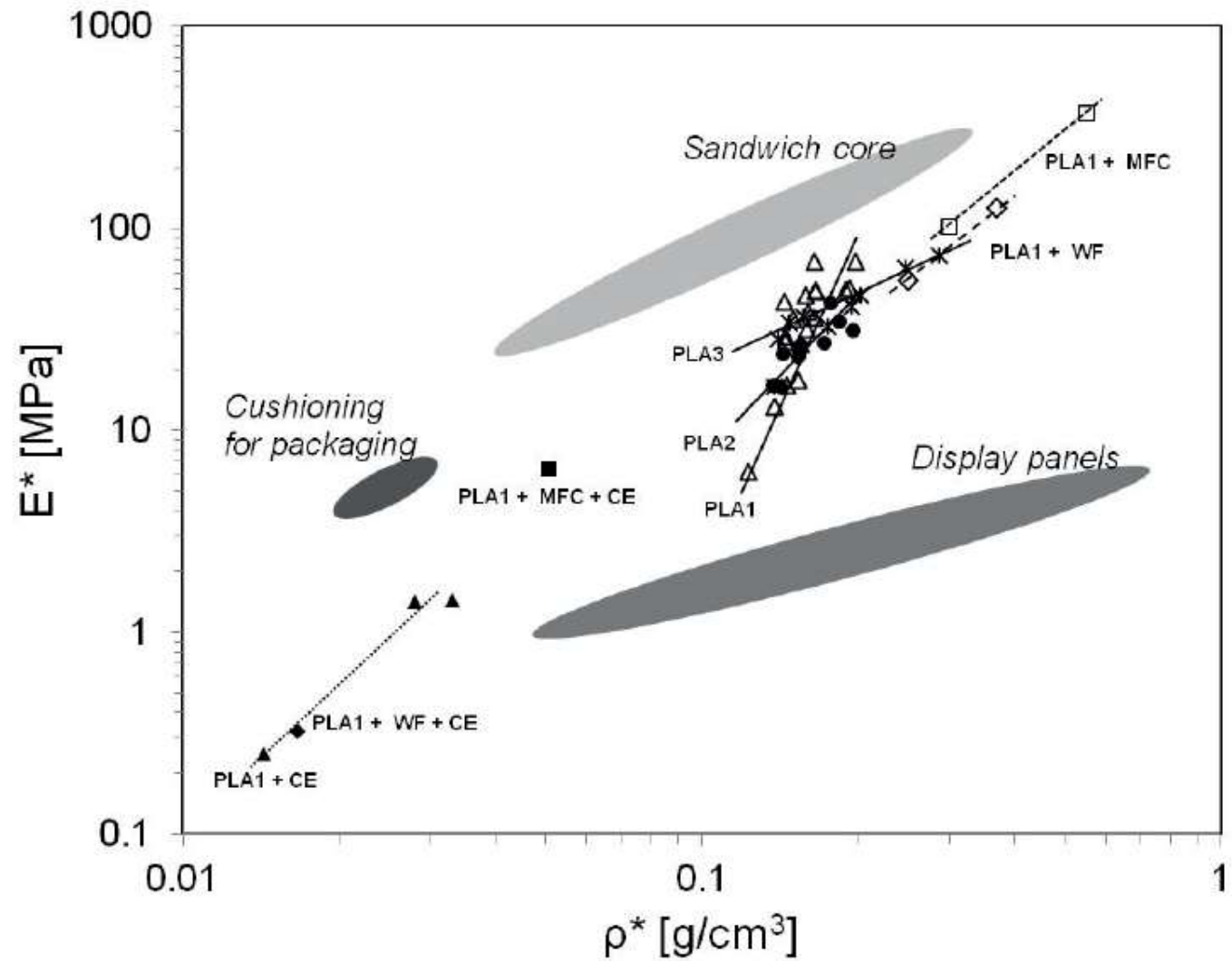


Process Structures Properties

$T_{sat} \downarrow$ $(T_1 > T_2)$	 Cell size $\downarrow$; wall thick. $\rightarrow$ / $\rho^* \uparrow$ / $E^* \uparrow$
$dp/dt \downarrow$ $(dp/dt_1 > dp/dt_2)$	 Cell size $\uparrow\uparrow$; wall thick. $\uparrow \rightarrow$ / $\rho^* \rightarrow$ / $E^* \uparrow$
$p_{sat} \uparrow$ $(p_1 < p_2)$	 Cell size $\downarrow\downarrow$; wall thick. $\rightarrow$ / $\rho^* \uparrow$ / $E^* \uparrow$
+ MFC	 Cell size $\downarrow\downarrow$; wall thick. $\uparrow\uparrow$ / $\rho^* \uparrow\uparrow$ / $E^* \uparrow\uparrow$
+ WF	 Cell size $\downarrow$; wall thick. $\uparrow\uparrow$ / $\rho^* \uparrow$ / $E^* \uparrow\uparrow$
+ CE	 Cell size $\rightarrow$; wall thick. $\downarrow\downarrow\downarrow$ / $\rho^* \downarrow\downarrow\downarrow$ / $E^* \downarrow\downarrow\downarrow$

Boissard, 2012

Process Structures Properties



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**



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



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

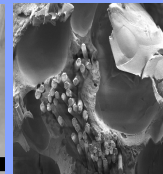
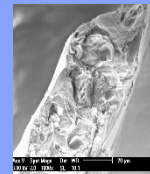
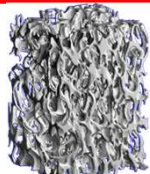
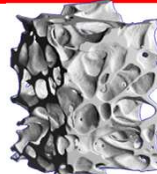
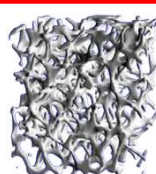
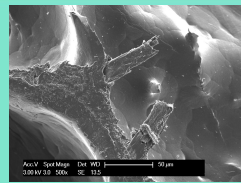
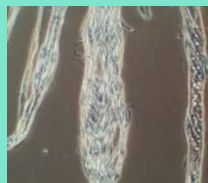
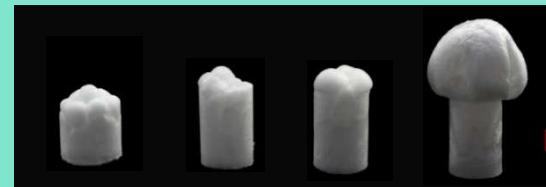
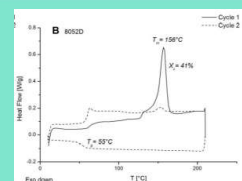
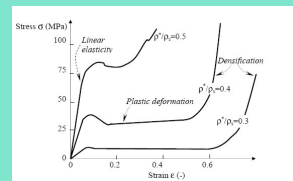


SMART-X natura

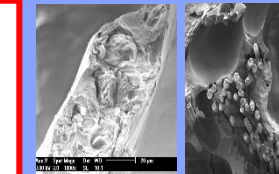
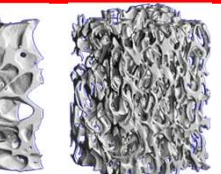
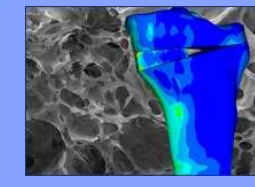
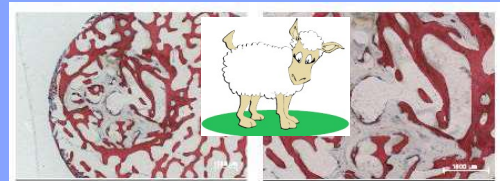
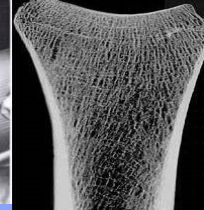
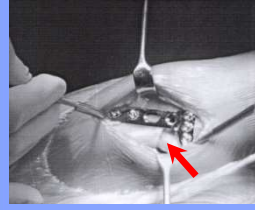
THE BIO-BASED DISPLAY BOARD
A TRUE GREEN ALTERNATIVE



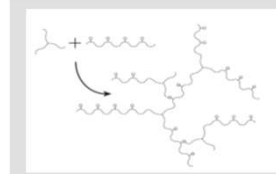
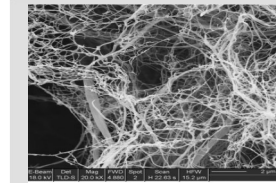
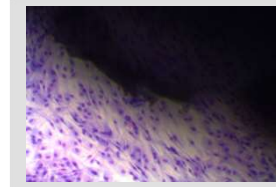
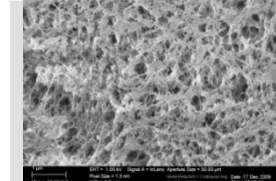
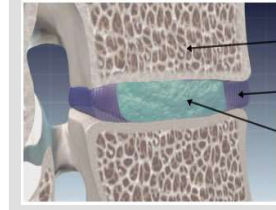
Biodegradable Packaging, architecture



Bioresorbable Bone implants



Biocompatible Intervertebral disks



PLA/ceramic composite foams for bone replacement

MFC hydrogel composites for intervertebral disks

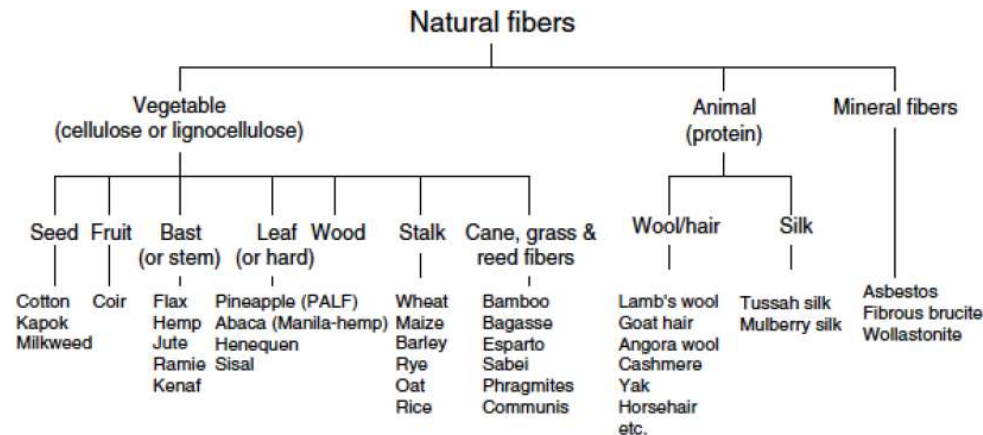
Outline

Polymer composites
in biomedical devices

Biodegradable composites
from renewable resources

Natural Fibre
bioComposites NFC

Natural Fibres for Composites



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.

Sustainability:
reduction of cradle-to-gate CO2 footprint
lifecycles of final products

bio-degradable

Lightweight

Damping

Hydrophilic

Processing

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

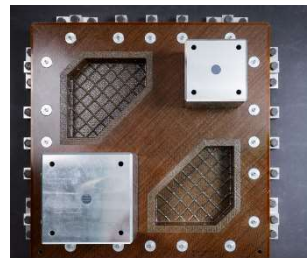


FlexForm door panel
from the Mercedes
M-Class and R-class:
jute(50%)/glass PP

<https://www.bcomp.ch/>



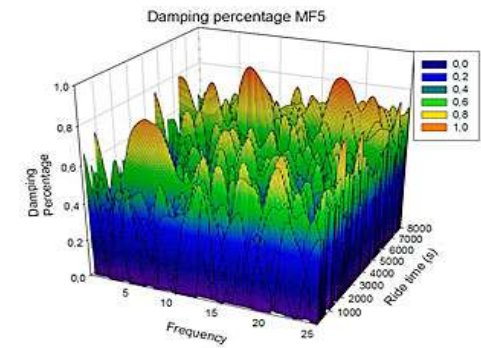
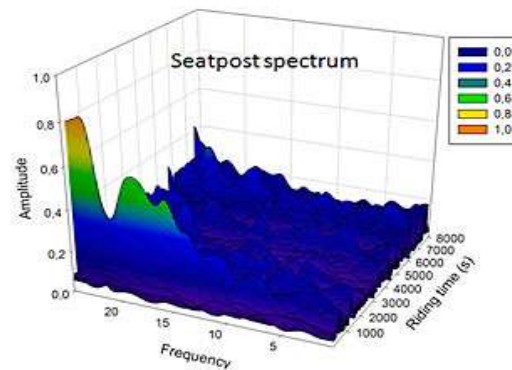
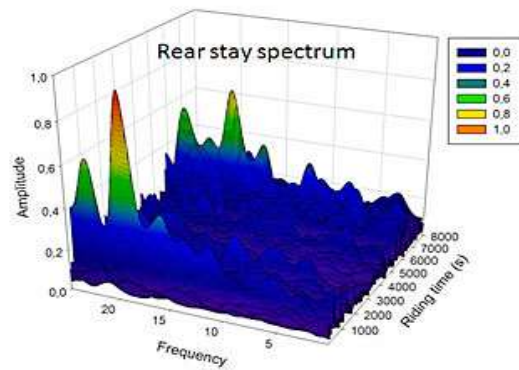
Thanks to the powerRibs™ technology, it is the first time that natural fibre composites can replace carbon fibres. ©McLaren



Ritsumasyi record-breaking bio-composite bridge



Damping ?



Energy absorption at different material scales

Damping phenomena

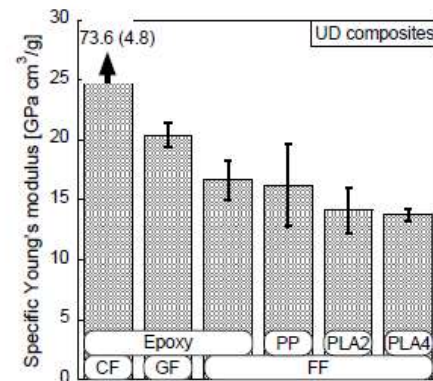
- dampers
- viscoelasticity

Materials

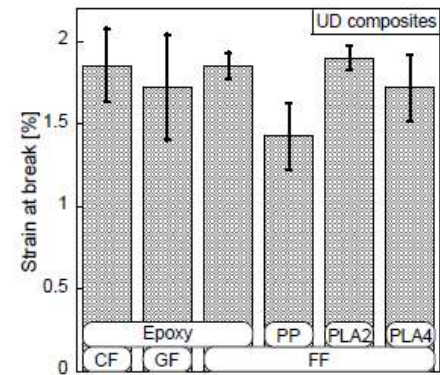
- elastomeric interlayers
- fibre type and orientation
- polymer matrix
- interphase

Materials and specific properties: Flax Fibre composites

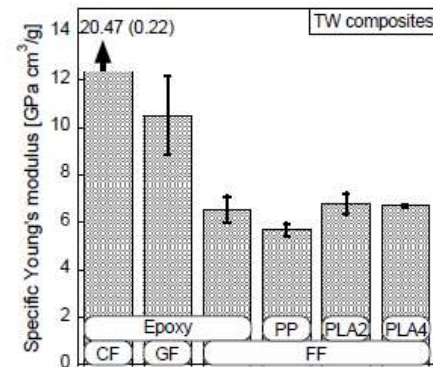
Fibres	Matrices	Fabrics	Process	Abbreviations
CF	EP	UD	RTM	CF_EP_UD
CF	EP	TW	RTM	CF_EP_TW
GF	EP	UD	RTM	GF_EP_UD
GF	EP	TW	RTM	GF_EP_TW
FF	EP	UD	RTM	FF_EP_UD
FF	EP	TW	RTM	FF_EP_TW
FF	PP	UD	CM	FF_PP_UD
FF	PP	TW	CM	FF_PP_TW
FF	PLA2	UD	CM	FF_PLA2_UD
FF	PLA2	TW	CM	FF_PLA2_TW
FF	PLA4	UD	CM	FF_PLA4_UD
FF	PLA4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



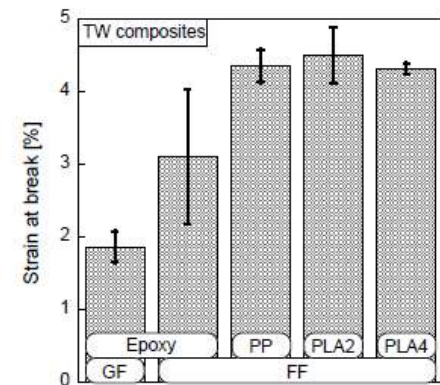
(a)



(b)

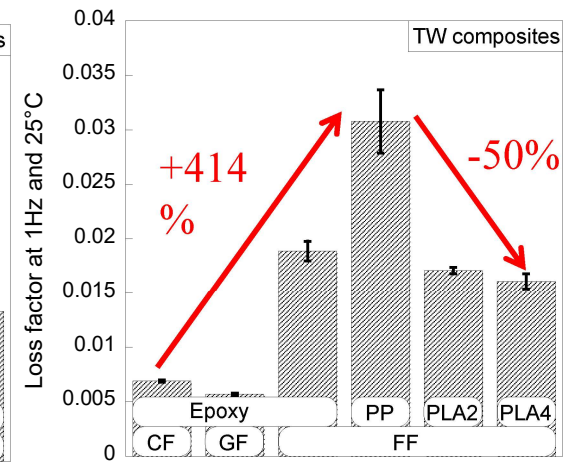
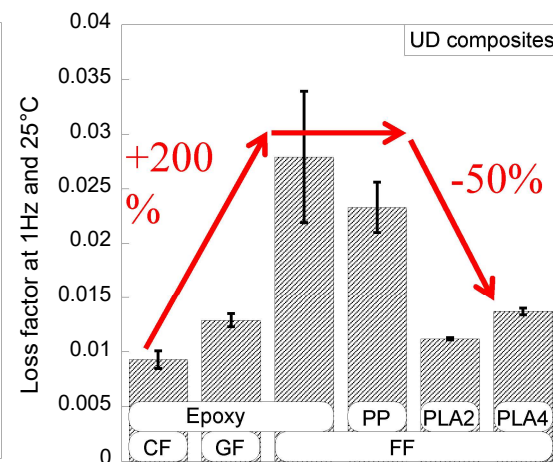
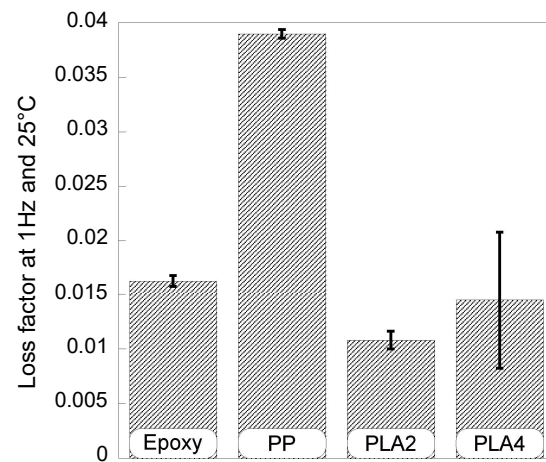


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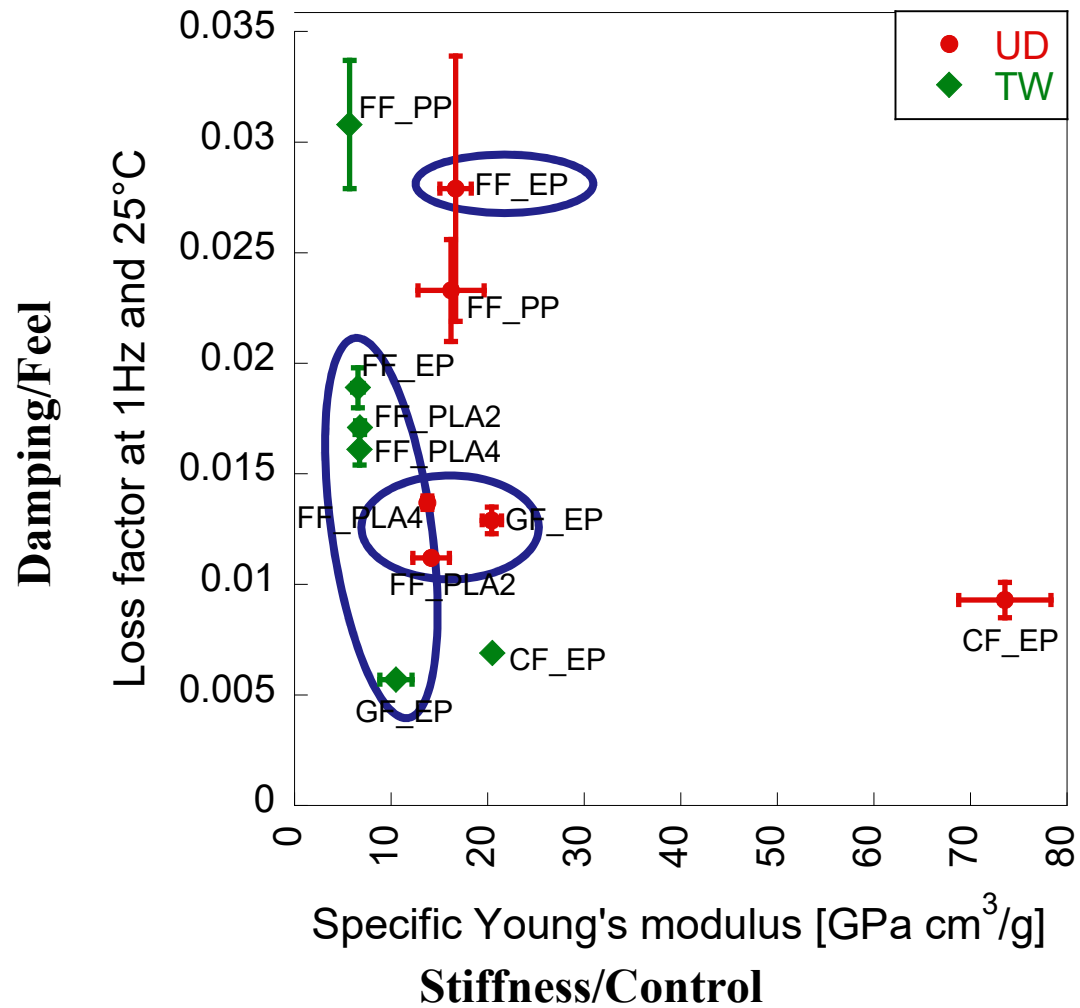


(d)

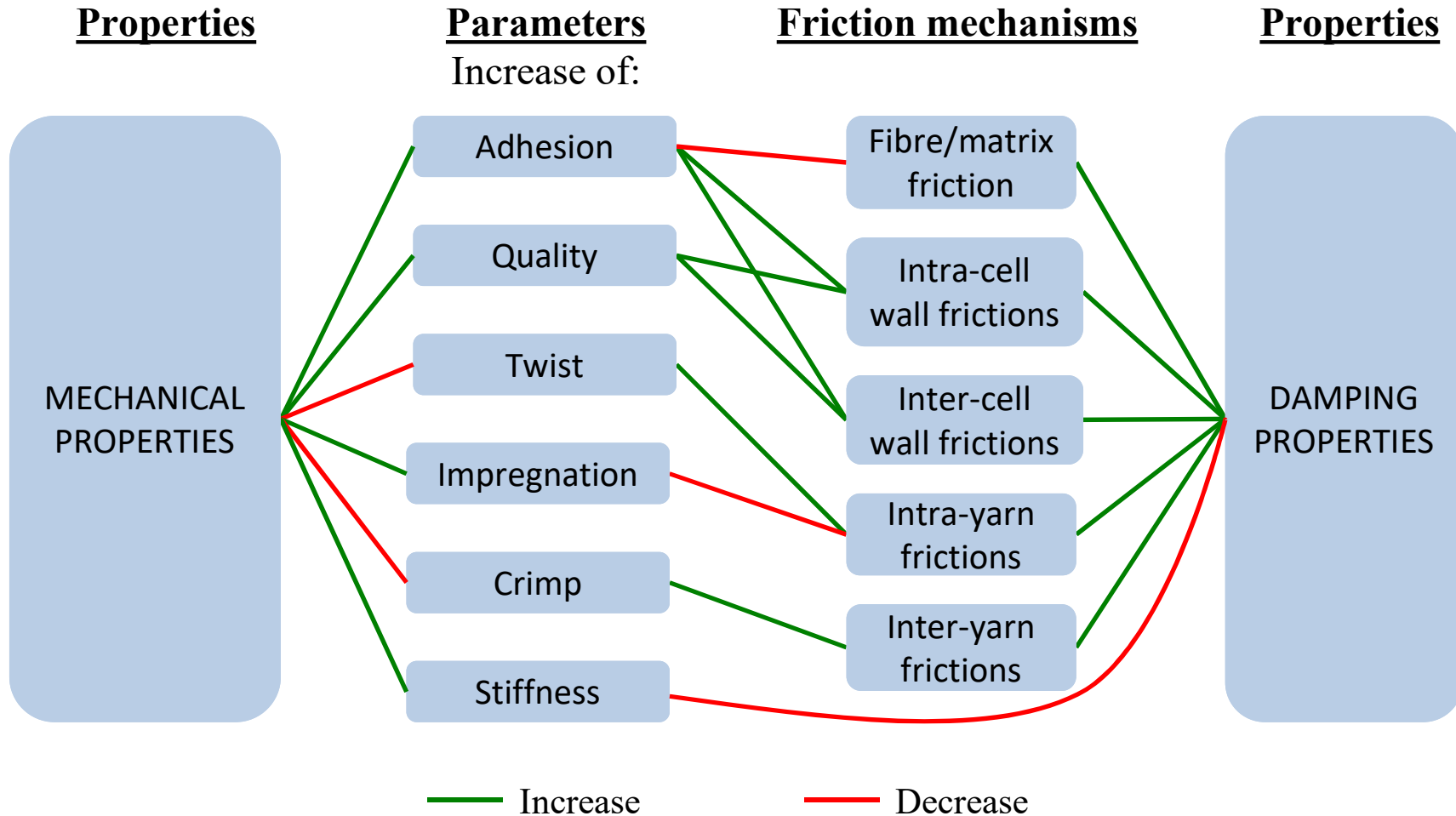
Damping properties of natural fibre composites



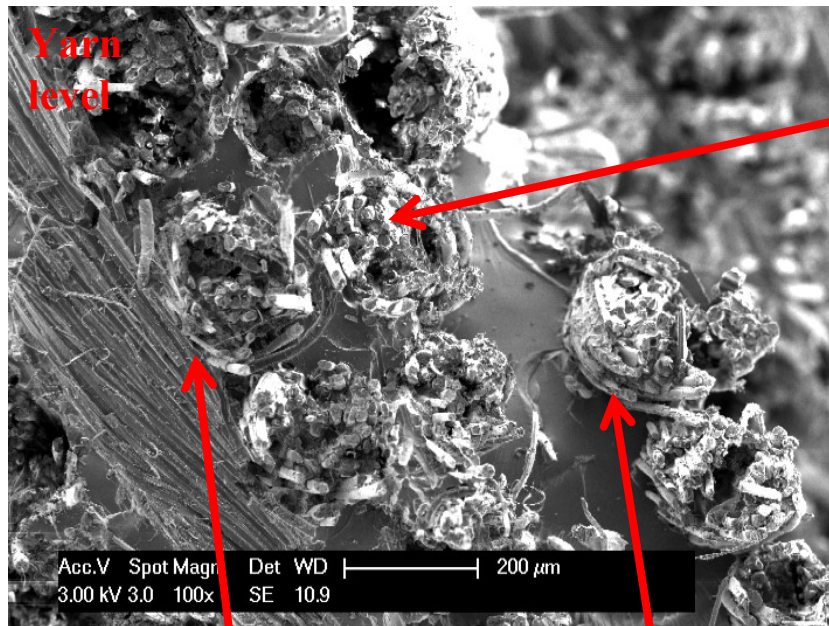
Stiffness versus damping properties



Coupled damping phenomena



Phenomena controlling damping



1. Inter-yarn friction

Friction between the yarns

Fibre (yarn)/matrix friction

4. Intra-cell wall friction

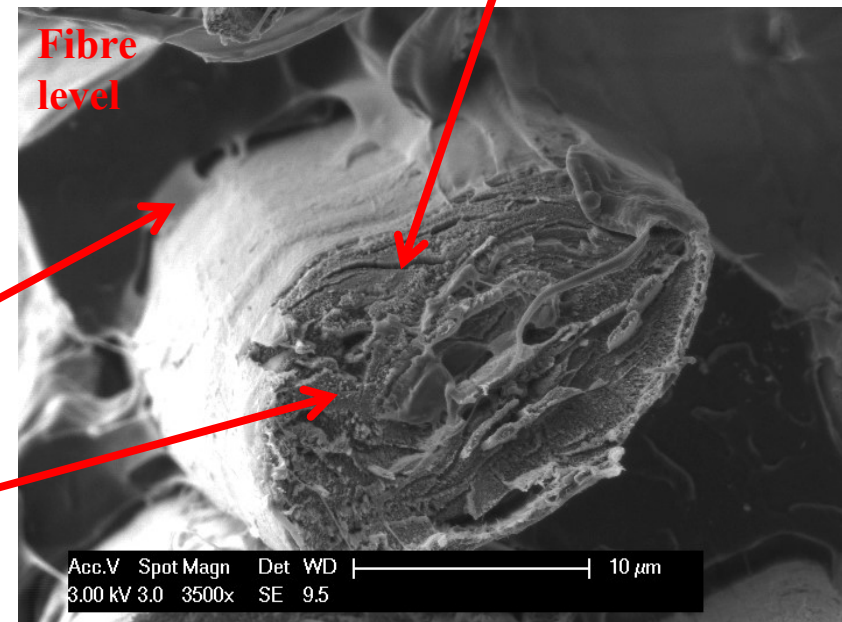
Friction between cellulose and hemicellulose

2. Intra-yarn friction

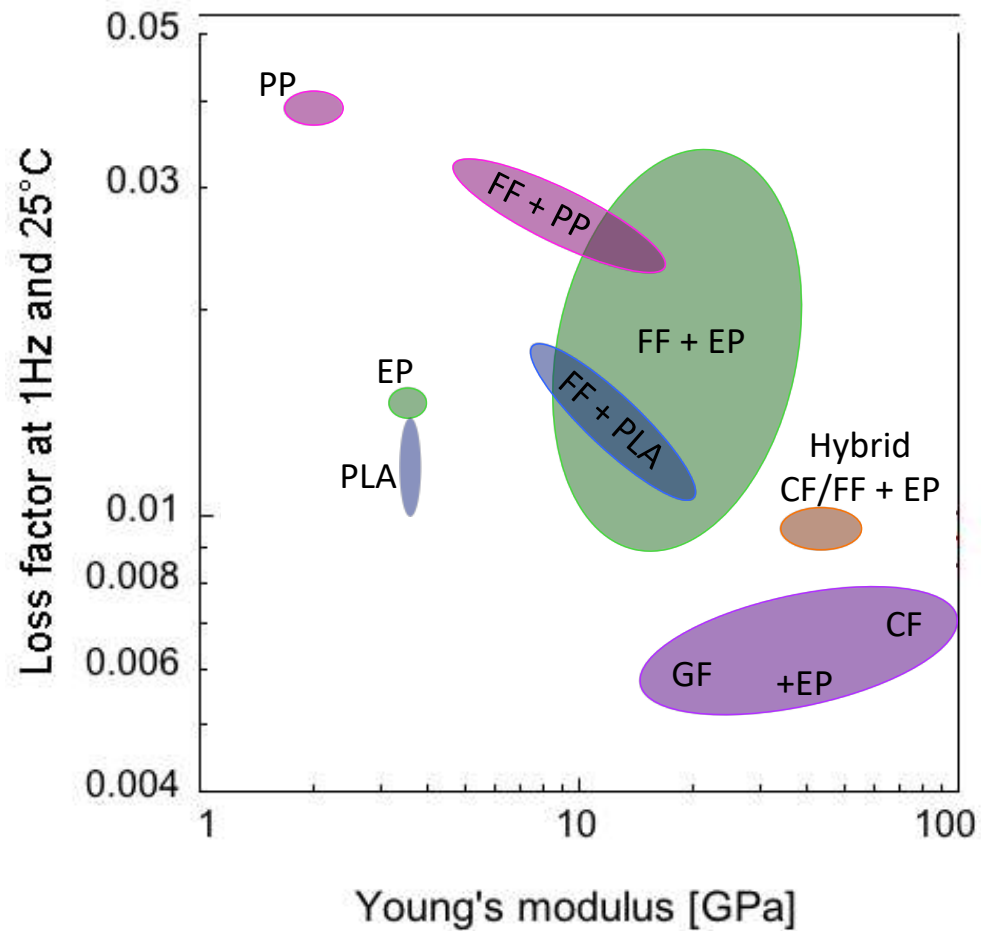
Friction between the elementary fibres

3. Inter-cell wall friction

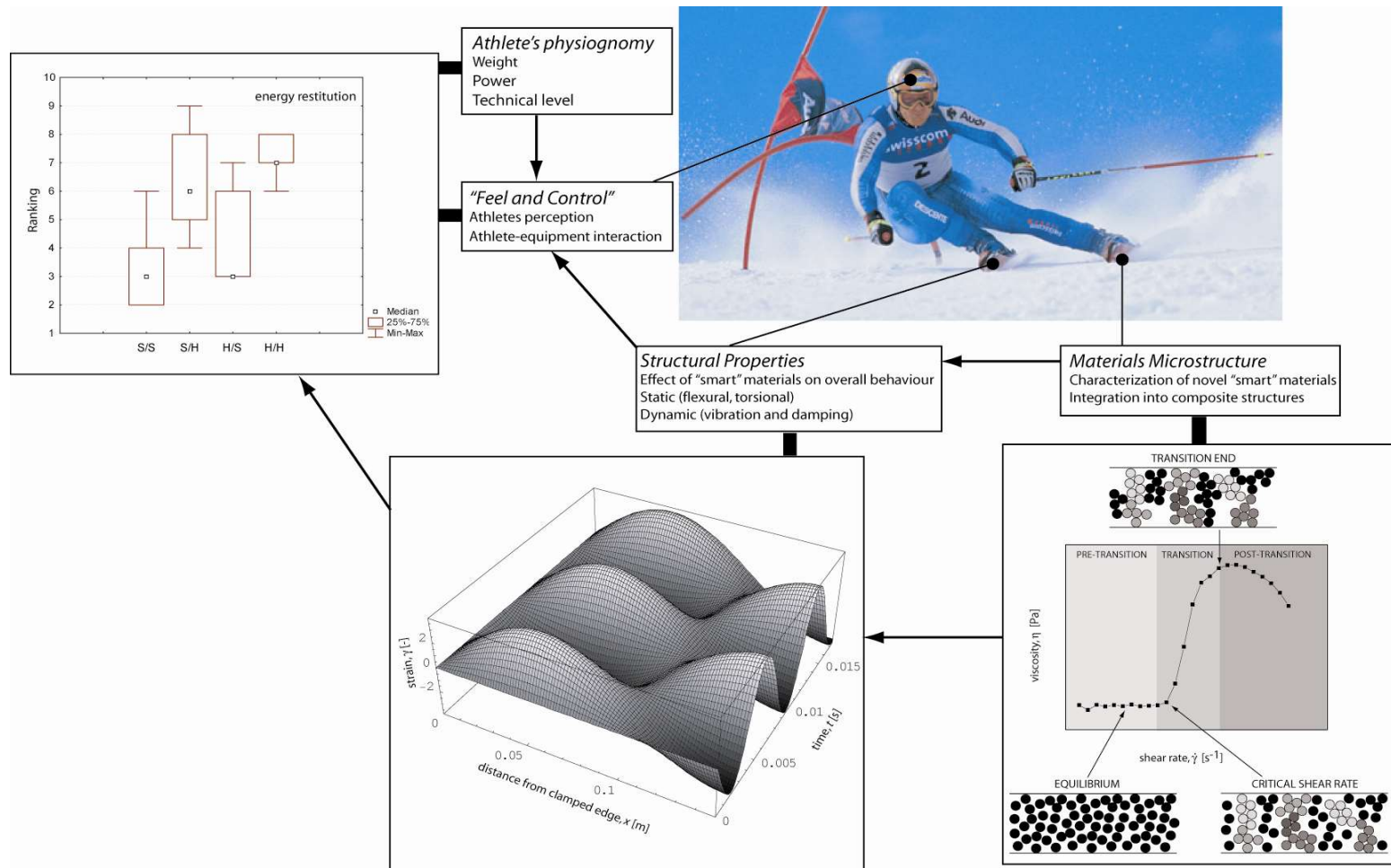
Friction between the cell walls



Damping map



Material-athlete interactions

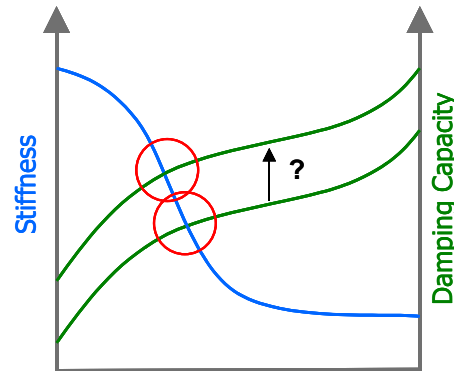
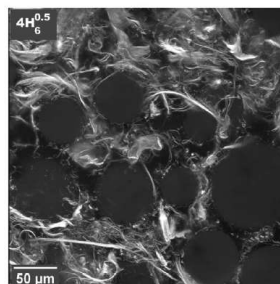
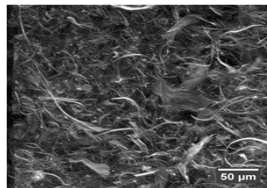
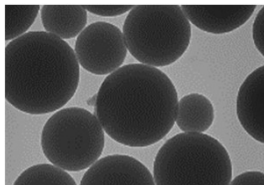
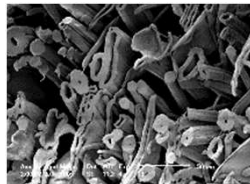
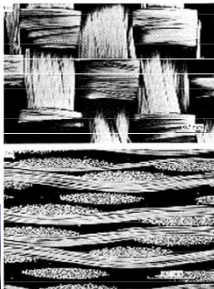


Tailored materials for controlled human-material interactions : feel and control

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'.

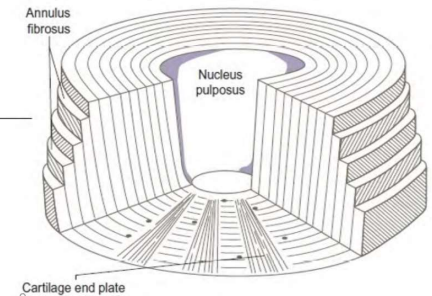
Applications envisaged: skis, tennis raquettes, prosthesis, implants...



Intervertebral disc



C



Knee articulation

