



Bio-inspired processing

Esther Amstad

Materials in nature



<http://news.berkeley.edu/2016/06/30/>



Y. Gu, *et al.*, *e-Polymers* **2020**, 20 (1), 443–457



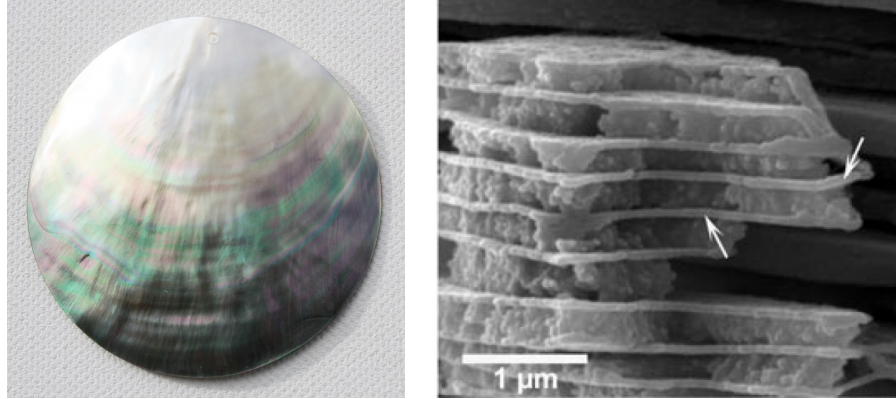
<http://www.followtheyin.com/>



<https://www.newscientist.com/article/dn26994>

Natural vs. manmade hard materials

Nacre



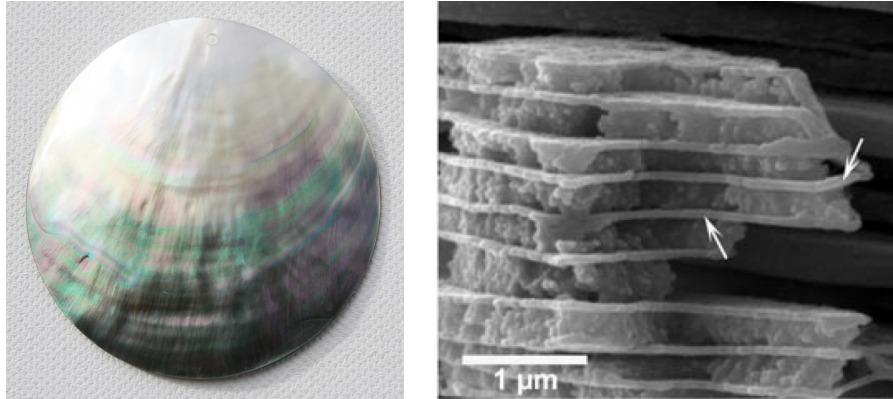
L. Addadi, et al., *Chemistry-a European Journal*, 2006, **12**, 981-987

Chalk



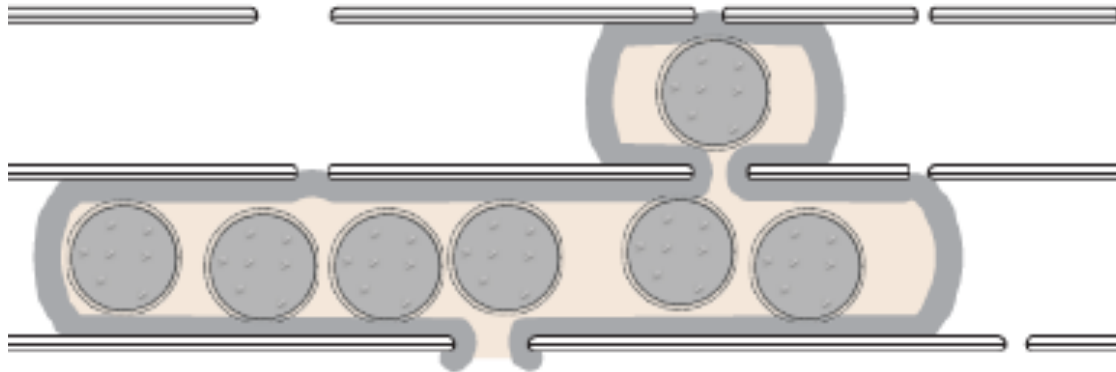
<https://chalkshop4.ru/mel/>

Nacre: A hard material produced by nature



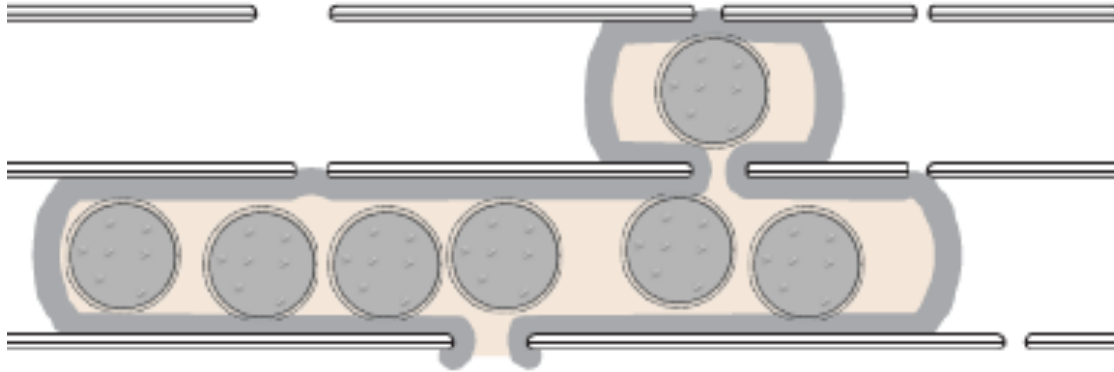
L. Addadi, et al., *Chemistry-a European Journal*, 2006, **12**, 981-987

Production of nacre



Adapted from Cartwright, J. H. E.; Checa, A. G. *Journal of the Royal Society Interface* **2007**, *4*, 491.

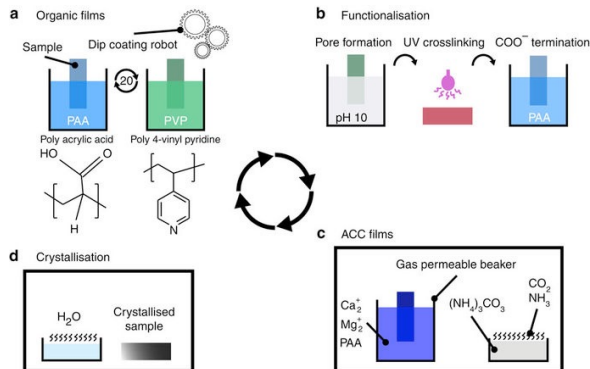
Production of natural vs. synthetic materials



Adapted from Cartwright, J. H. E.; Checa, A. G. *Journal of the Royal Society Interface* **2007**, *4*, 491.

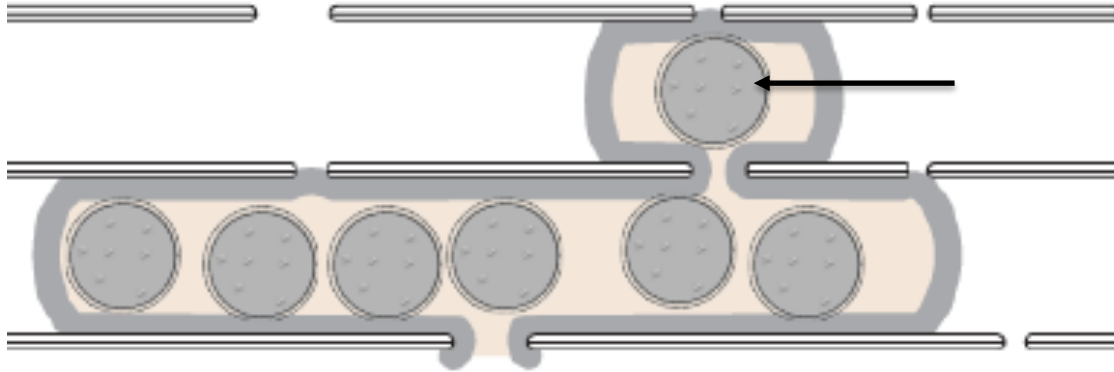
Some differences between the natural and synthetic processing of minerals:

- Confinement
- Control over location of crystallization



A. Finnemore, et al., *Nat. Comm.*, 2012, **3**

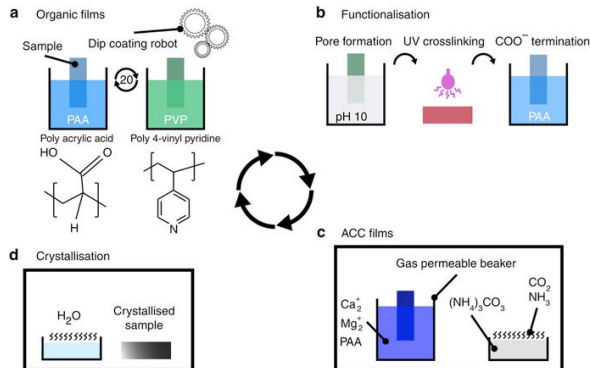
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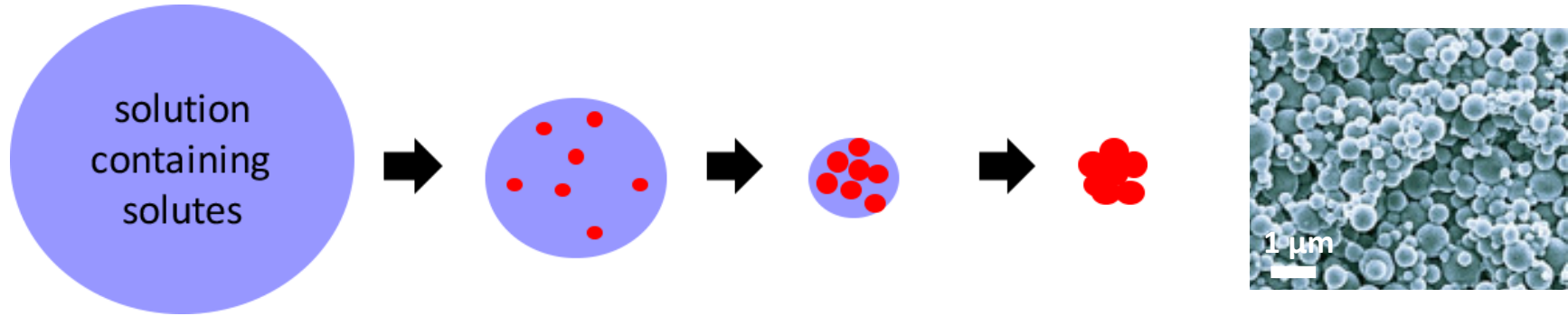
Some differences between the natural and synthetic processing of minerals:

- **Confinement**
- Control over location of crystallization

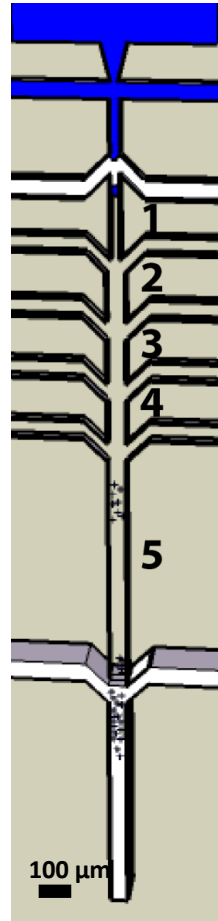


A. Finnemore, et al., *Nat. Comm.*, 2012, **3**

Solvent-free kinetic quenching the production of CaCO_3



Microfluidic spray-drying



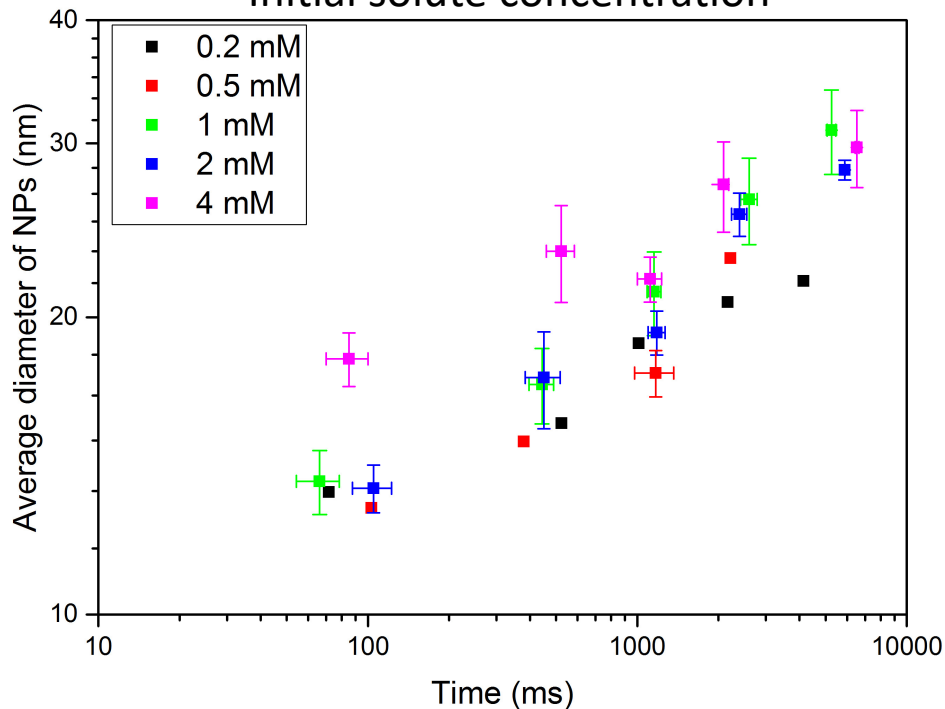
movie 1000 × slowed down

Influence of processing conditions on particle size

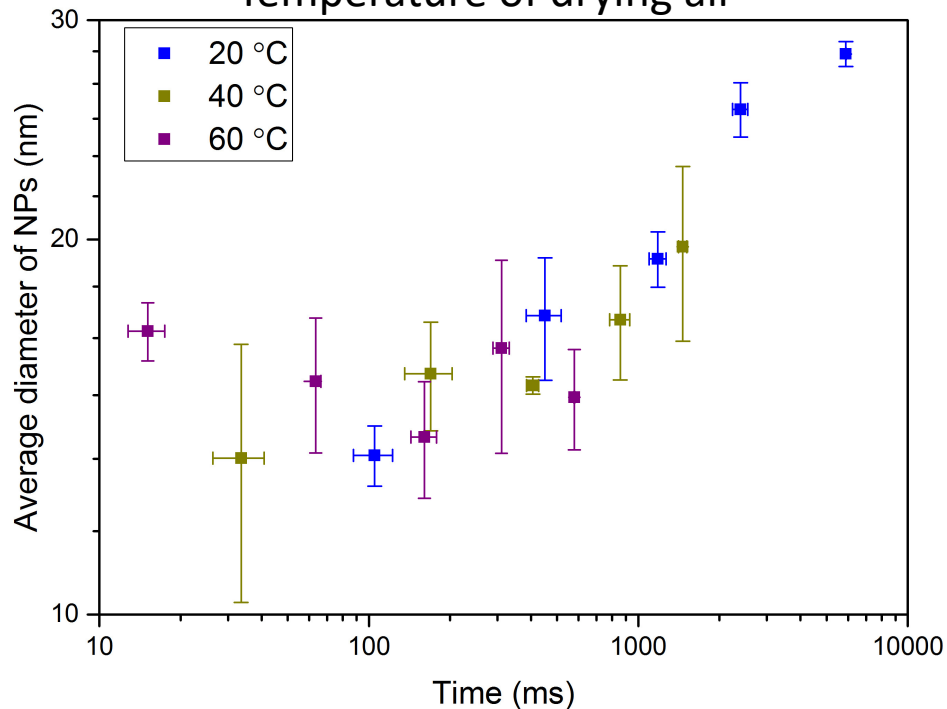


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Du

Initial solute concentration



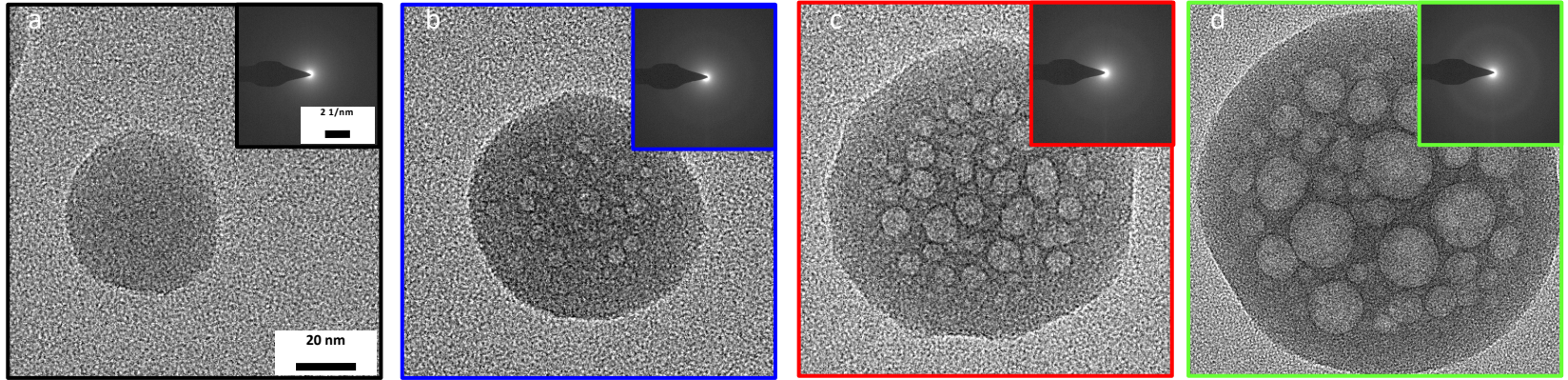
Temperature of drying air



Influence of particle size



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~45 nm

~100 ms

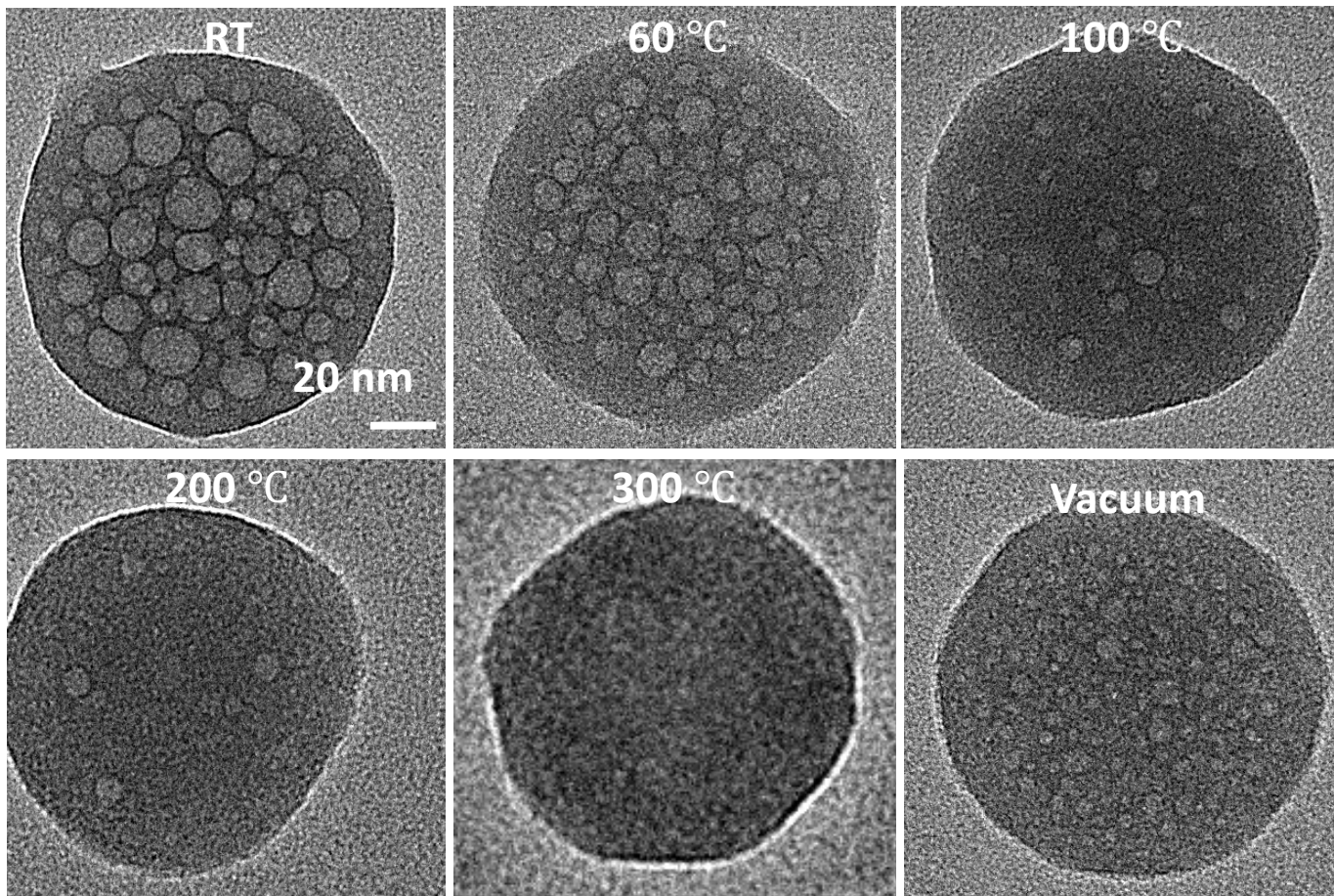
particle size

formation time

~130 nm

~10 s

Influence of storage temperature

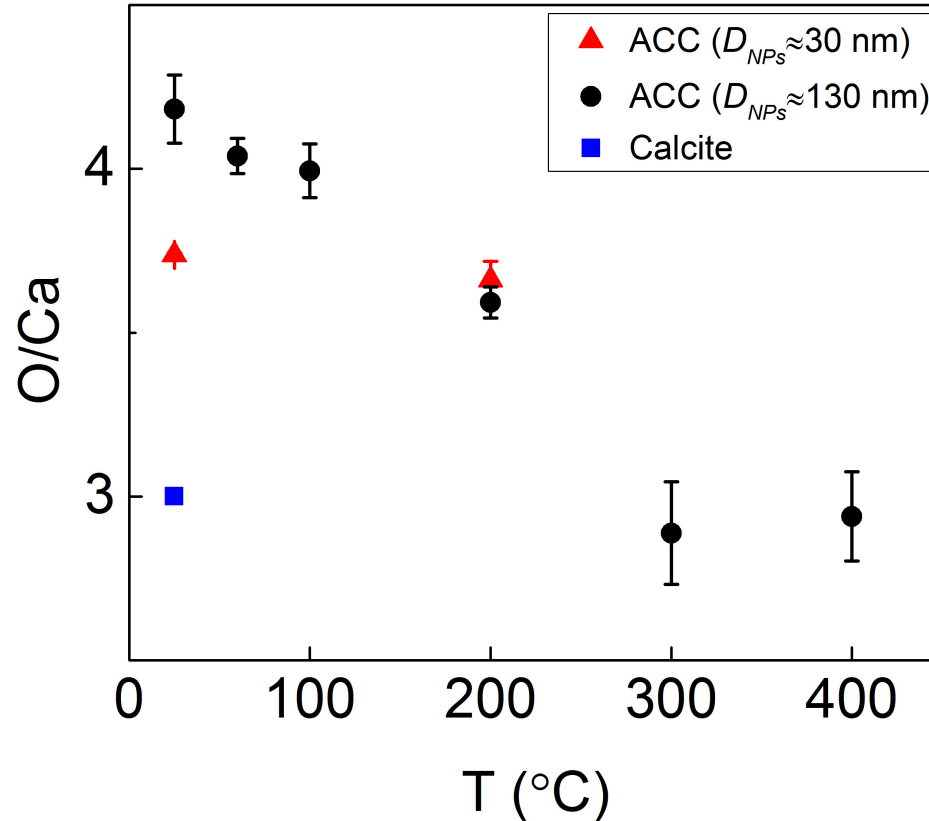


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Degree of hydration of amorphous CaCO_3 particles



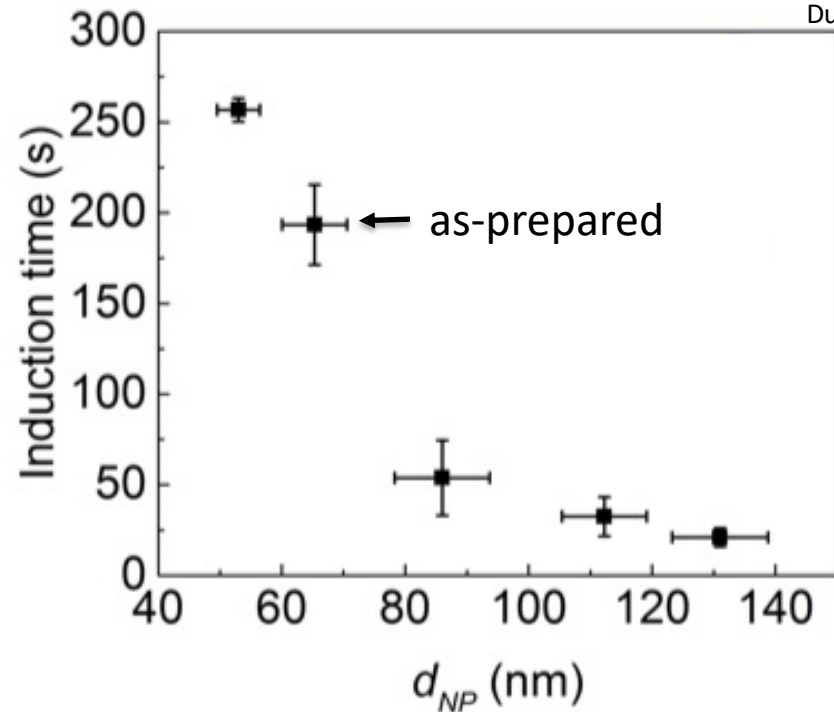
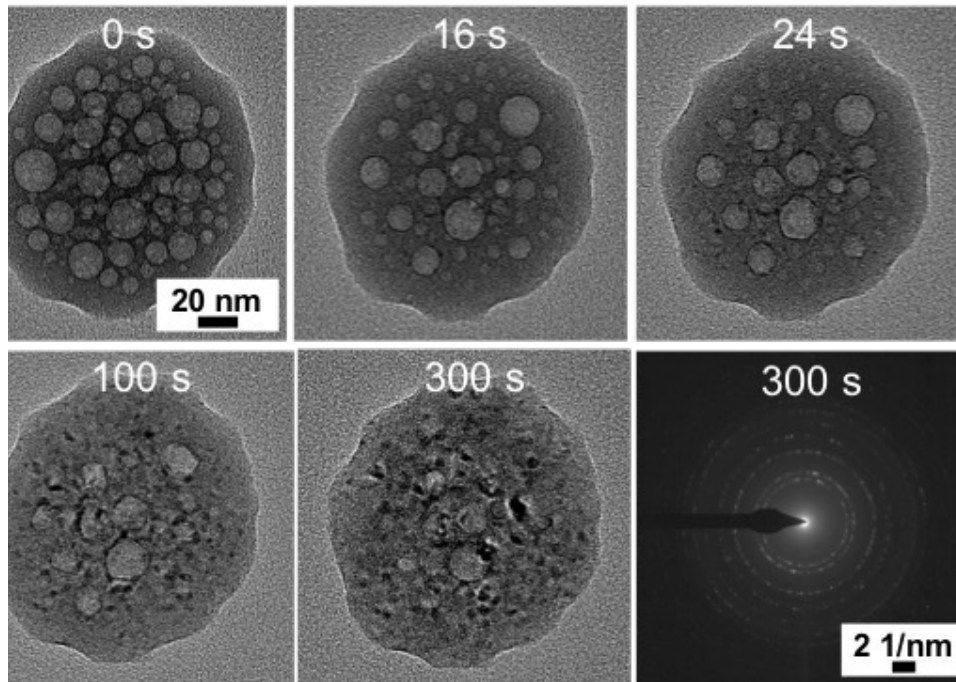
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Influence of particle size on structural stability



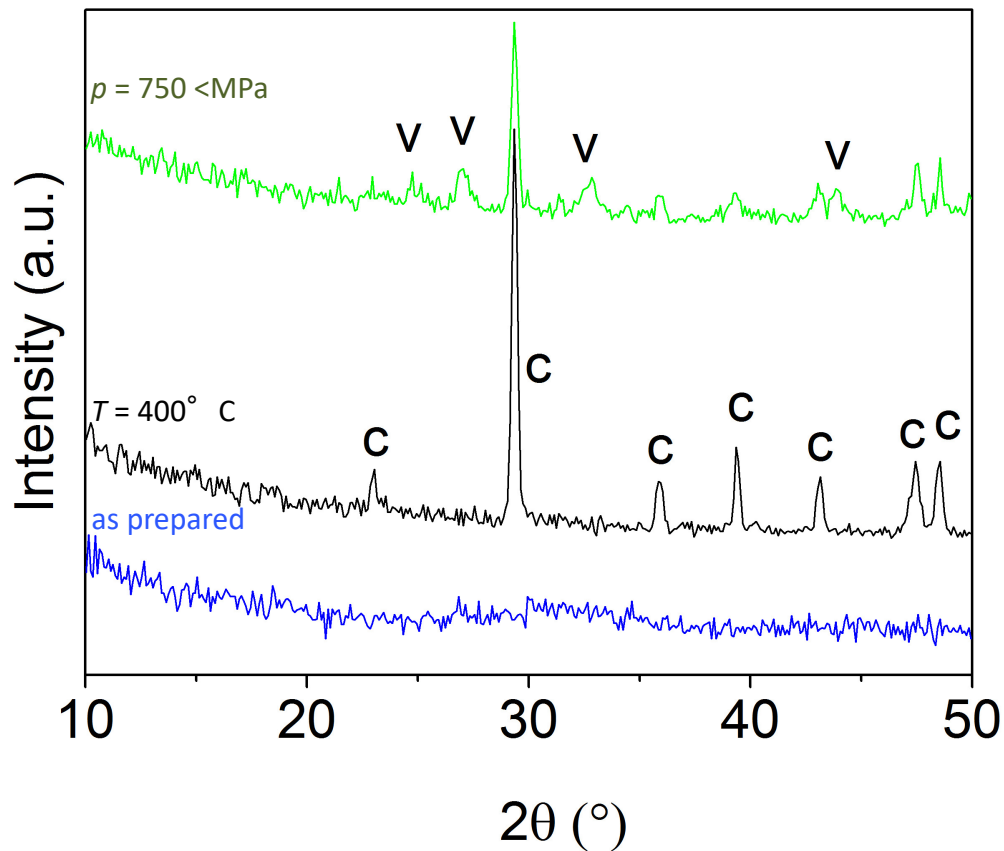
Huachuan Du



Pressure-induced crystallization



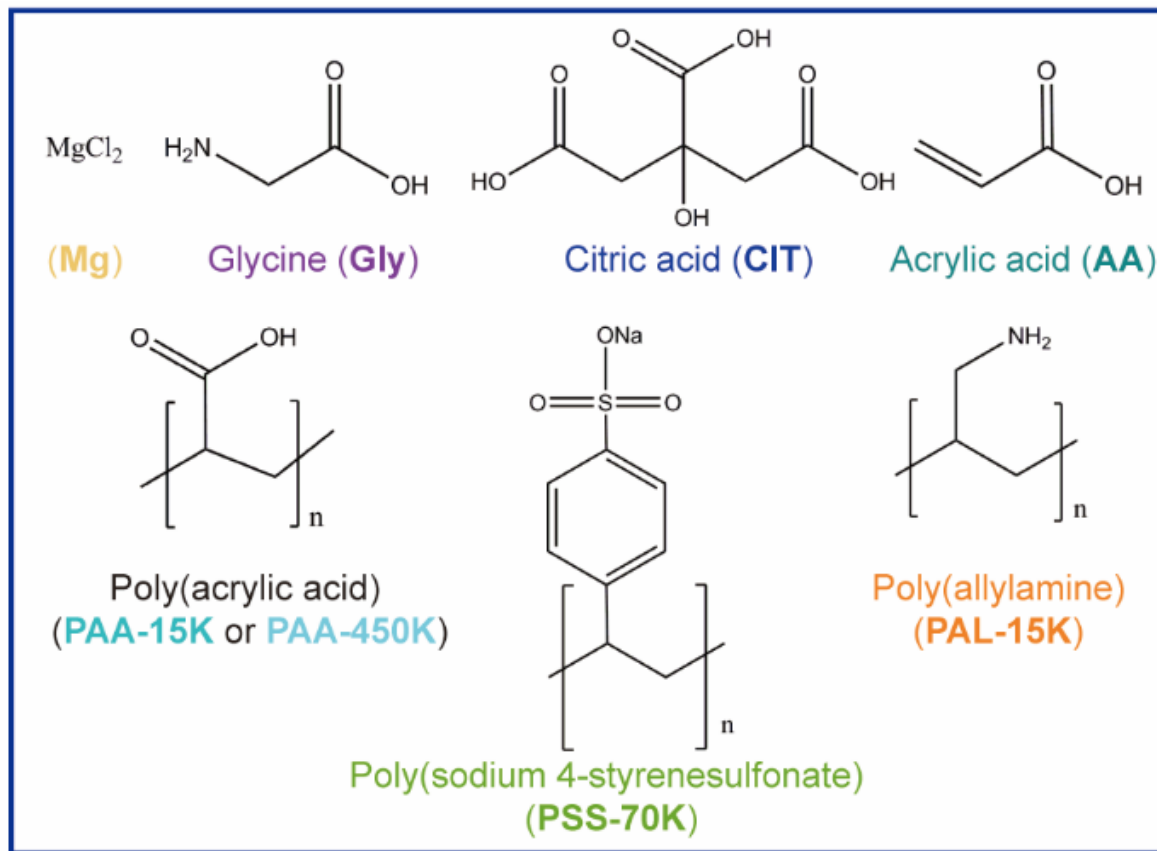
Huachuan
Du



Influence of additives on structural stability



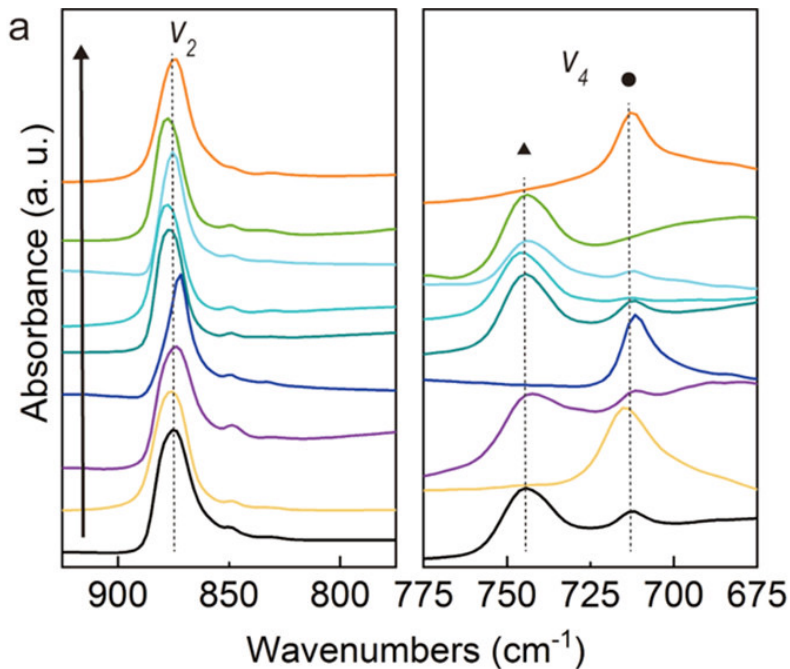
Huachuan
Du



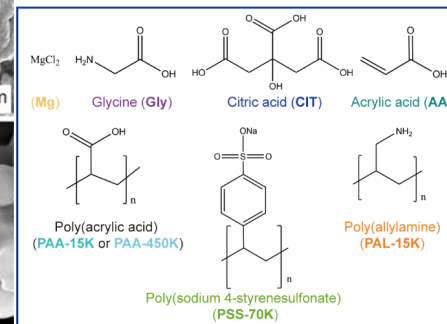
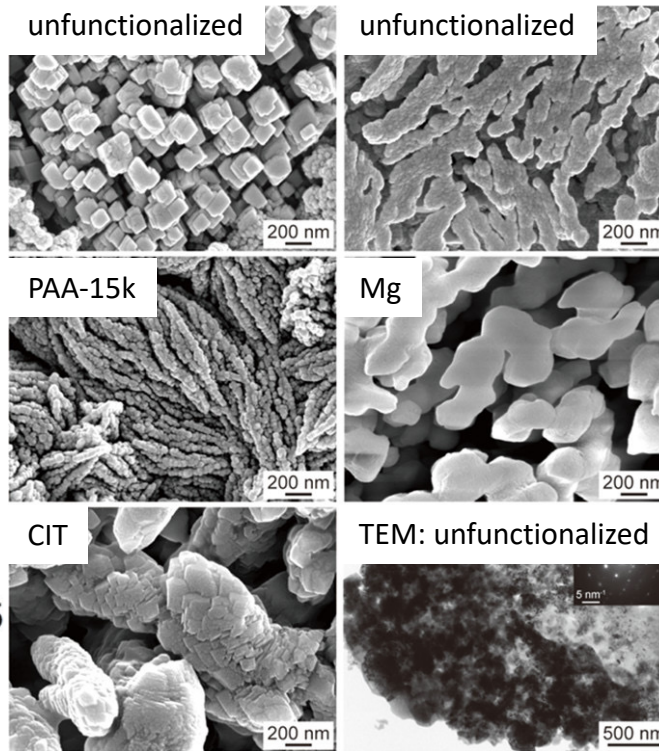
Influence of additives on humidity-induced crystallization



Huachuan Du



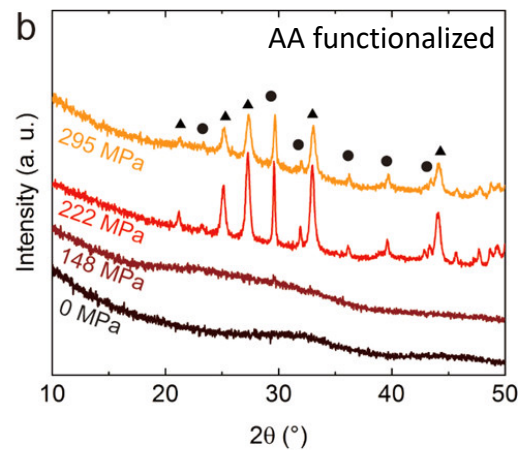
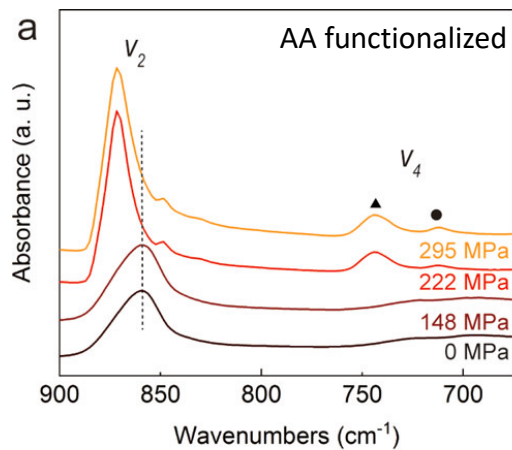
● calcite
▲ vaterite



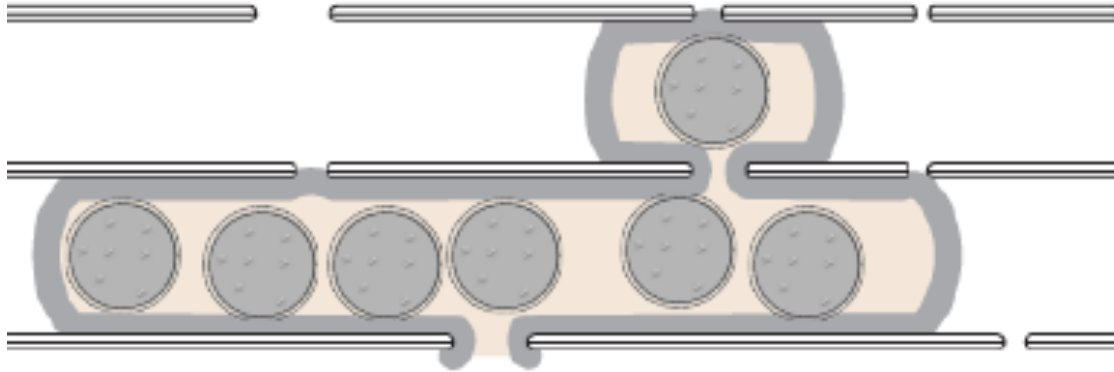
Pressure-induced crystallization



Huachuan
Du



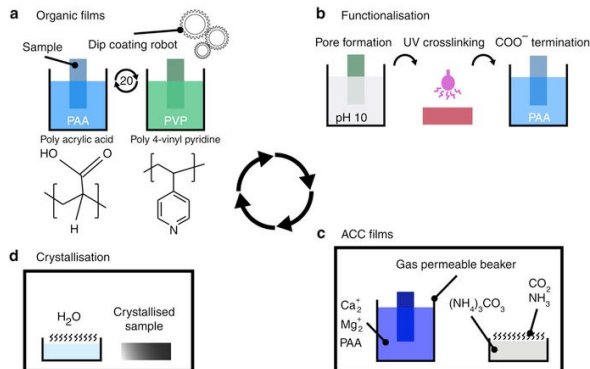
Production of natural vs. synthetic materials



Adapted from Cartwright, J. H. E.; Checa, A. G. *Journal of the Royal Society Interface* **2007**, *4*, 491.

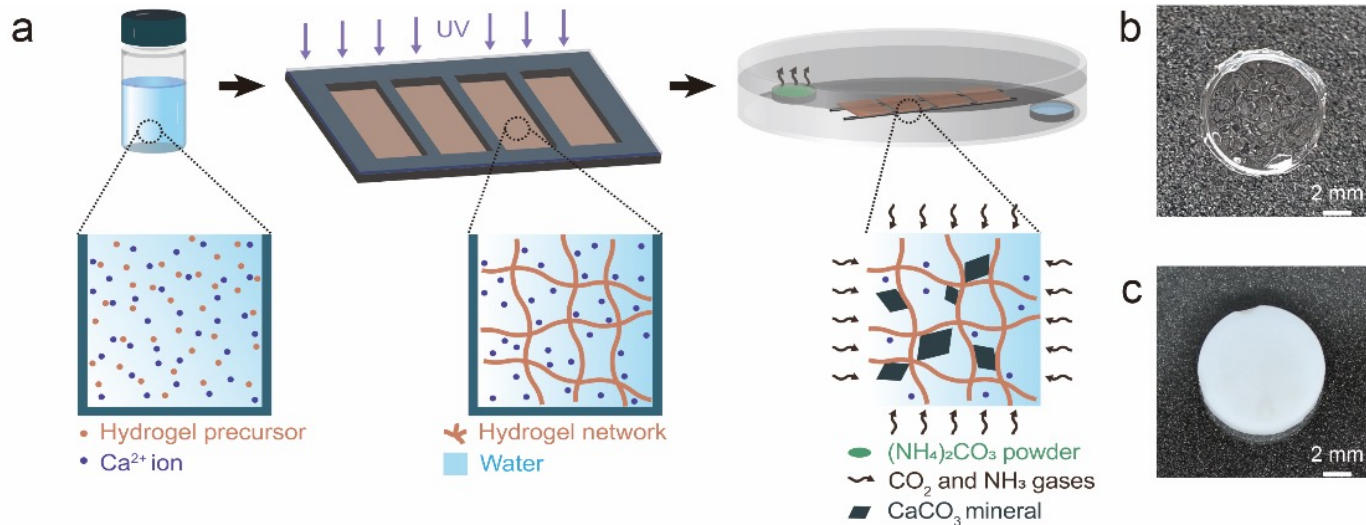
Some differences between the natural and synthetic processing of minerals:

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A. Finnemore, et al., *Nat. Comm.*, 2012, **3**

Mineralization of hydrogels

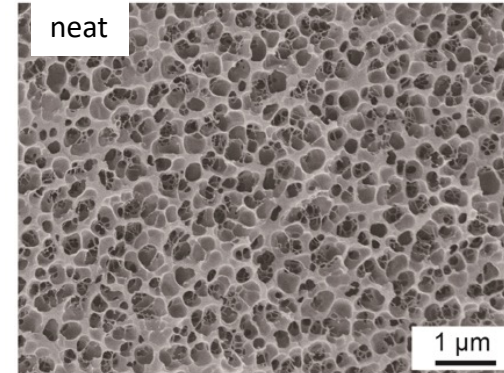
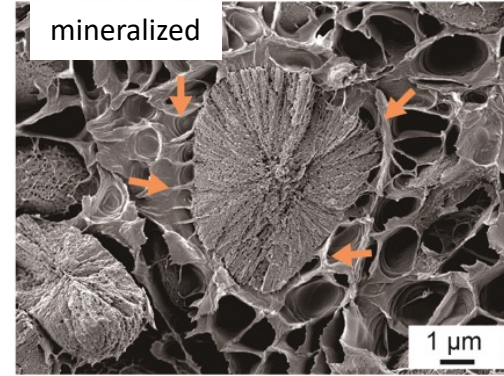
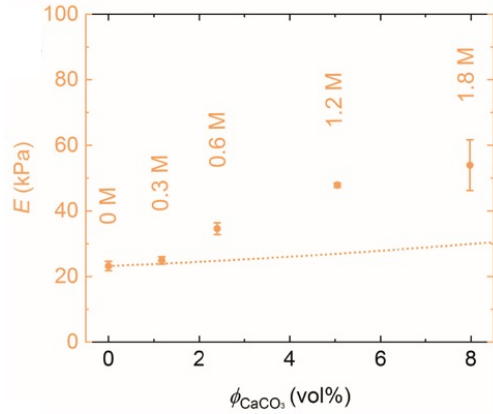


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Influence of mineralization on mechanical properties



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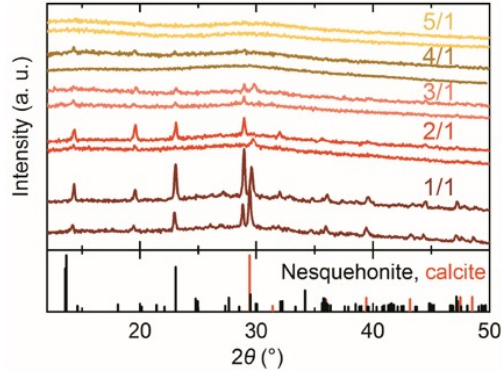


Influence of Mg^{2+} on the mineral structure and mechanical properties of the composite

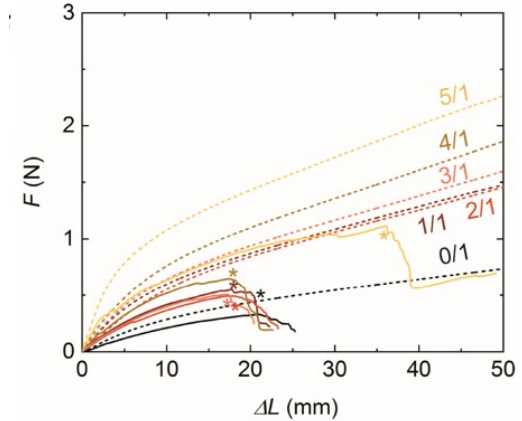
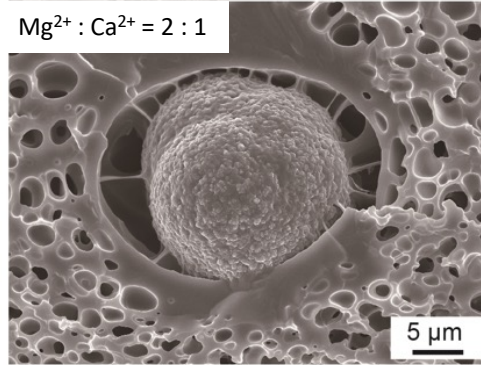


Huachuan Du

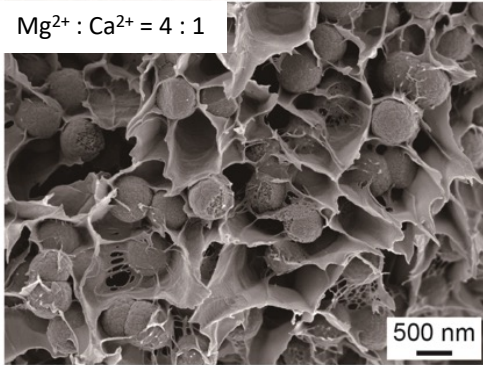
$Mg^{2+} : Ca^{2+}$ ratio



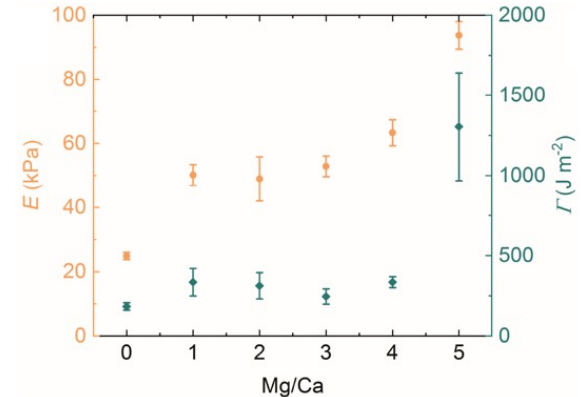
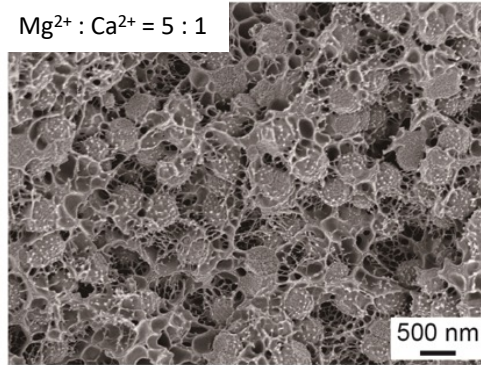
$Mg^{2+} : Ca^{2+} = 2 : 1$



$Mg^{2+} : Ca^{2+} = 4 : 1$



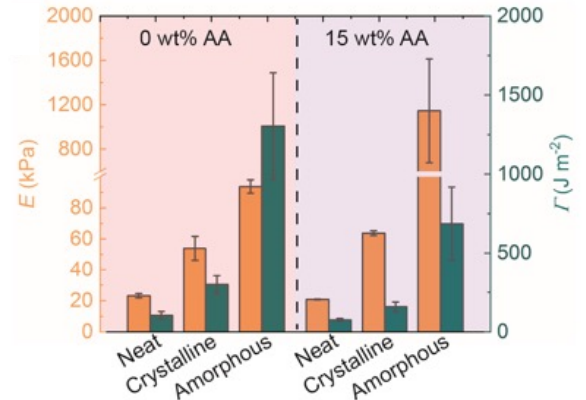
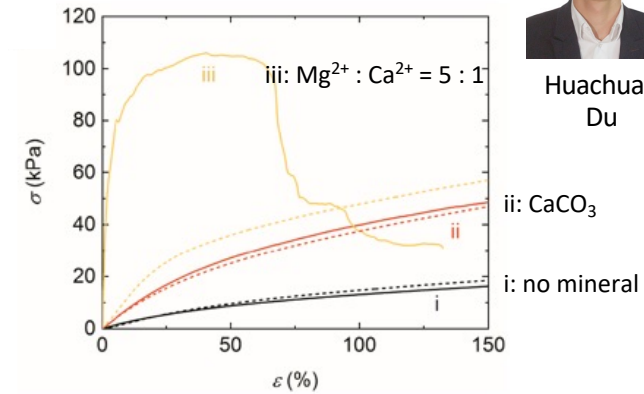
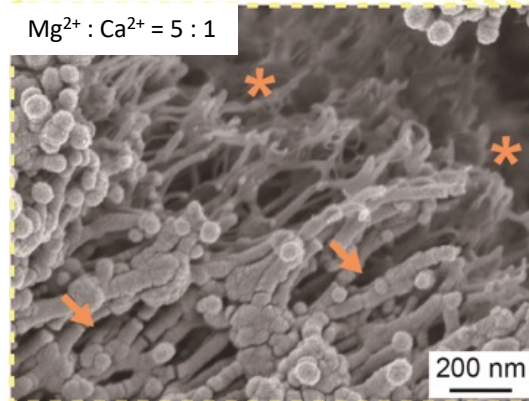
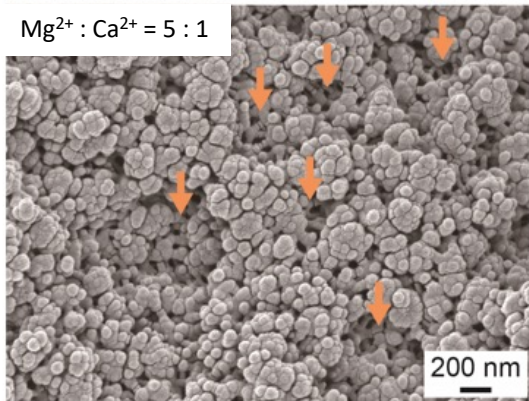
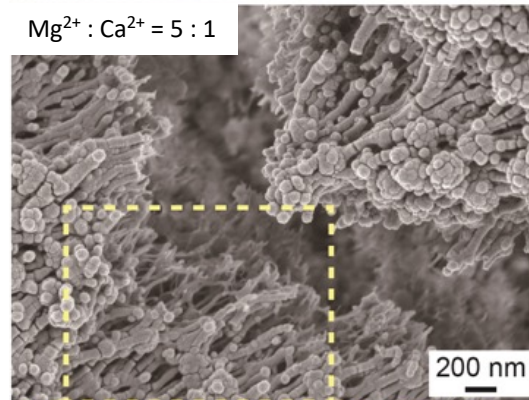
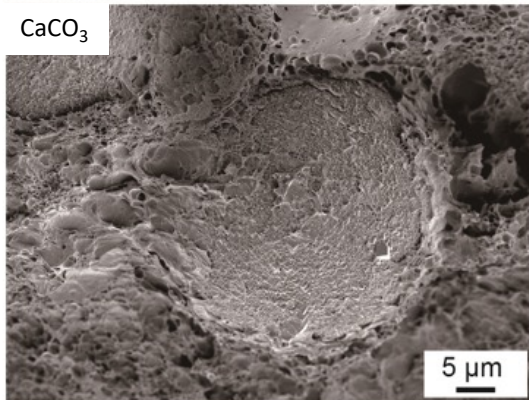
$Mg^{2+} : Ca^{2+} = 5 : 1$



Influence of hydrogel-mineral interaction



Huachuan Du

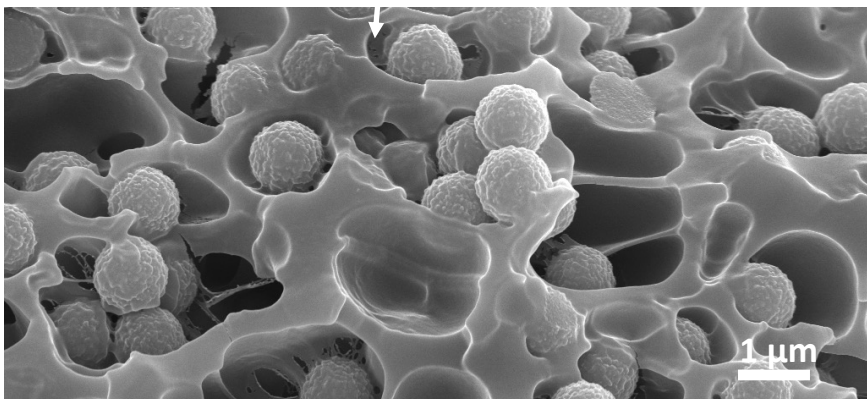
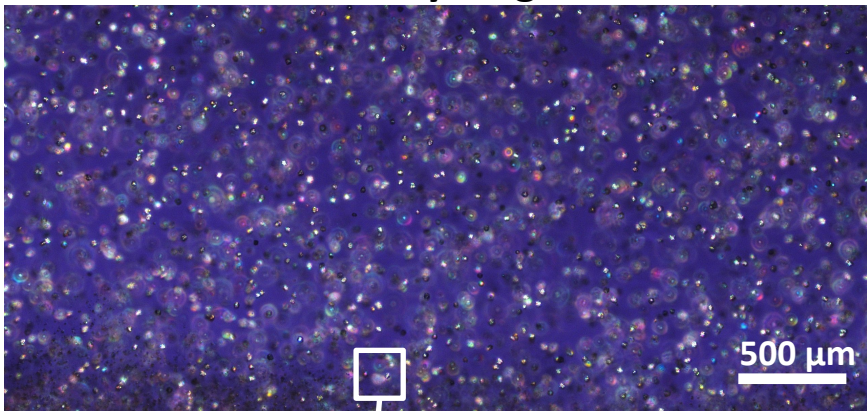


Mineralization of hydrogels

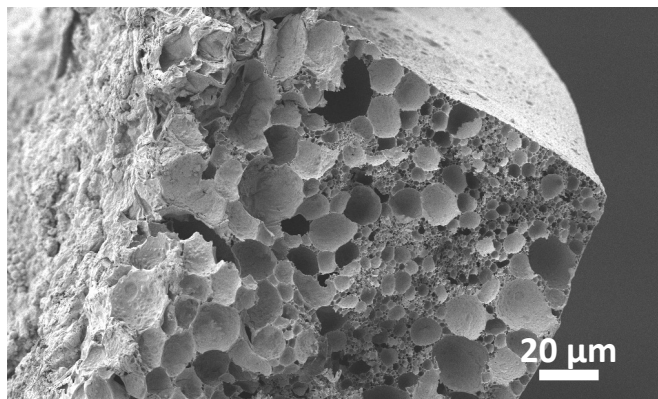
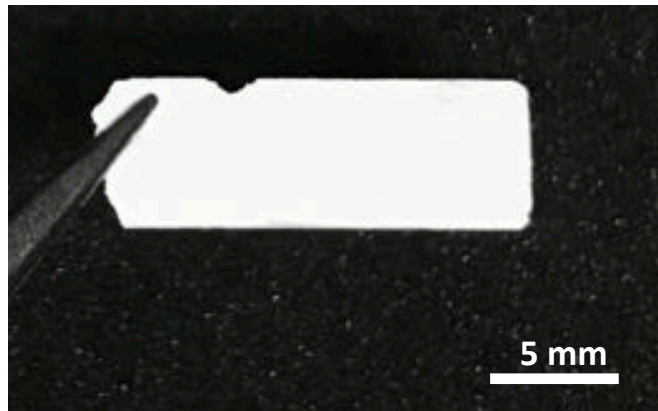


Huachuan
Du

Bulk hydrogels

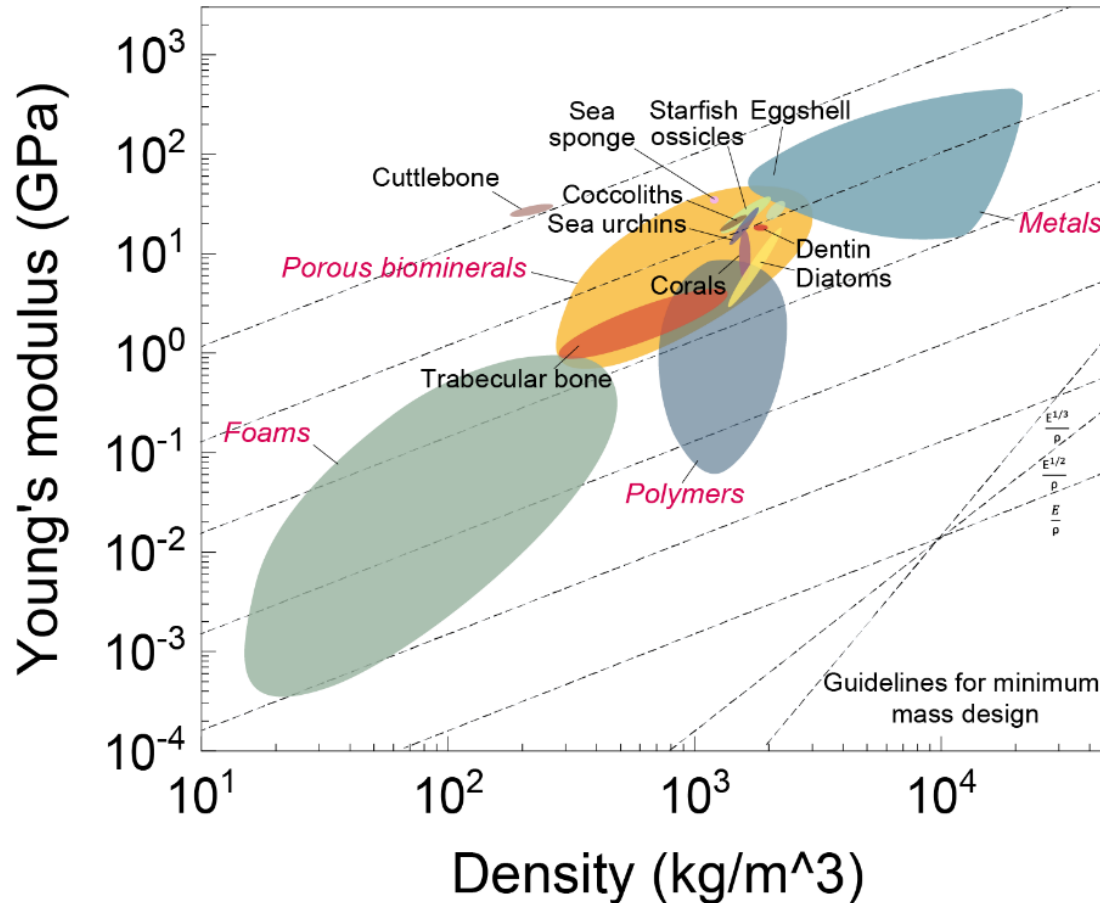


Porous minerals?



Ran
Zhao

Porous minerals

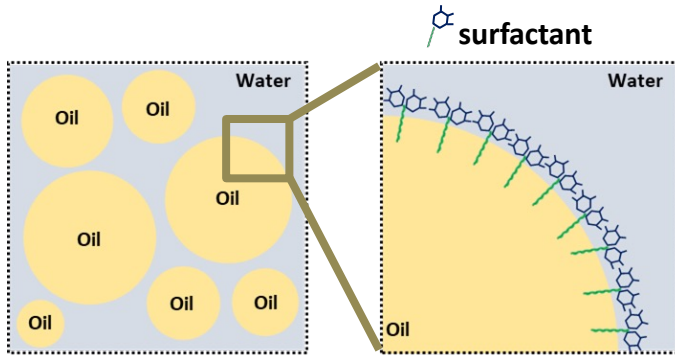


Ran Zhao

Mineralization of emulsion drops

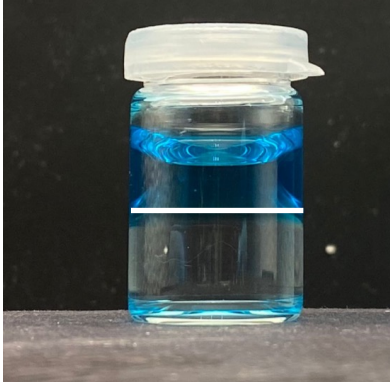


Ran
Zhao

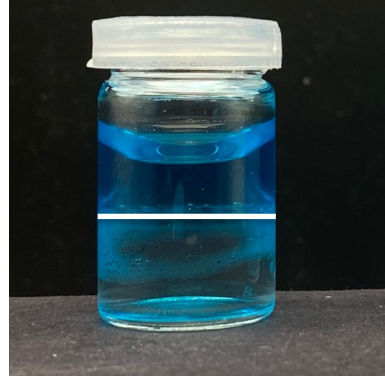


Stabilization of emulsions

Before emulsification



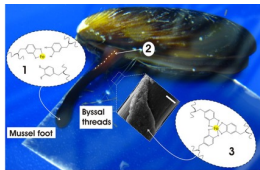
T = 0



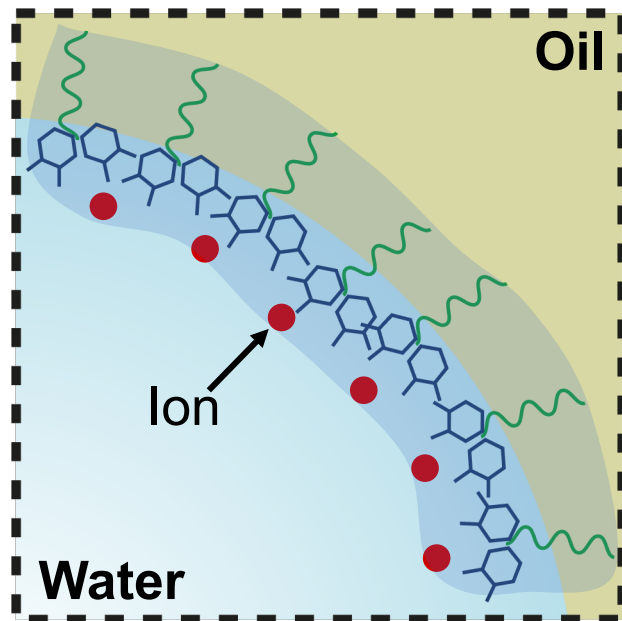
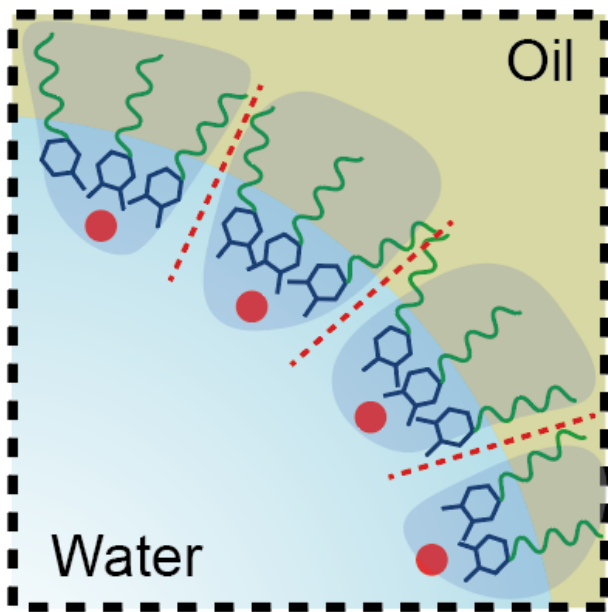
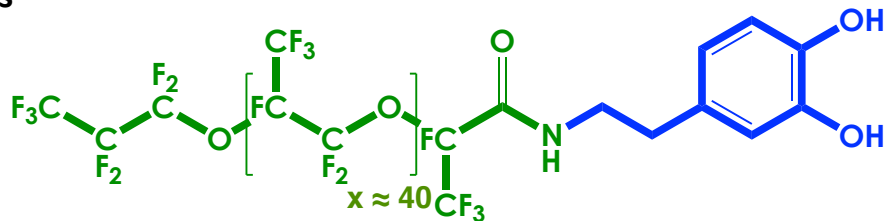
Gaia
DeAngelis

Ionic crosslinking of surfactants

Adhesion of the mussel byssus



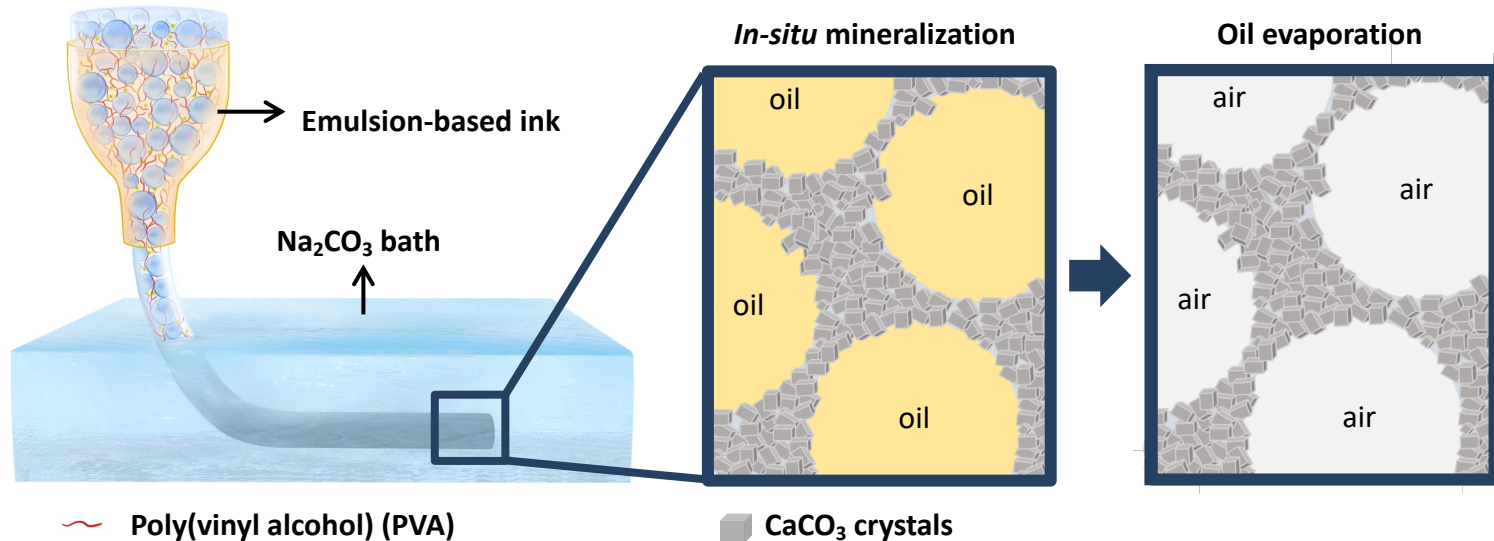
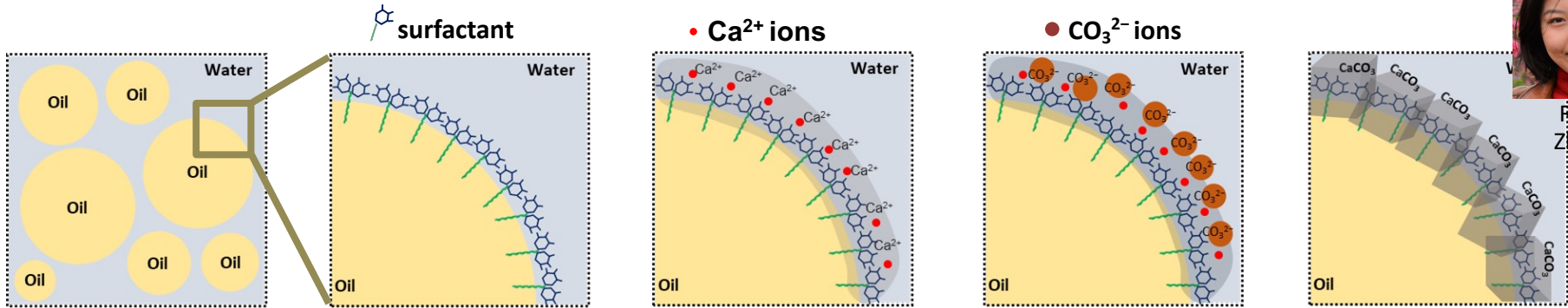
Holten-Andersen, N.; et al.,
PNAS, 2011, 108, 2651–2655



Mineralization of emulsion drops



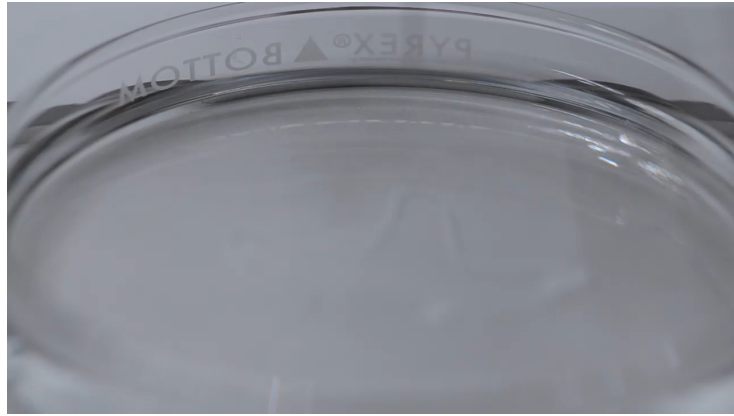
Ran Zhao



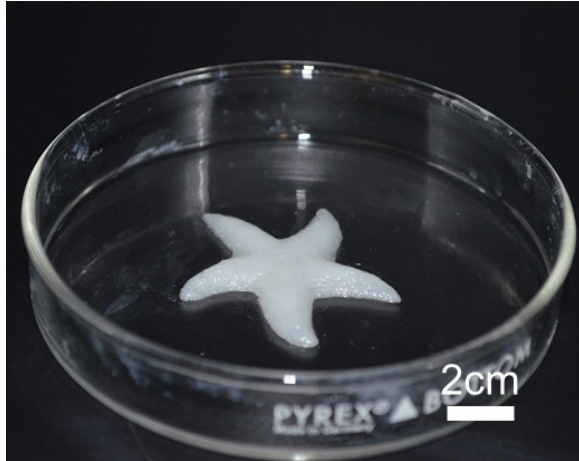
3D printing of porous CaCO_3



Ran
Zhao



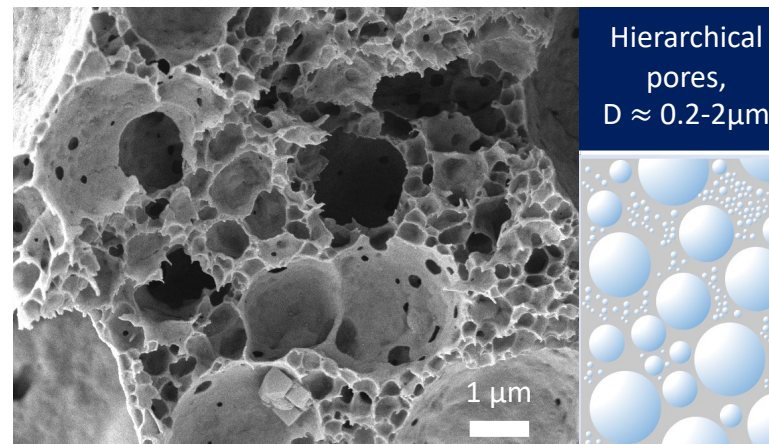
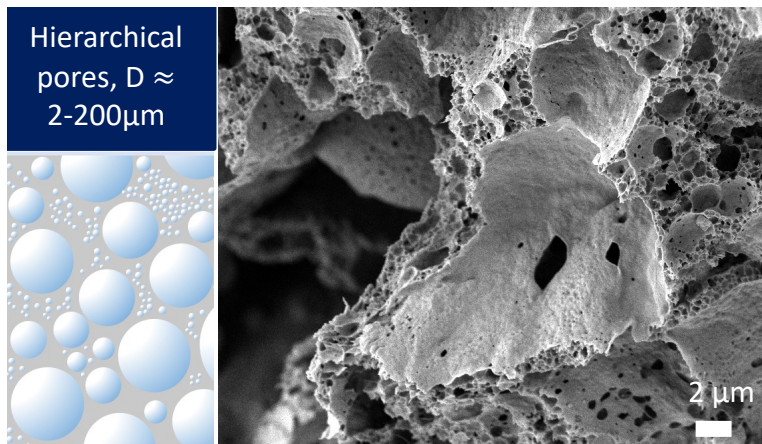
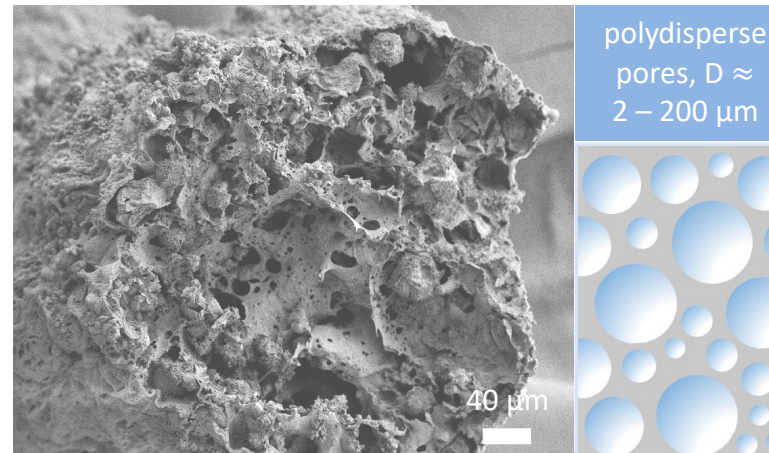
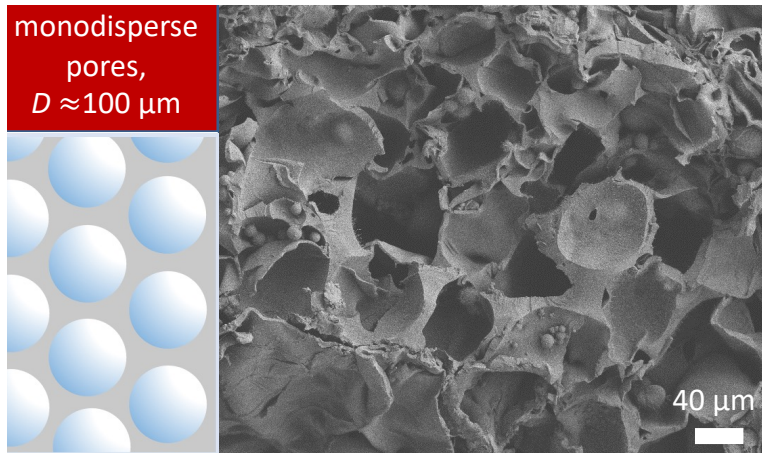
32 × real time



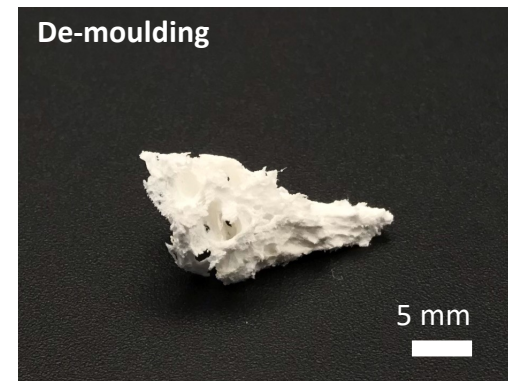
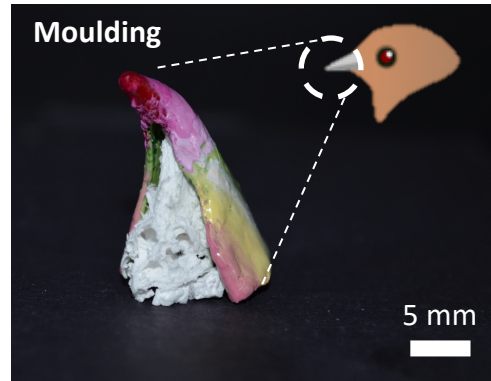
Microstructure of 3D printed CaCO_3



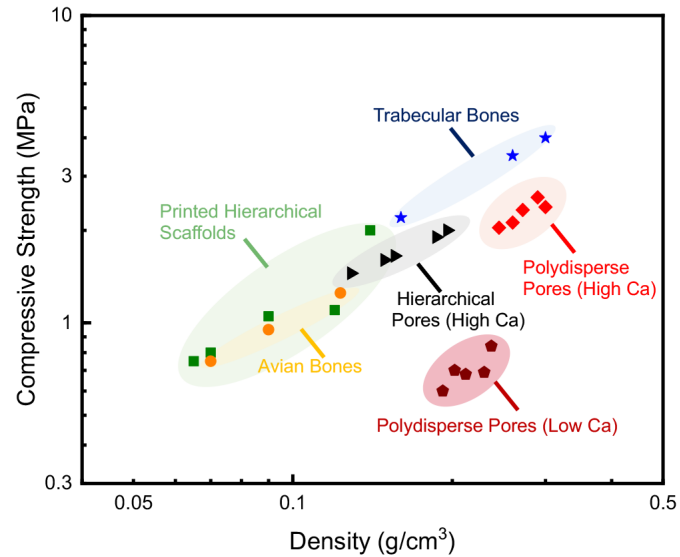
Ran
Zhao



Casting toucan beaks



Ran
Zhao



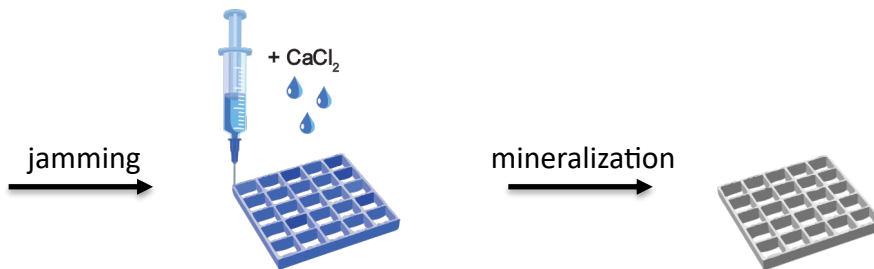
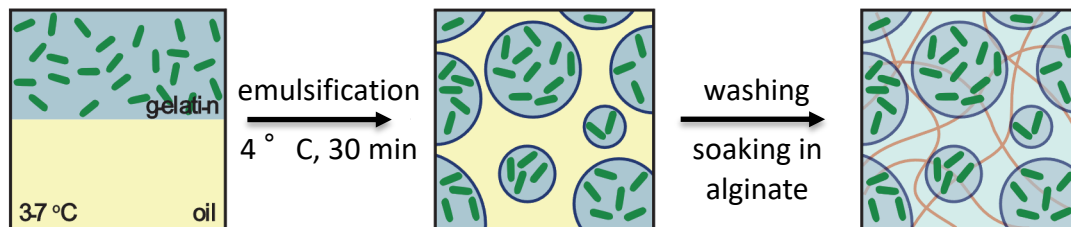
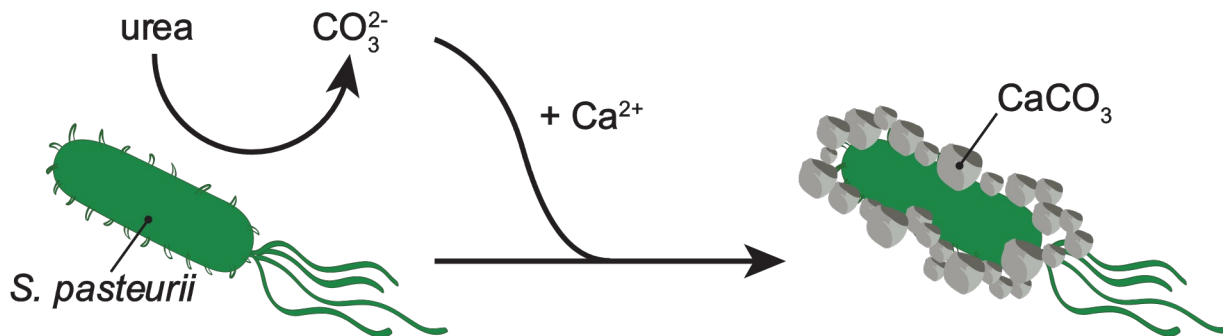
"Living" 3D printed composites



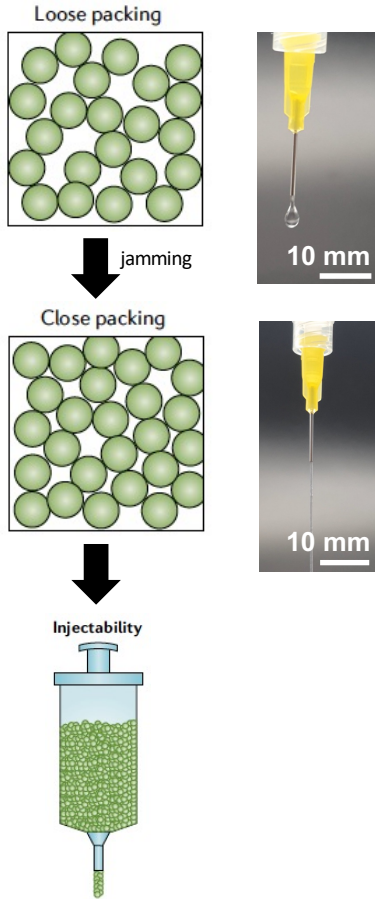
Lorenzo Lucherini



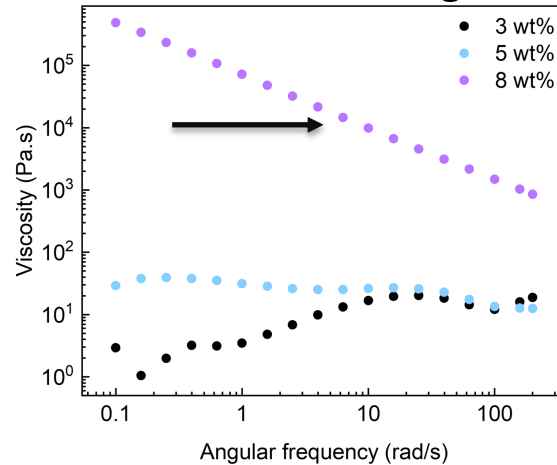
Matteo Hirsch



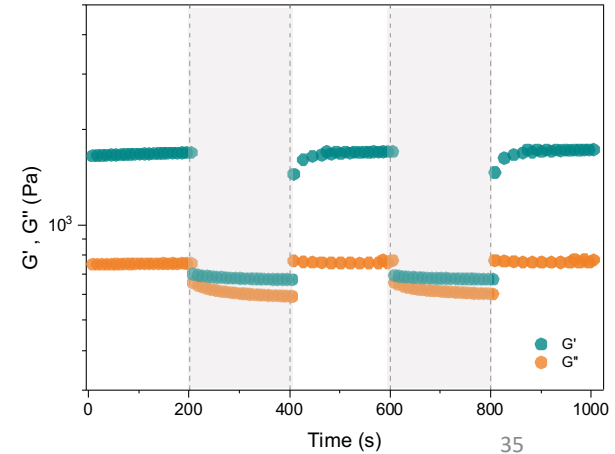
3D printing of granular hydrogels



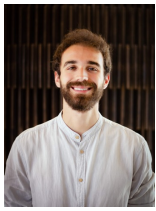
shear thinning



fast stress recovery



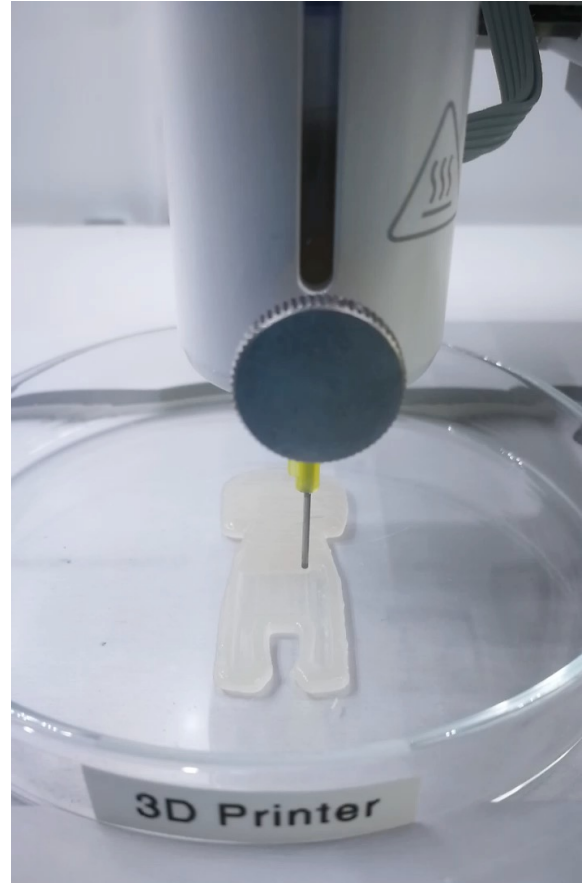
3D printing of bacteria-loaded microgels



Lorenzo
Lucherini



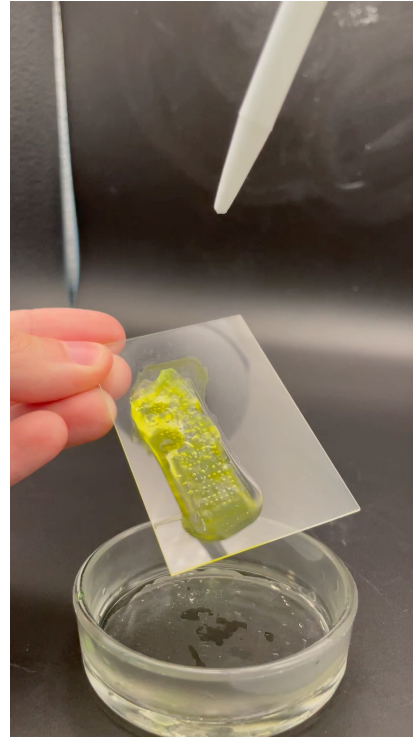
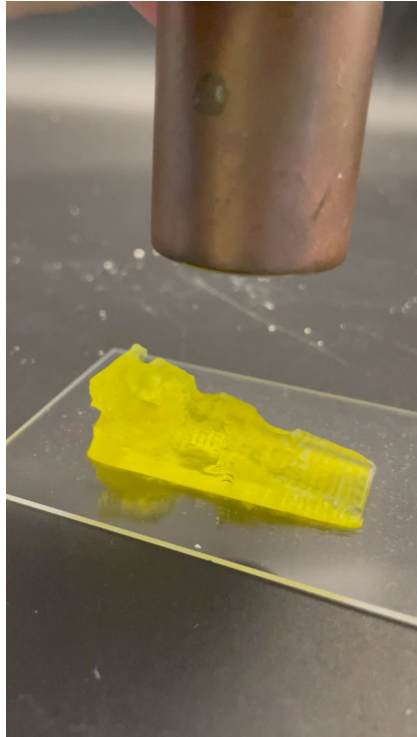
Matteo
Hirsch

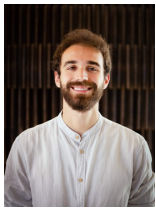


Mechanics of soft granular materials



Matteo
Hirsch



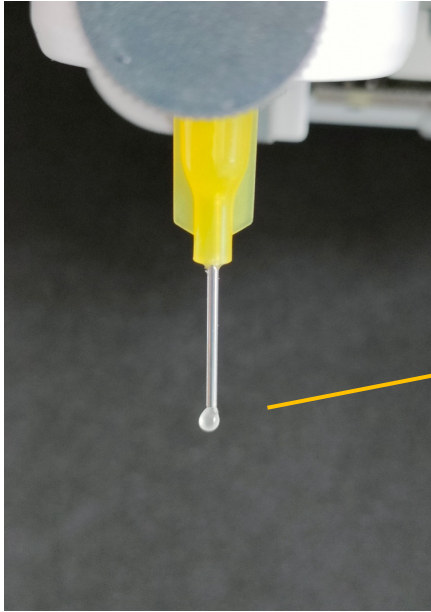


Lorenzo Lucherini

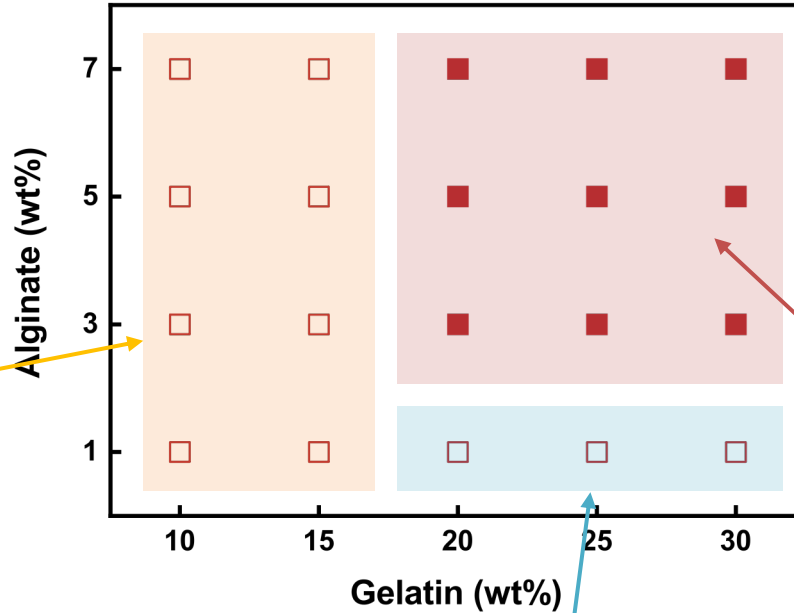
3D printing of bacteria-containing emulsions



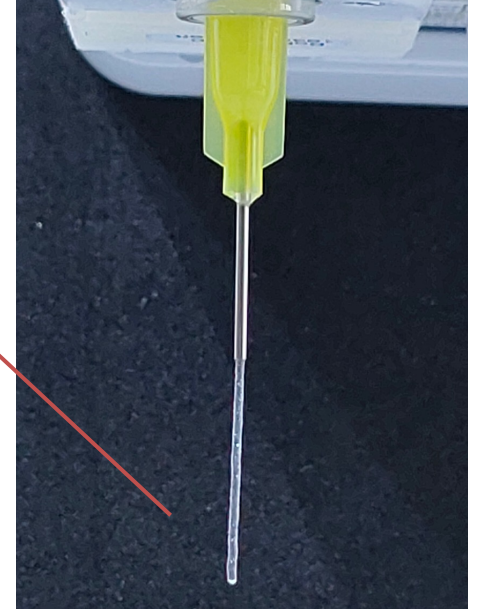
Matteo Hirsch



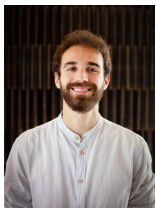
Dripping



Not stable



Extrusion

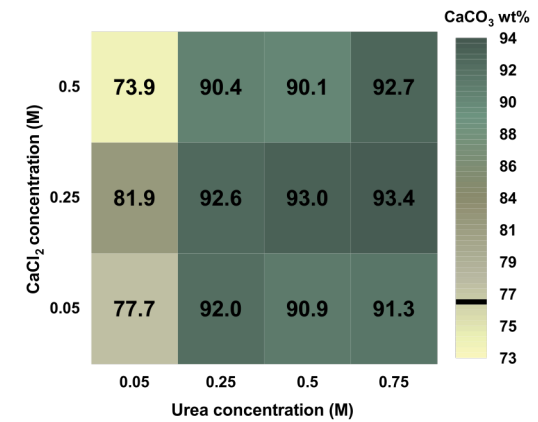
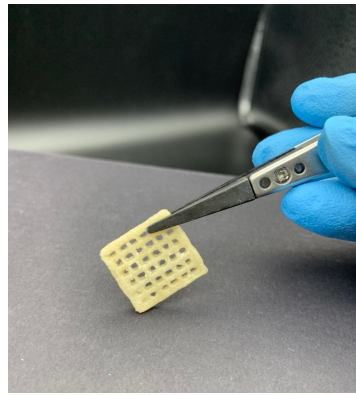
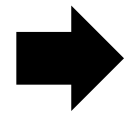
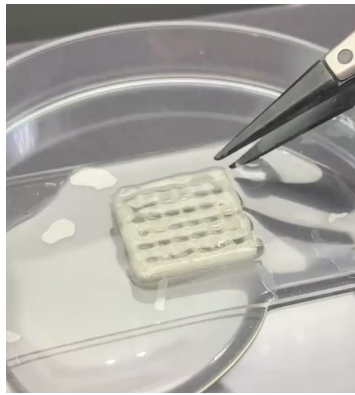
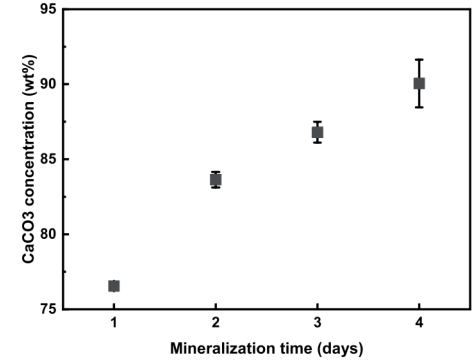
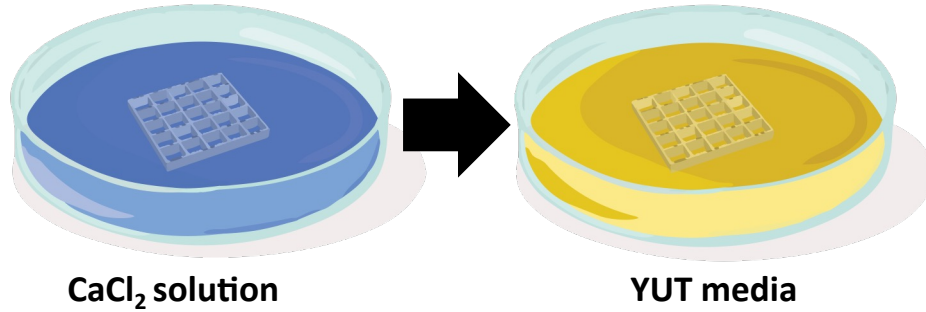


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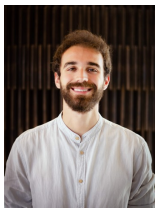
Mineralization of 3D printed structures



Matteo Hirsch



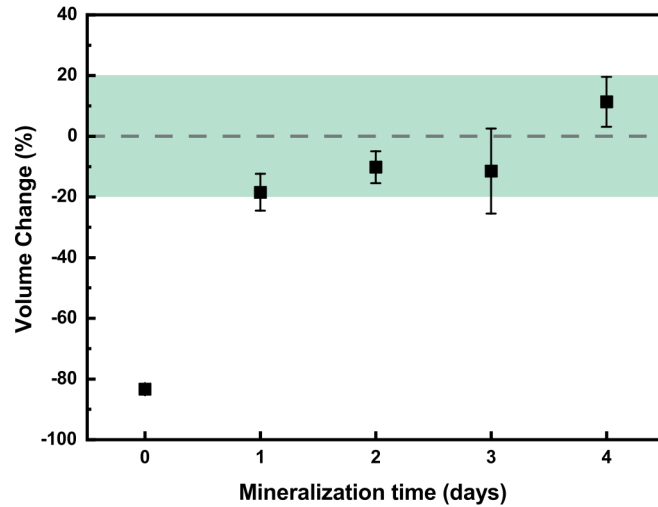
Shrinkage of mineralized scaffold



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Hirsch



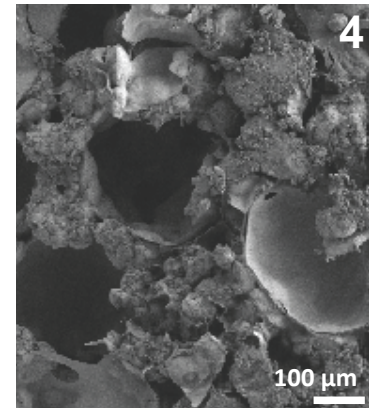
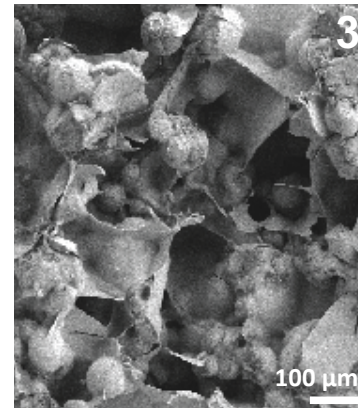
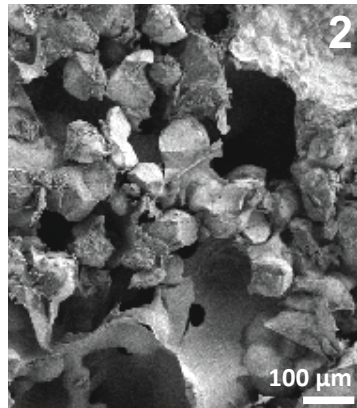
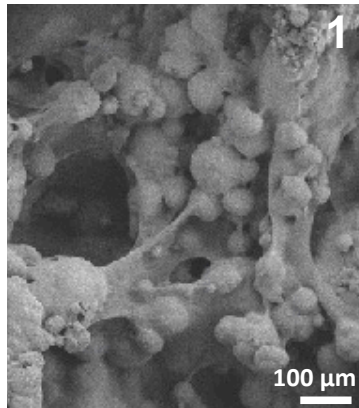
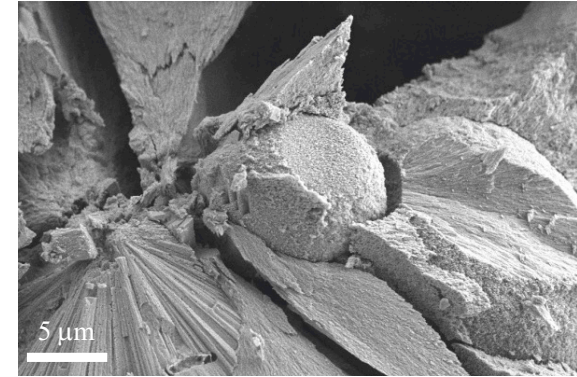
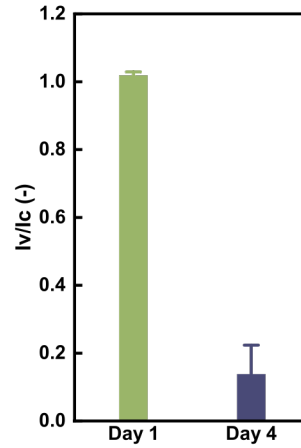
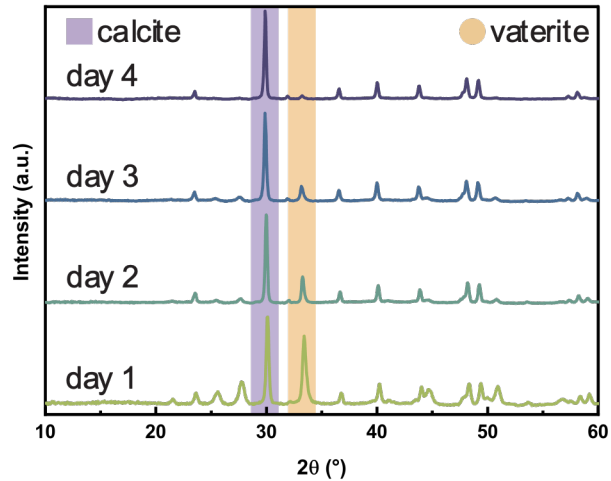
Structure of mineralized samples



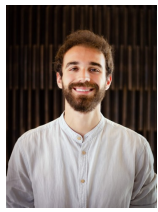
Lorenzo Lucherini



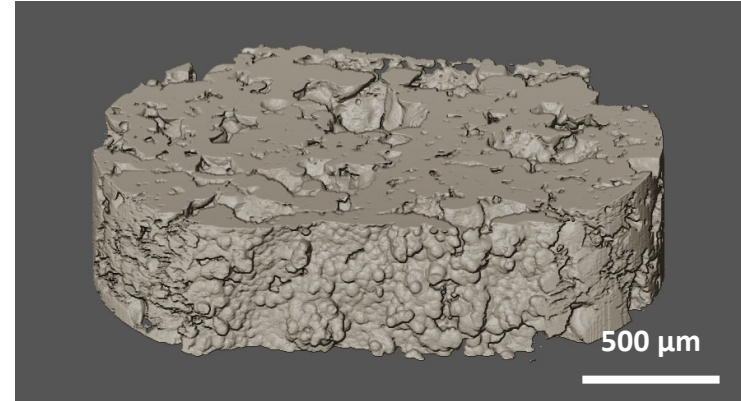
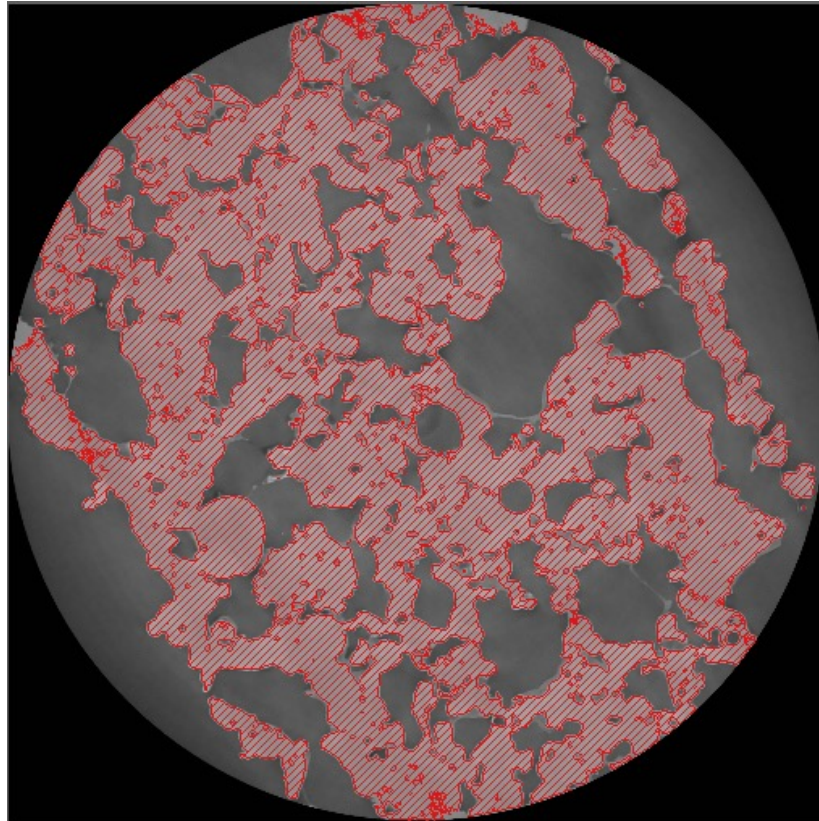
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Structure of 3D printed composites

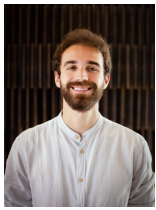


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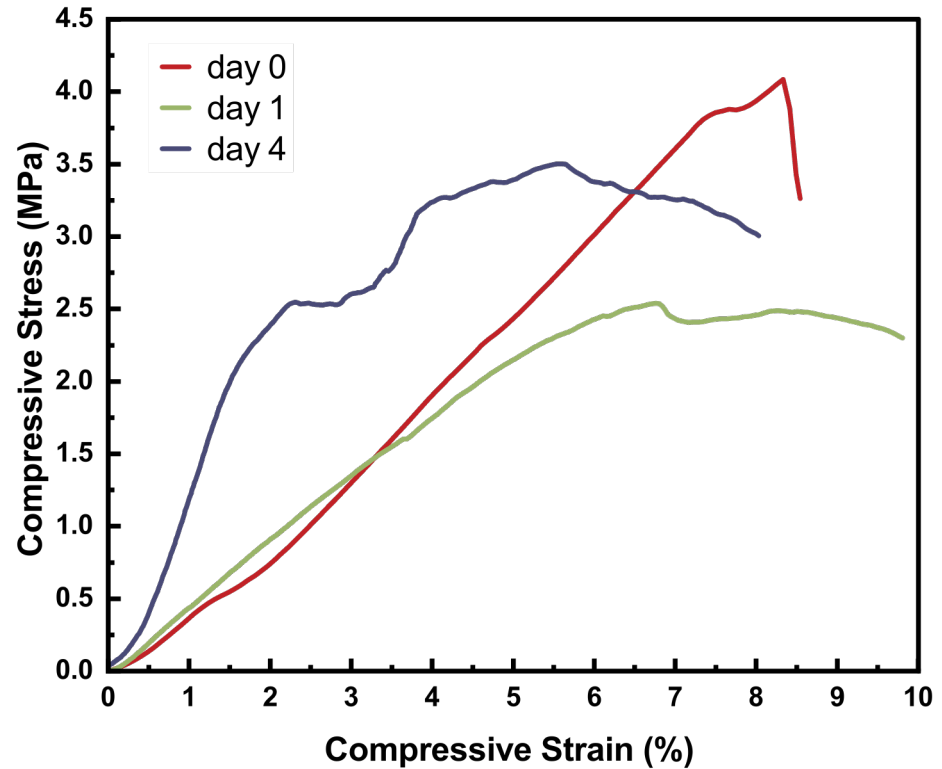
Mechanics of mineralized composite



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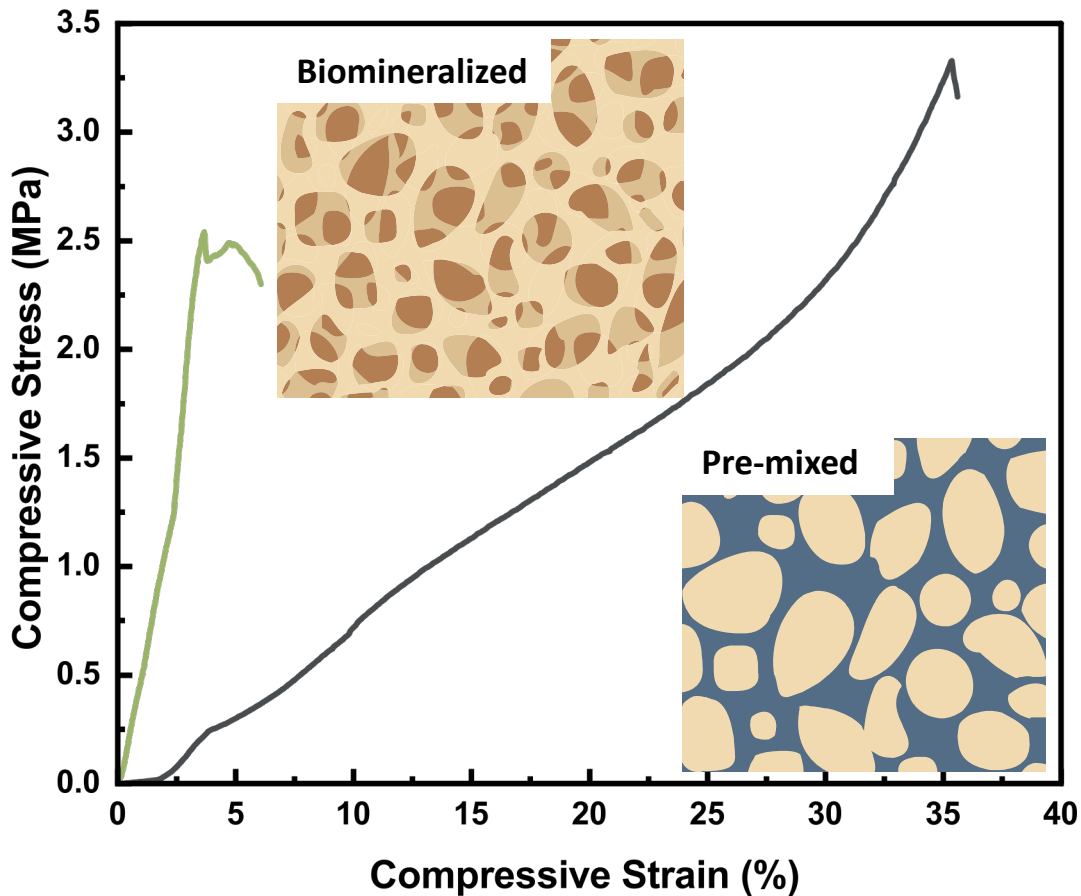
Biom mineralization vs. pre-mixing



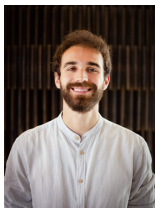
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How do you process this material in practice?



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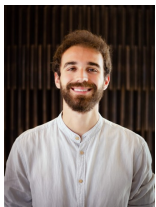
print →



grow →



Where might this material be useful?



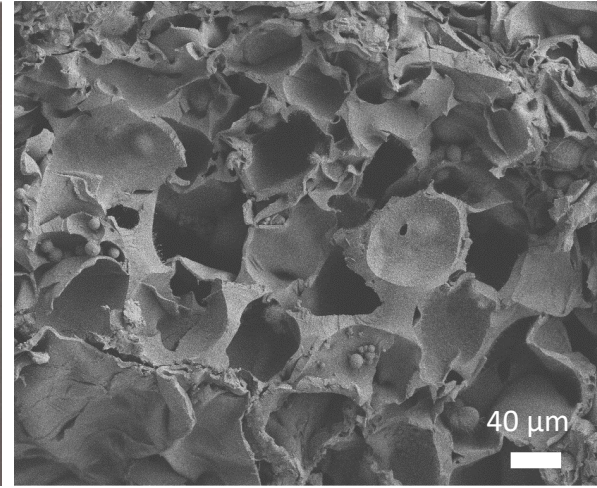
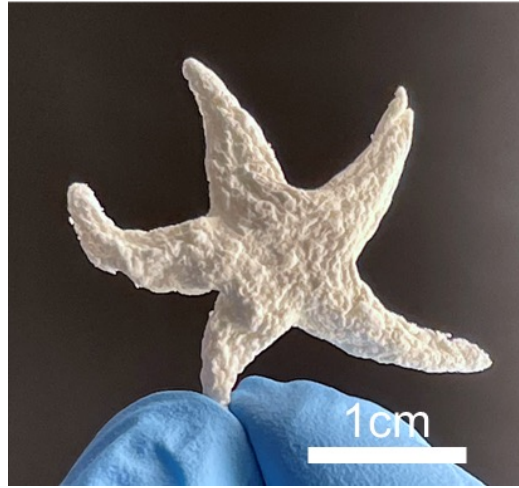
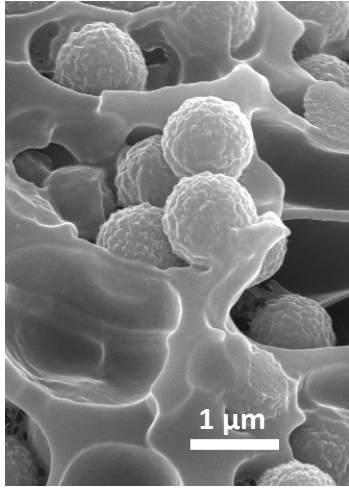
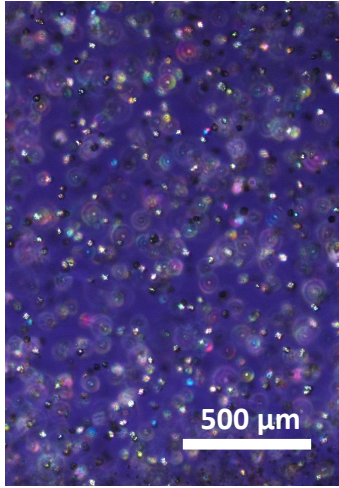
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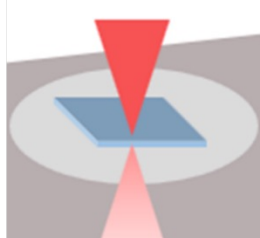
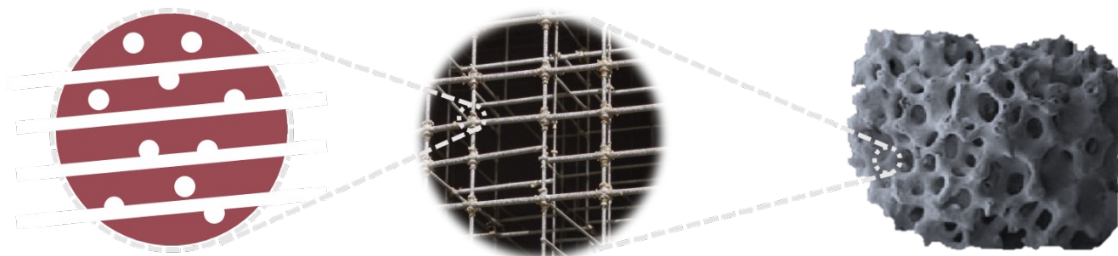
Conclusions



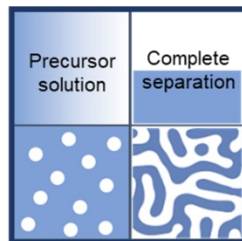
Outlook



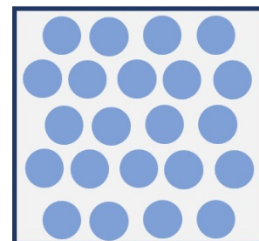
Ran
Zhao



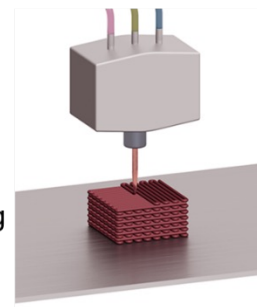
Laser-based printing



Phase separation

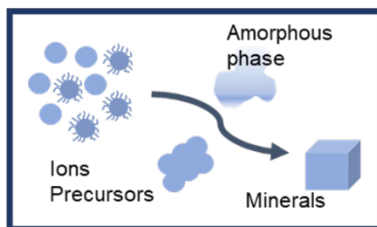


Sacrificial templating

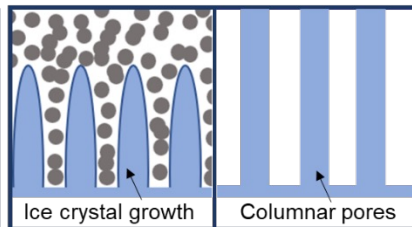


Direct ink writing
Material jetting

...



Biom mineralization



Freeze casting

R. Zhao, E. Amstad, *in print in Small*



Funding



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