Voronoi-type porous materials obtained by nonlinear elasticity

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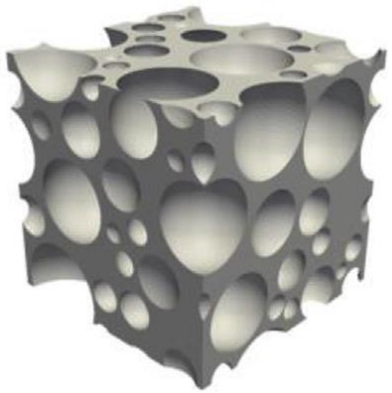
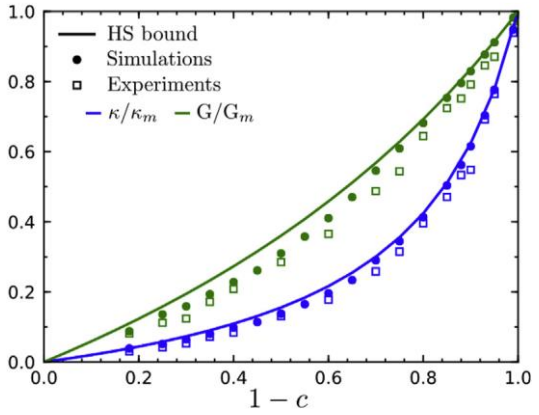
Introduction- Random porous materials

- Random 3D RSA* microstructures

Tarantino, M.G., Zerhouni, O., Danas, K. (2019). Random 3D-printed isotropic composites with high volume fraction of pore-like polydisperse inclusions and near-optimal elastic stiffness, Acta Materialia, 175, 331-340.

*RSA: Random sequential adsorption



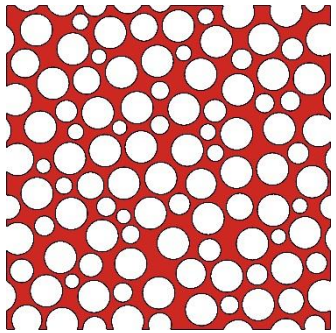


- Random 2D RSA microstructures

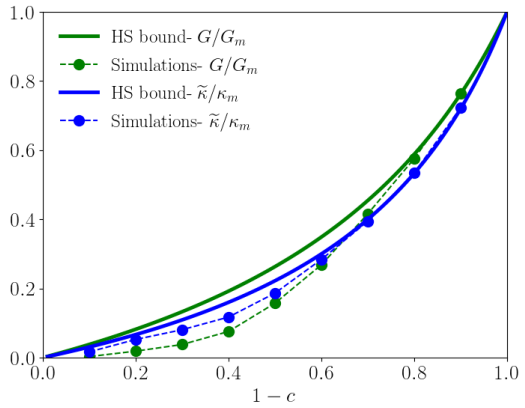
Anoukou, K., Brenner, R., Hong, F., Pellerin, M., Danas K. (2018). Random distribution of polydisperse ellipsoidal inclusions and homogenization estimates for porous elastic materials, Computers Struct. 210, 87-101

Randomness → Shape ✓

Uniform Ligament thickness ✗



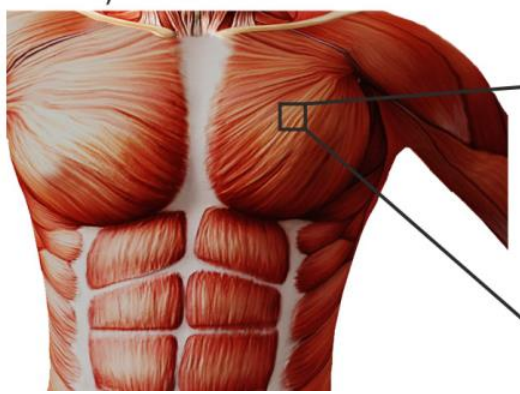
2D RSA



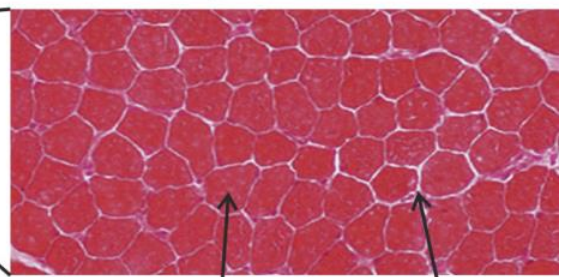
- Eroded Voronoi → **E-Voronoi**

Spyrou, L., Brisard, S., Danas, K. (2019). Multiscale modeling of skeletal muscle tissues based on analytical and numerical homogenization, J. Mech. Behavior Biomed. Mater., 92, 97-117.

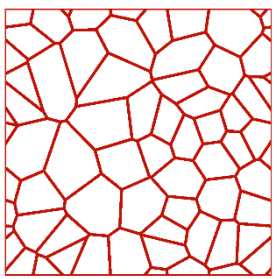
a) Macroscale



b) Microscale
Histological cross-section



c) Numerical Approximation



E-Voronoi

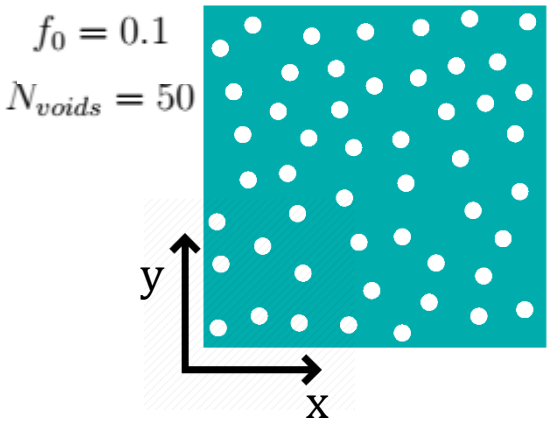
Randomness → Shape ✓

Uniform Ligament thickness ✓

Mechanically deformed Voronoi-type porous materials ----> M-Voronoi

➢ Computer fabrication

1- Creating 2D random porous microstructure with 2D RSA algorithm



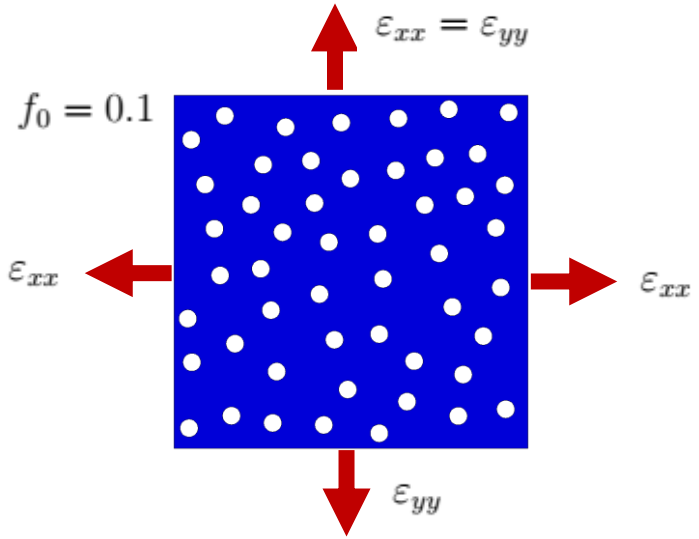
2- Applying biaxial loading: $\varepsilon_{xx} = \varepsilon_{yy}$

For incompressible neo-Hookean material:

$$W(\boldsymbol{F}) = \frac{\mu}{2}(\boldsymbol{F}.\boldsymbol{F} - 3)$$

μ is the shear modulus
$\boldsymbol{F}$ is the deformation gradient tensor

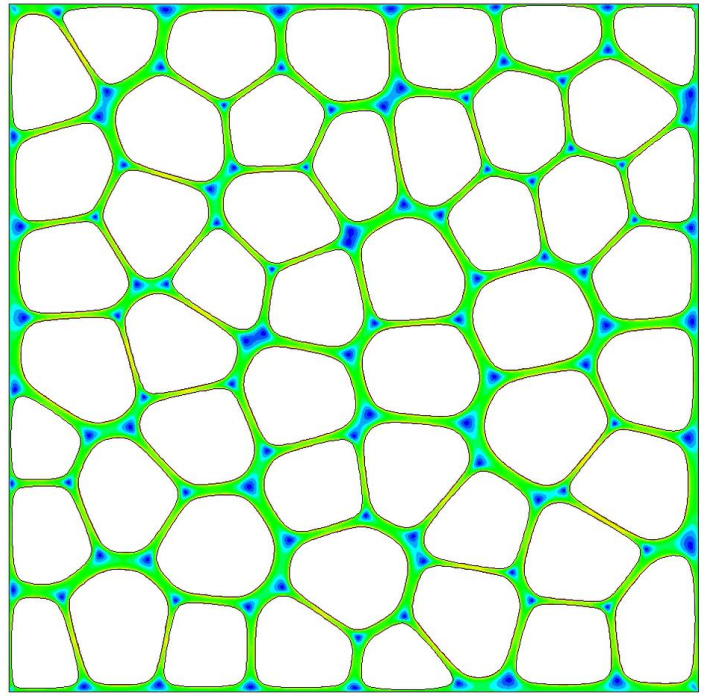
$$\boldsymbol{\varepsilon} = \boldsymbol{F} - \boldsymbol{I}$$



Affine Boundary Condition:

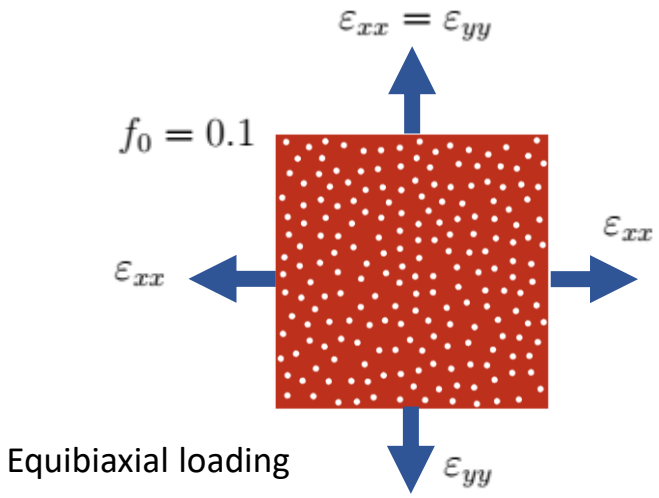
$$\boldsymbol{u} = \boldsymbol{\varepsilon}.\boldsymbol{X}$$

Straight edges remain straight!



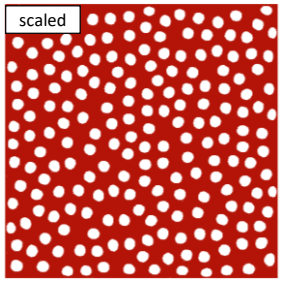
Creation of Voronoi microstructures

Porosity Evolution of M-Voronoi materials

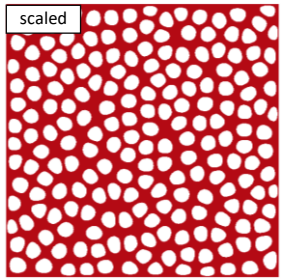


Equibiaxial loading

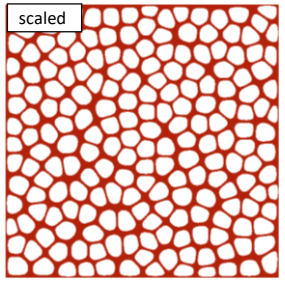
- Very high porosities can be obtained



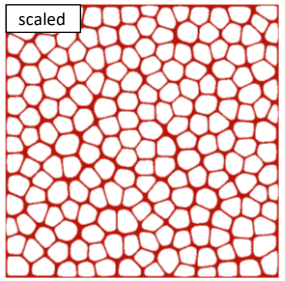
$f = 30\%$



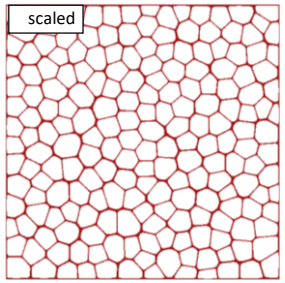
$f = 50\%$



$f = 70\%$



$f = 80\%$



$f = 90\%$

$\boldsymbol{F}$: Deformation gradient tensor $\quad \boldsymbol{F} = \boldsymbol{I} + \boldsymbol{\varepsilon}$ → Macroscopic fields, No rotation

f_0 : Initial Porosity

f : Final Porosity

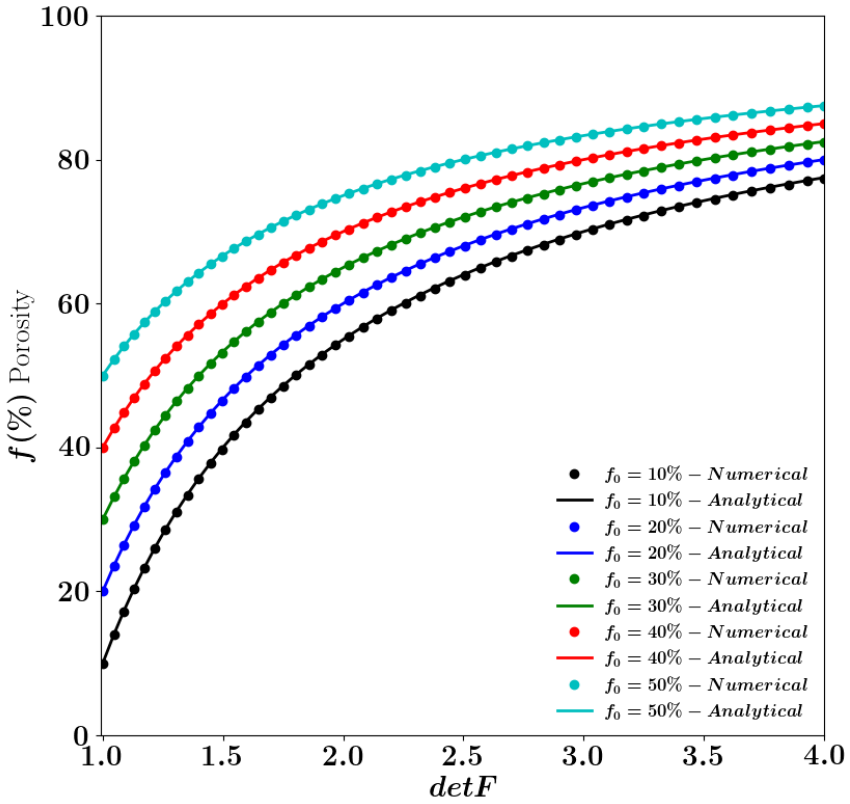
Final volume → $V = det\boldsymbol{F}\, V_0$ ← Initial volume

Matrix phase → $det\boldsymbol{F}_m = 1$

- Considering incompressible material:

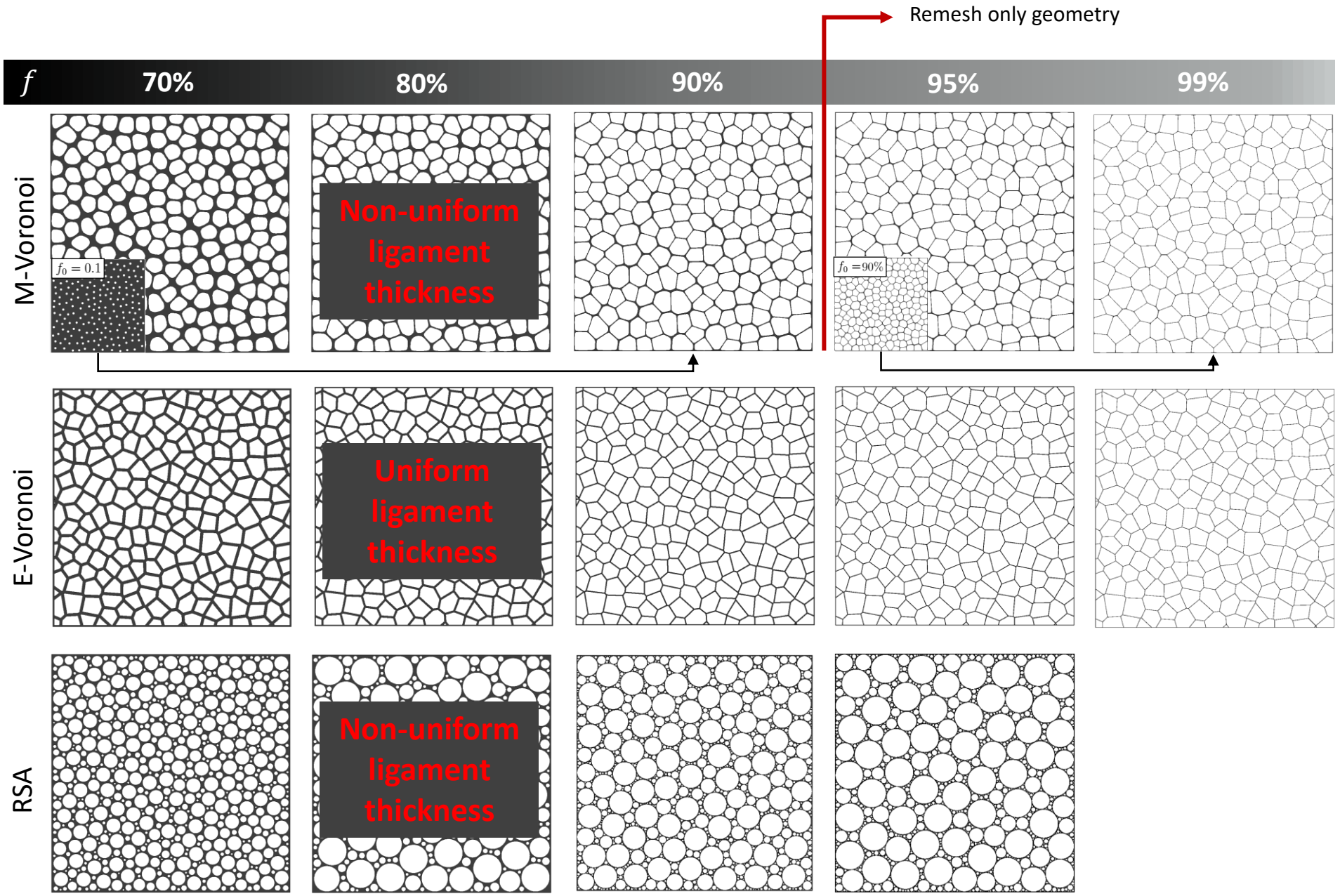
$$f = 1 - \frac{1 - f_0}{det\boldsymbol{F}}$$

Only $det\boldsymbol{F}$ controls porosity

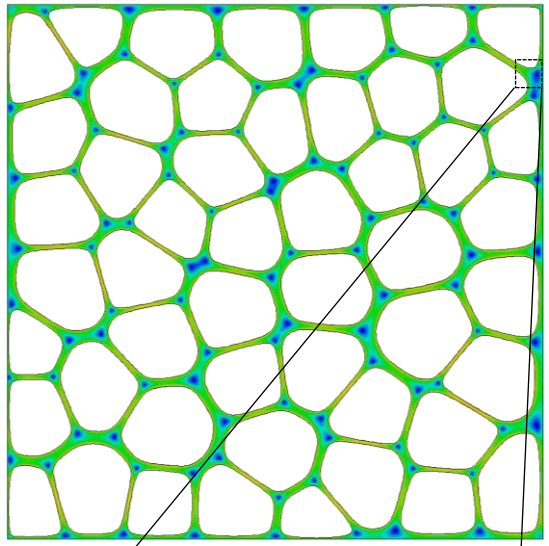


Highly porous materials

- High porosities up to 99% can be achieved with larger strains.
- Different initial porosities will lead to different final Voronoi-type structure.
- M-Voronoi and E-Voronoi structures are almost similar at very high porosities.
- With RSA algorithm the maximum porosity would be 97% but not printable.

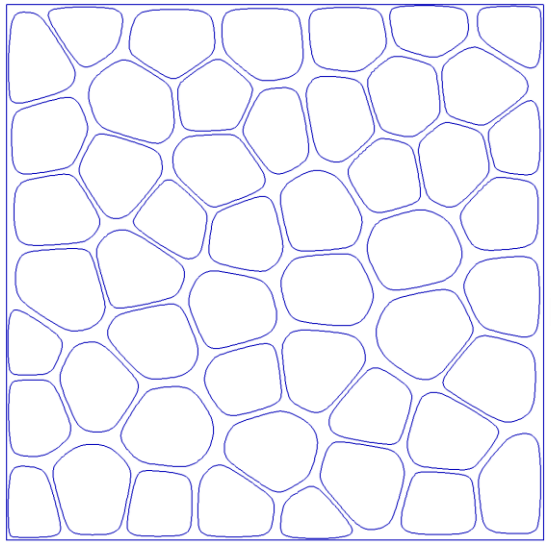


Creation of M-Voronoi porous materials- Virtual fabrication



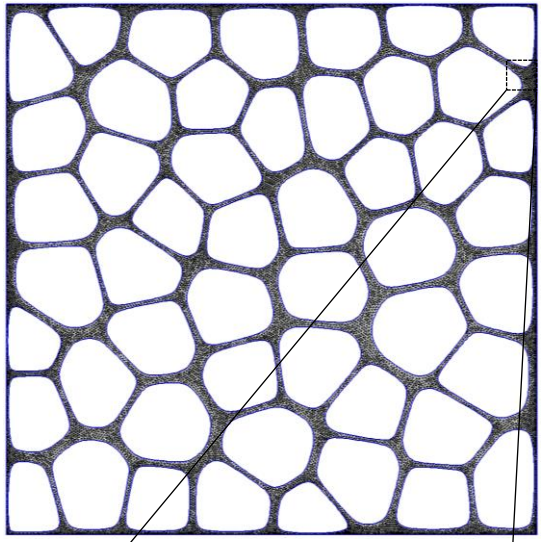
Max Principal logarithmic strain field

Extracting Geometry

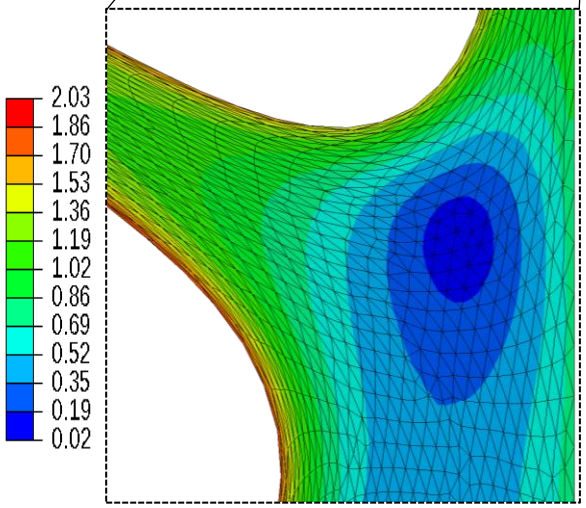


Gometry created from deformed orphan mesh

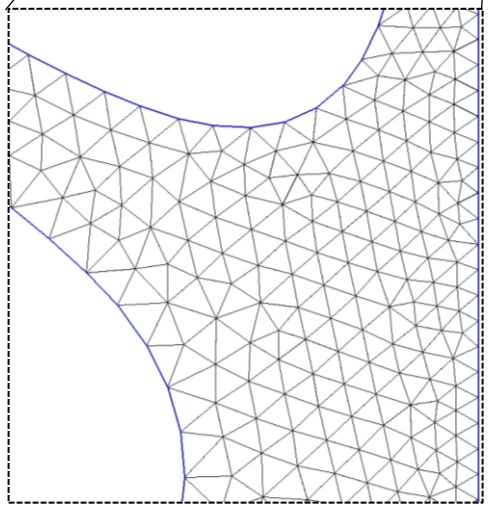
Remeshing



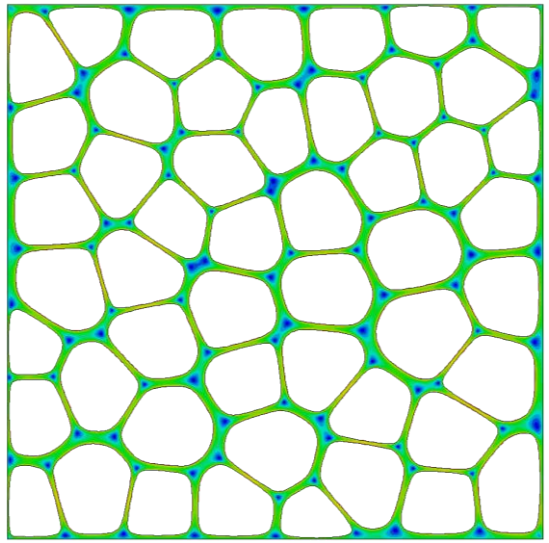
New mesh



Deformed mesh

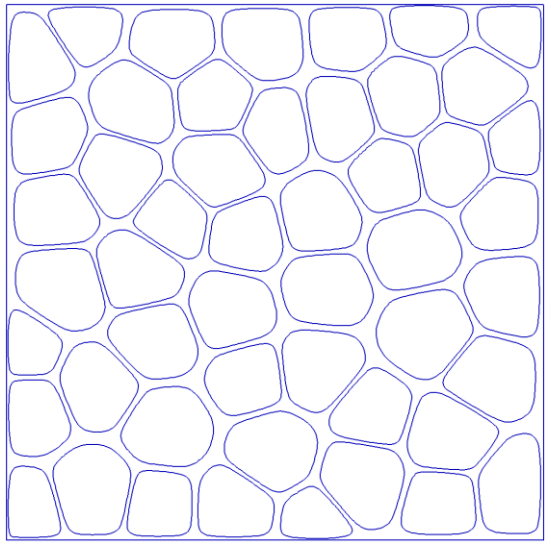


Creation of M-Voronoi porous materials- 3D printing



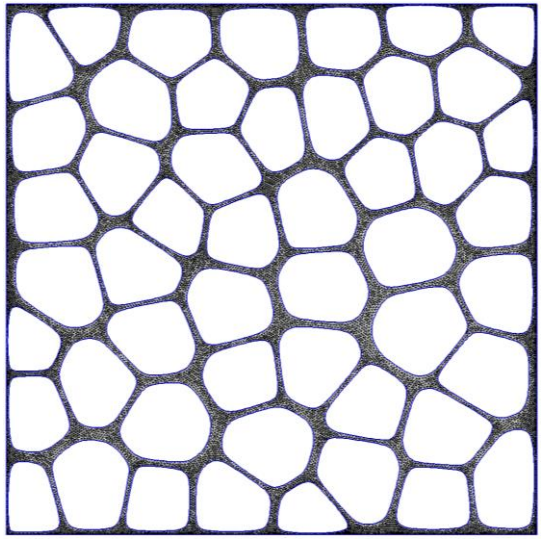
Max Principal logarithmic strain field

Extracting Geometry



Gometry created from deformed orphan mesh

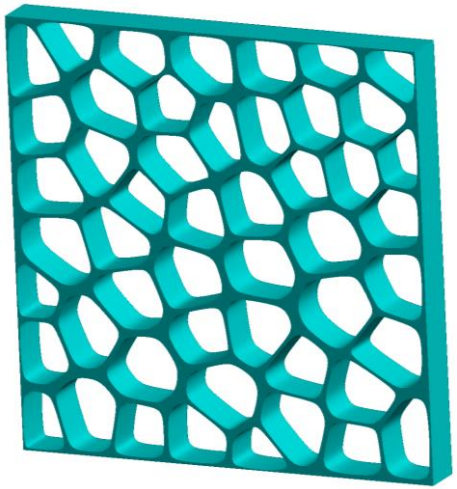
Remeshing



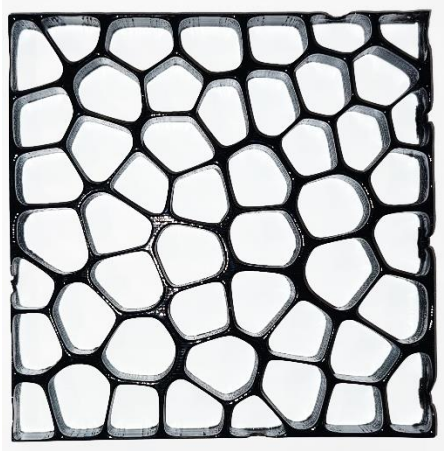
New mesh

STL

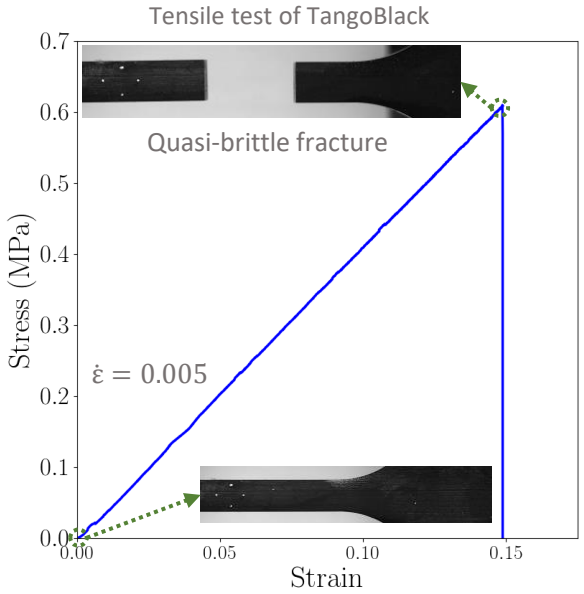
Rescale



3D-printing

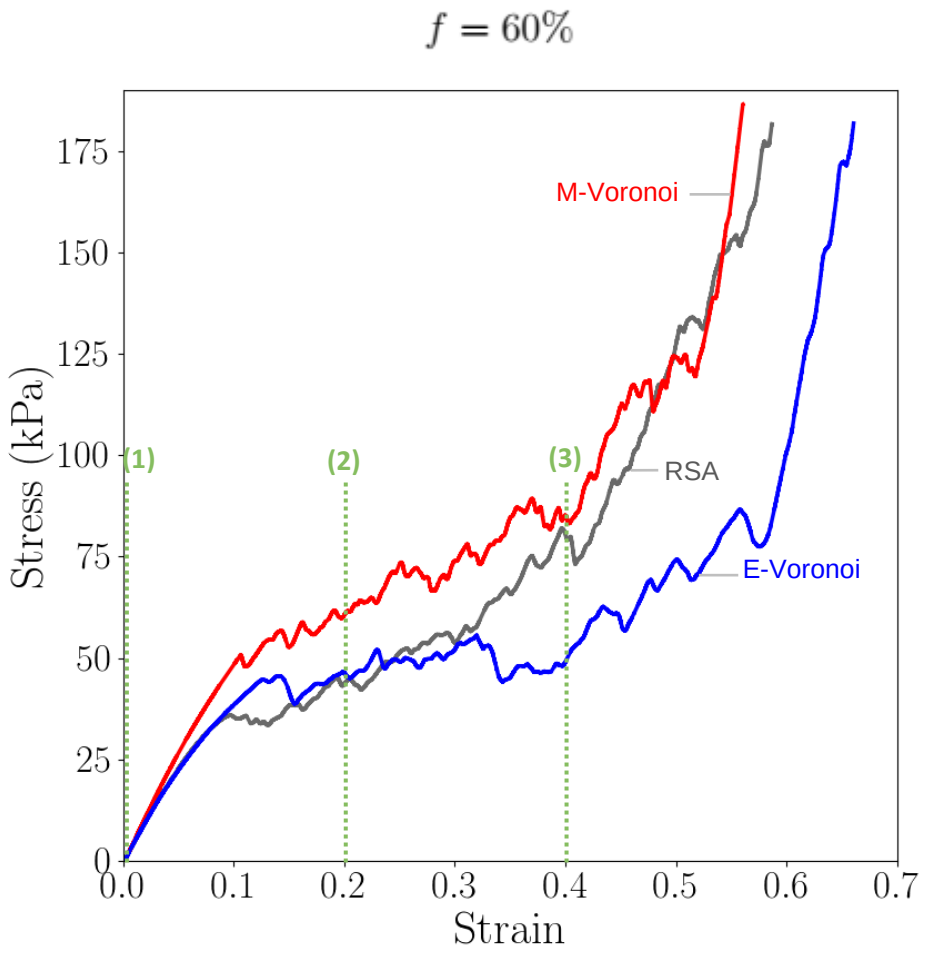


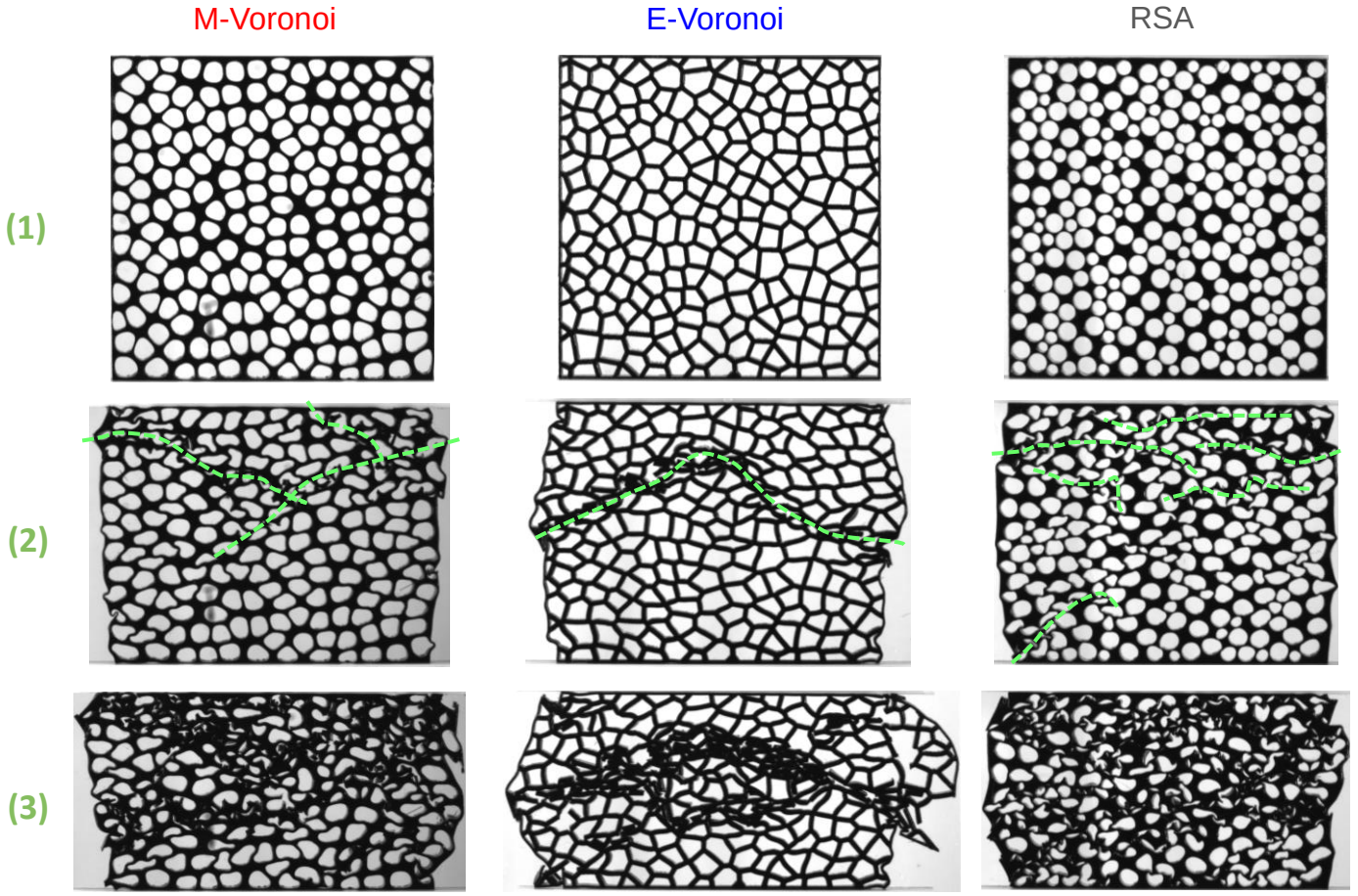
3D-printed Structure with TangoBlack
LMS- Stratasys 3d printer



Experimental results

- **Compression tests**





Experimental results

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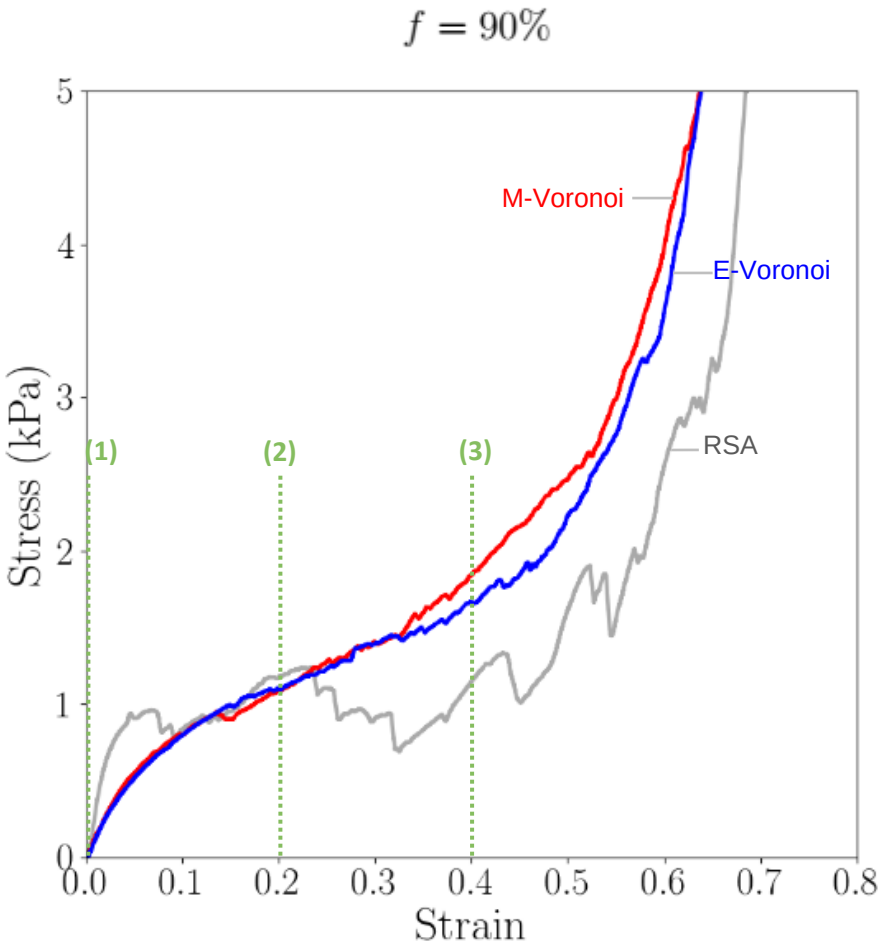

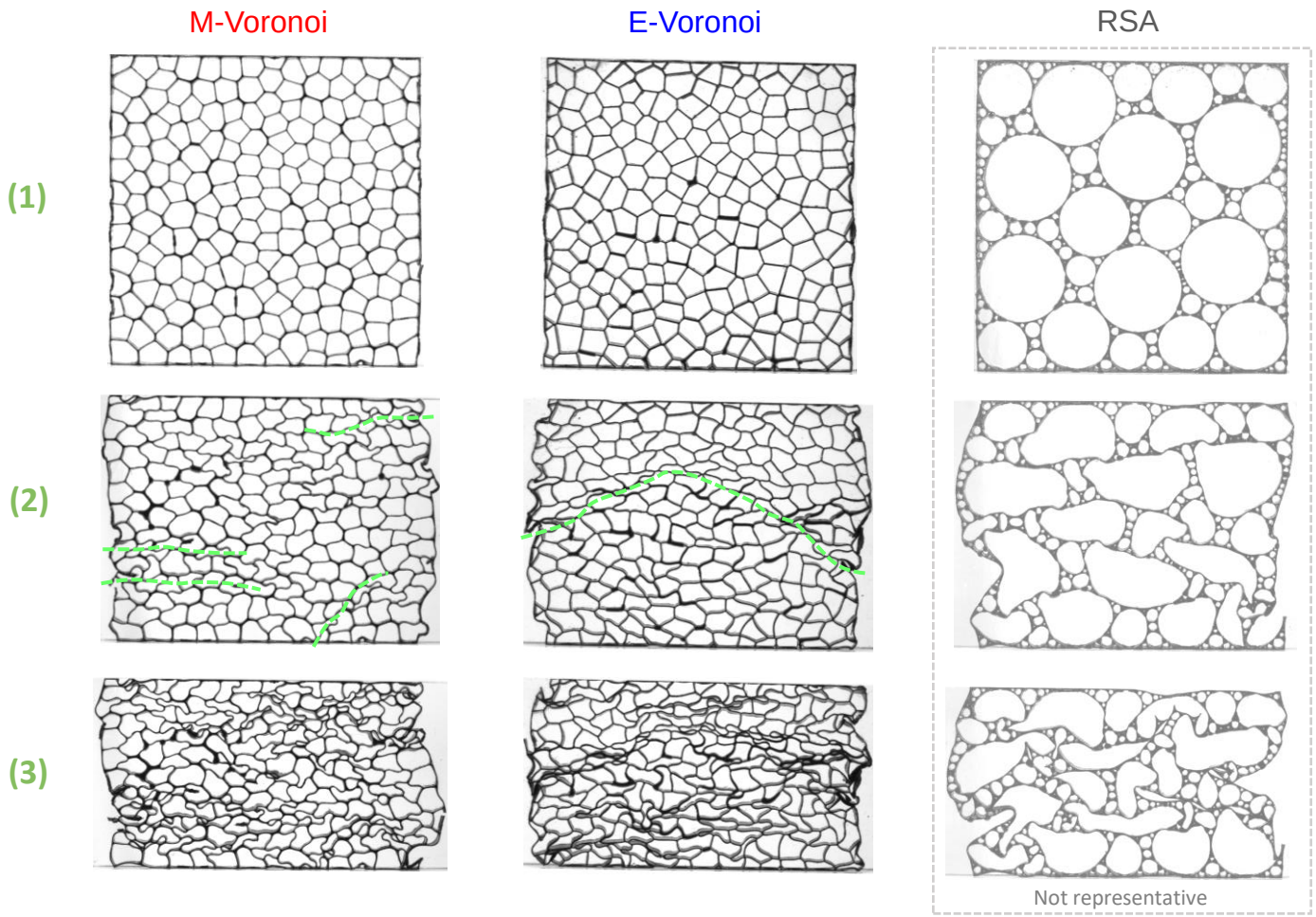

Experimental results

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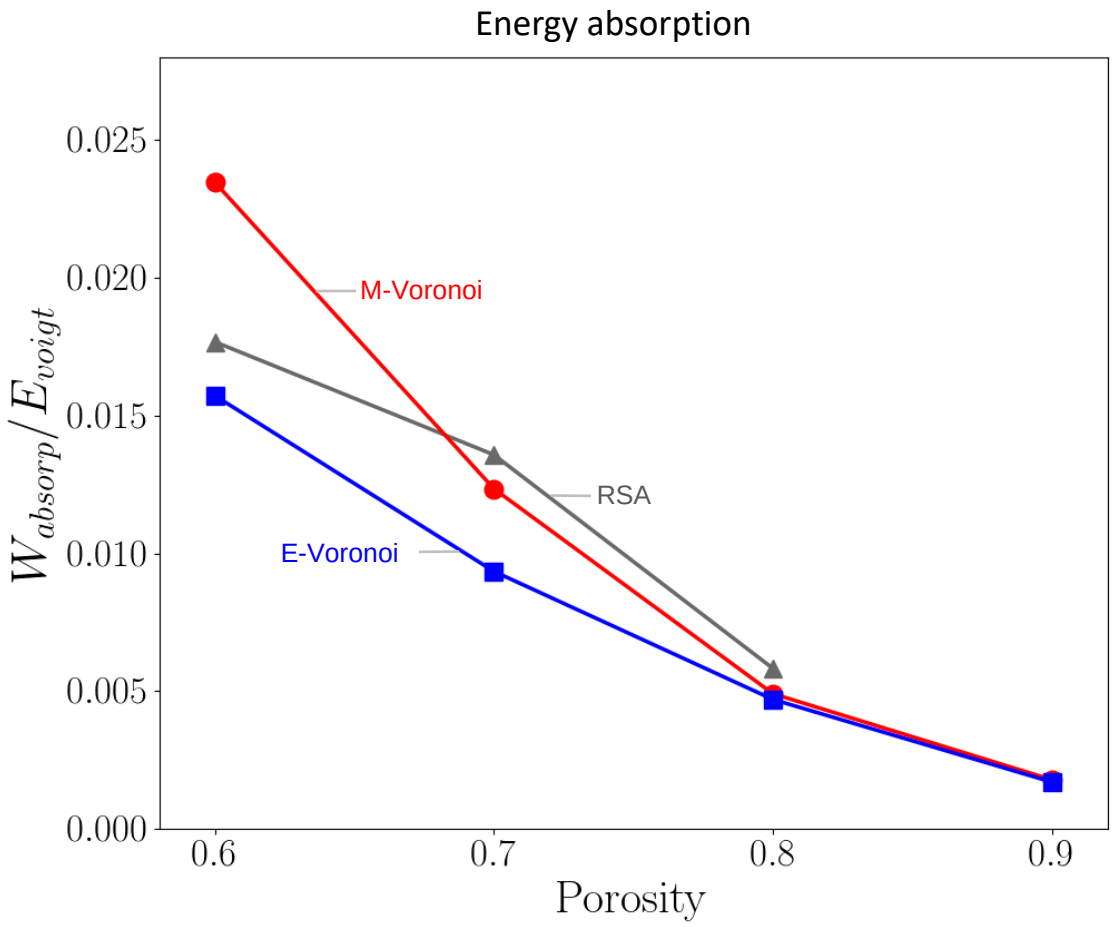

M-Voronoi > E-Voronoi

Thank you for your attention ☺