New insights on the mechanical properties of cork in compression

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Cork in Science and Applications
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Cork material and applications: market data

Lightweight material

Thermal-acoustic insulation properties

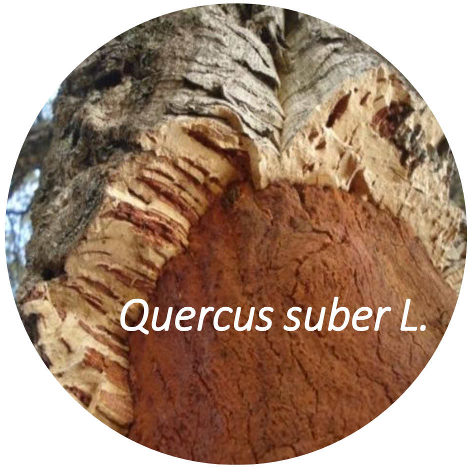
O_2 O_2

Barrier properties to gases

Chemical stability

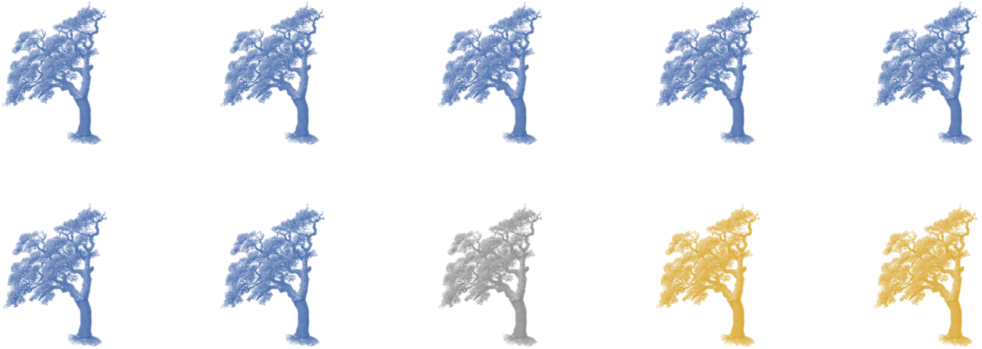
Low permeability to liquids

Mechanical properties in compression



Natural cork stoppers – 41.2%

Other type of cork stoppers – 32.4 %



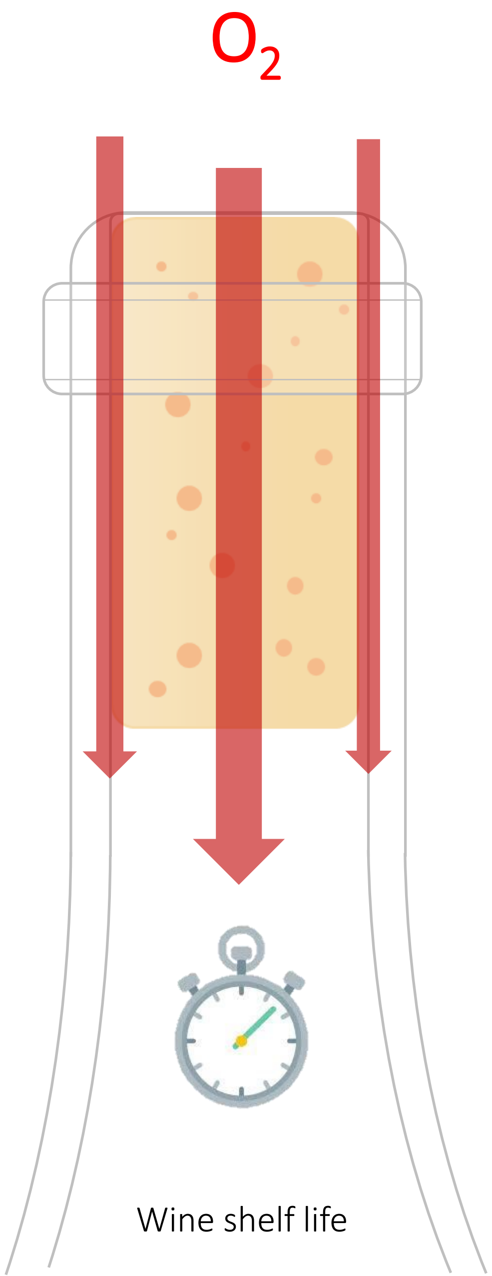
Wine industry – 73.5%

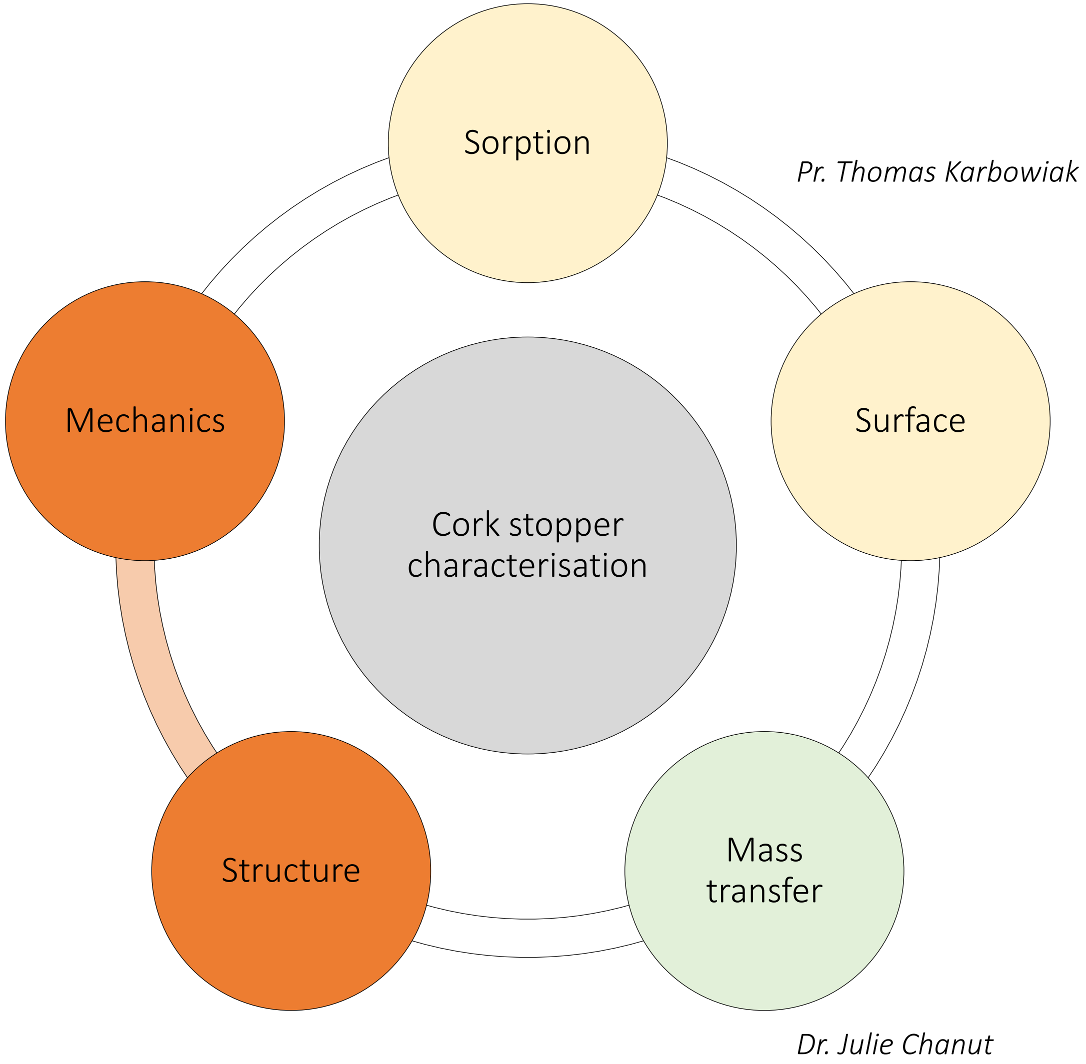
Building material – 24.1%

Raw material – 0.9%

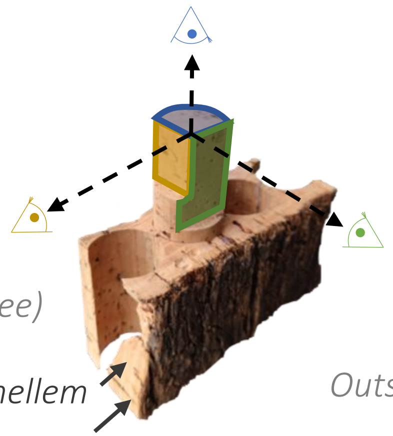
Other cork products – 1.5%

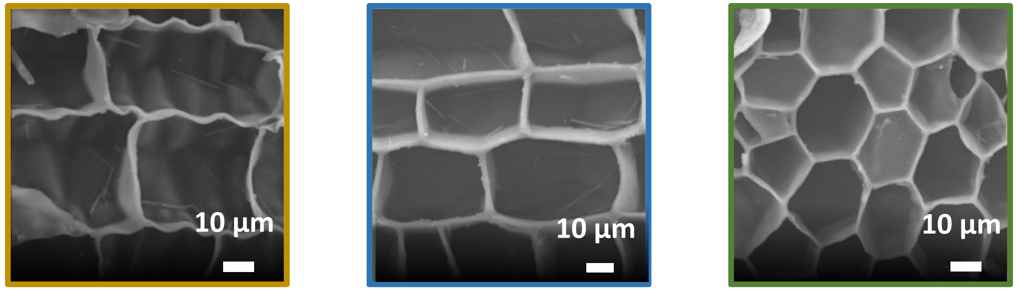
APCOR, (2020) Cork Yearbook


O_2
Wine shelf life


Sorption
Surface
Mass transfer
Structure
Mechanics
Cork stopper characterisation
Pr. Thomas Karbowiak
Dr. Julie Chanut

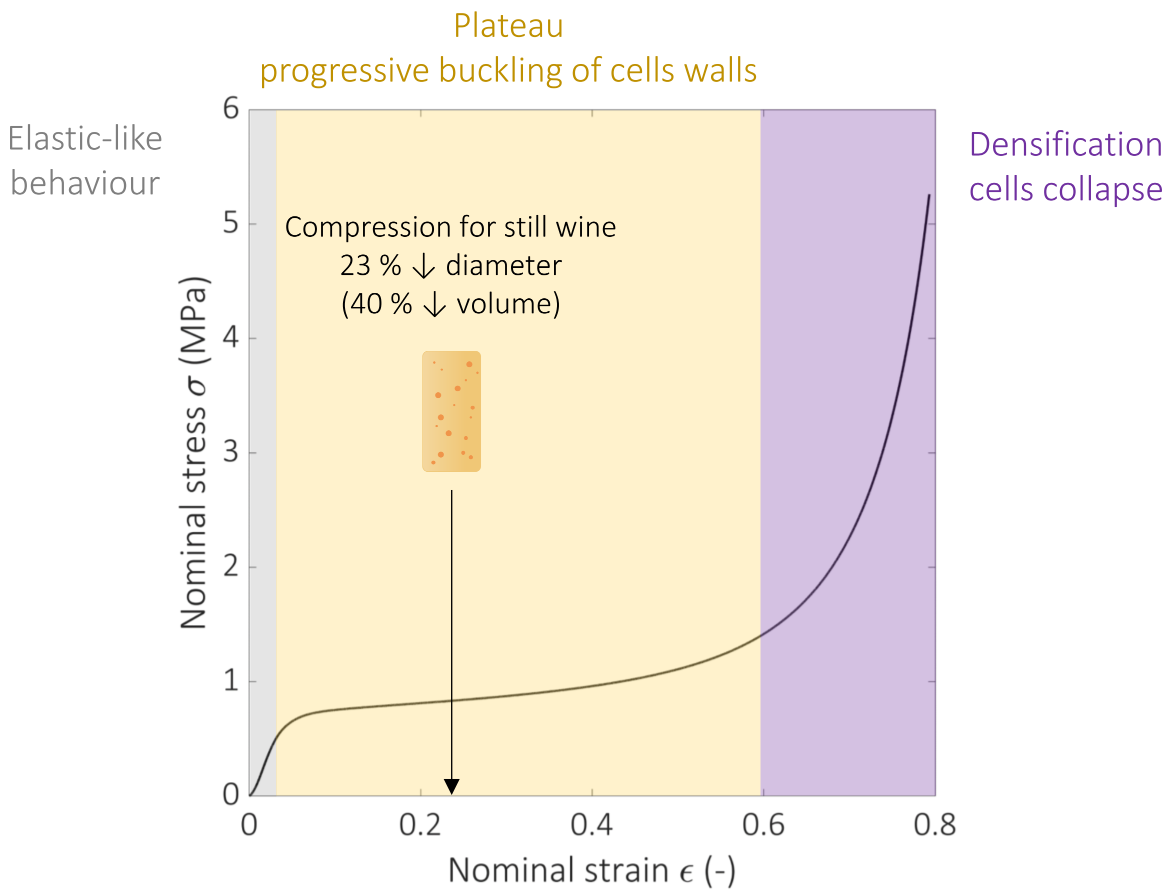
The anisotropic structure of cork and its compressive behaviour

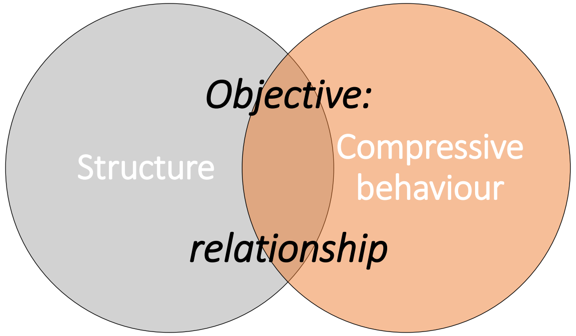




Radial Axial Tangential

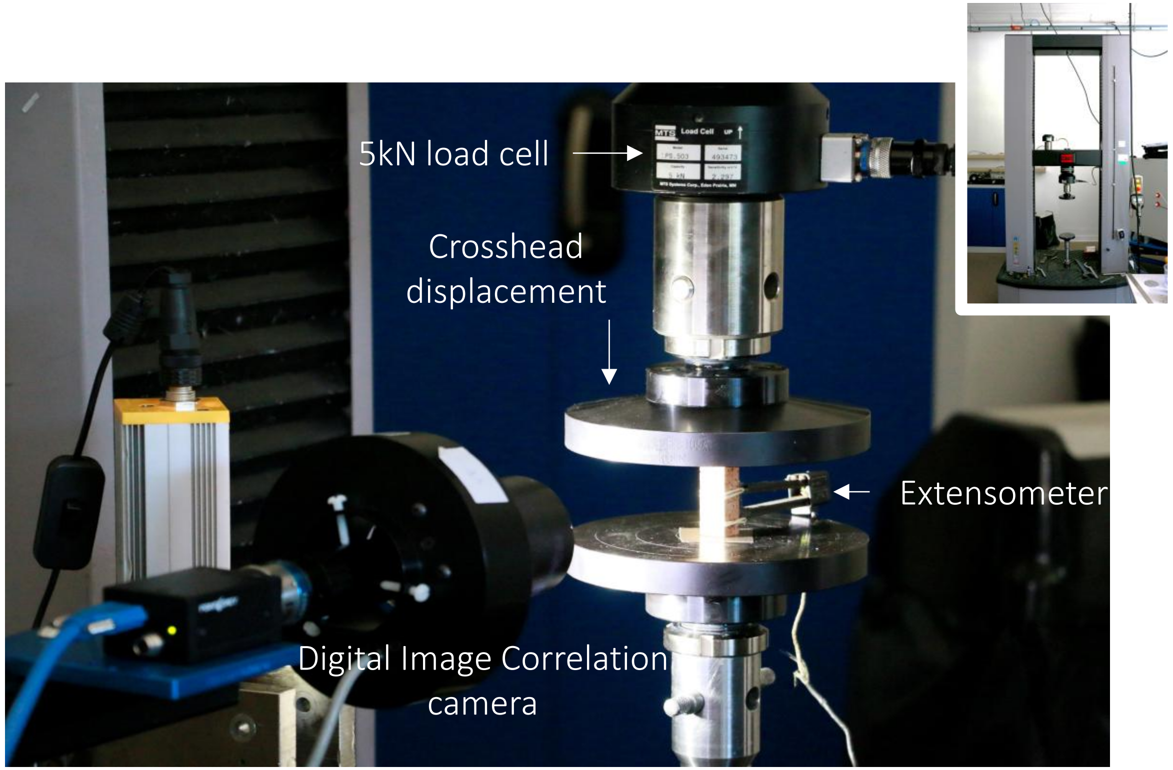
Scanning electron microscopy (SEM) observations of cork cells
Crouvisier-Urion, K., et al. (2019)





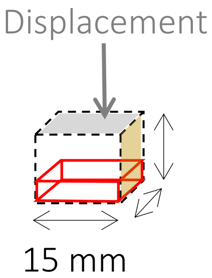
1. Quasi-static compression test (QS):
   - Crosshead (crosshead displacement rate of 1 mm·min^{-1})
   - Extensometer (INSTRON 2620 with a gauge length of 12.5 mm and strain range of ± 40 %)
   - Digital Image Correlation (DIC)
     (PointGrey® GrassHoper camera equipped with a telecentric objective Edmund 0.20x)

2. Progressive repeated loading test (PRL):
   - Crosshead (crosshead displacement rate of 1 mm·min^{-1})

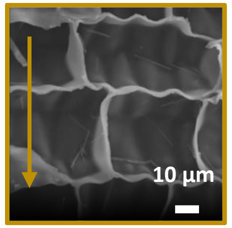


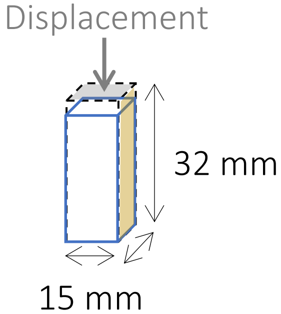
Samples were stored at 25°C and 53% RH until equilibrium (~3 months)

Compression along the tangential direction



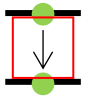
Cube





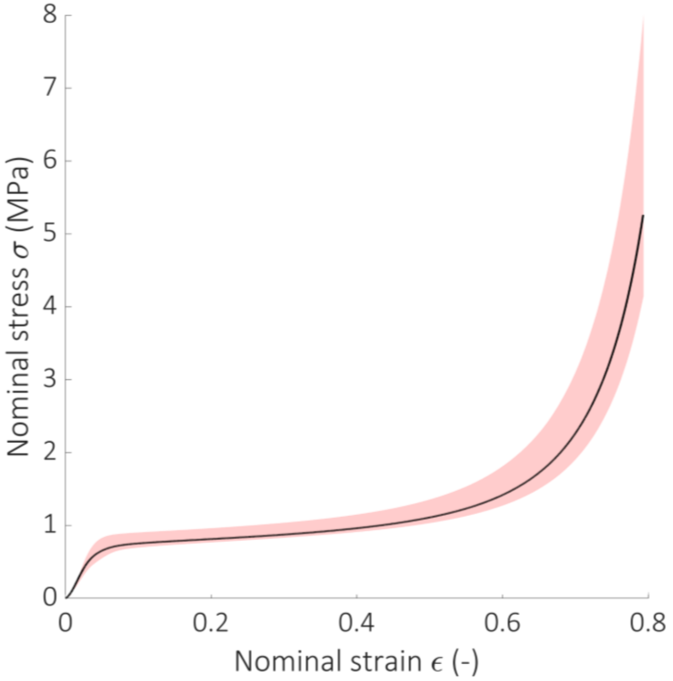
Parallelepiped

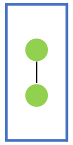
QS: comparison of devices for the determination of the elastic modulus of cork



Crosshead displacement

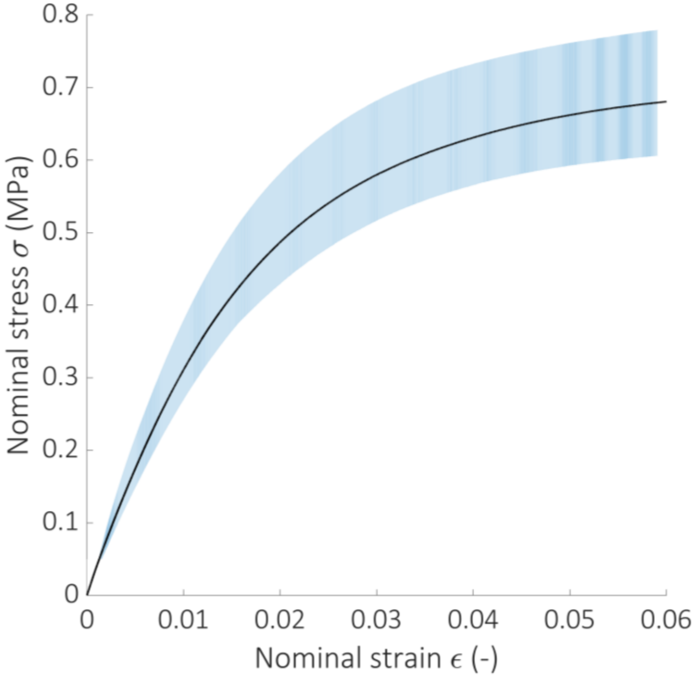
Global measurement of strain between the fix and mobile steel platens.

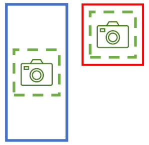




Extensometer

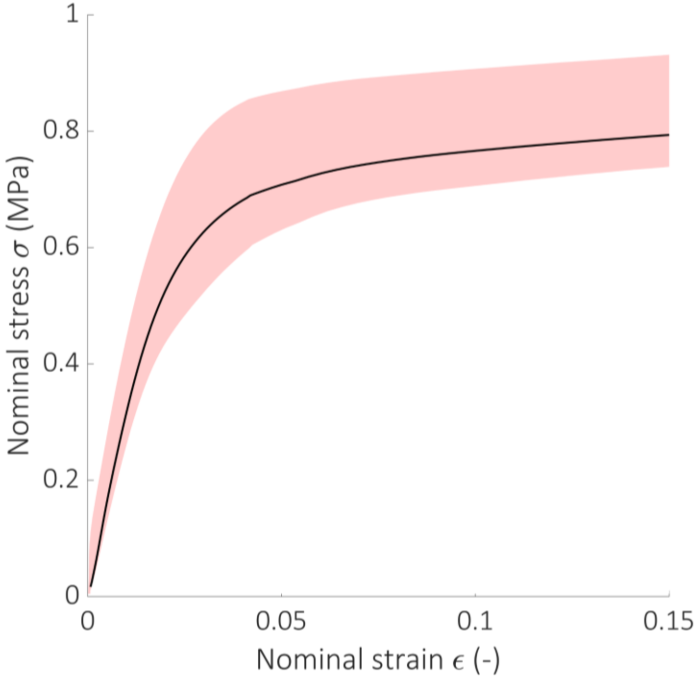
Local measurement of strain in the middle of the sample.



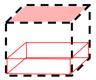


Digital Image Correlation (DIC) camera

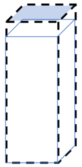
Strain measured by pixel displacement from a referent image.



Elastic modulus: calculated from the slope of the elastic region of the nominal strain-stress curve



E = 19.7 ± 5.1 ^{a} (MPa) E = Non measurable E = 30.8 ± 4.2 ^{b} (MPa)



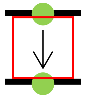
E = 23.0 ± 1.1 $^{\alpha}$ (MPa) E = 30.1 ± 3.7 $^{\beta}$ (MPa) E = 24.9 ± 1.6 $^{\alpha}$ (MPa)

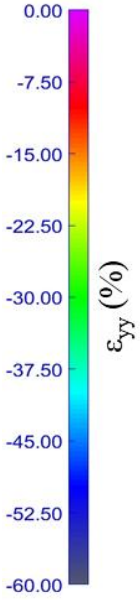
Regardless of the device used, the elastic modulus of cork remains in the same order of magnitude

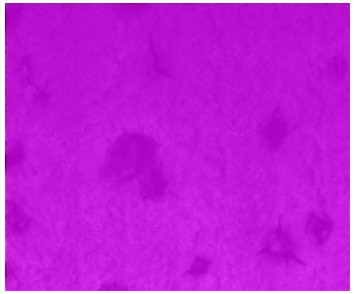
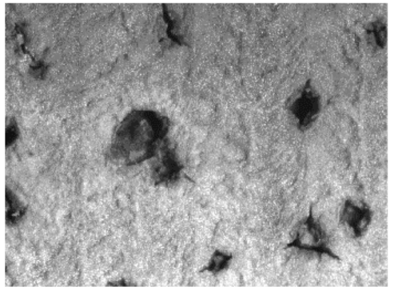
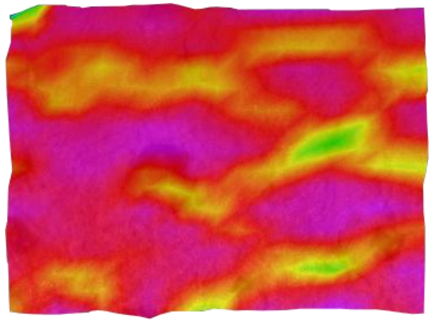
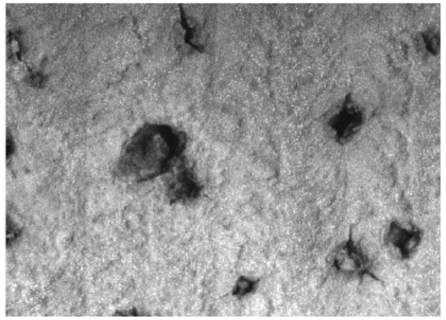
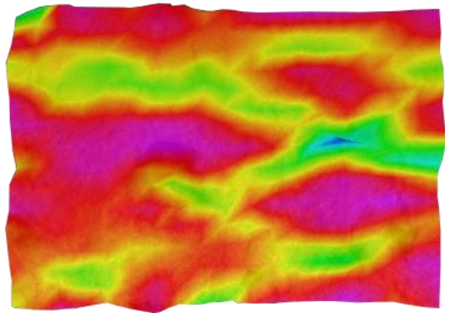
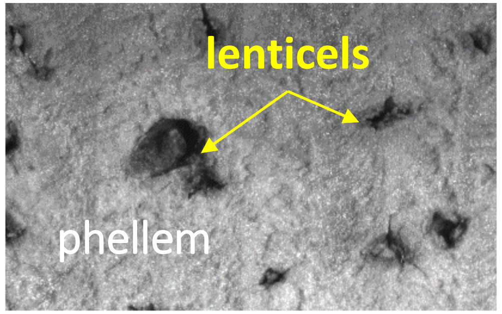
*$^{a,\,b}$ and $^{\alpha,\,\beta}$ *Statistics: One-way ANOVA ($p < 0.05$)*

QS: contribution of lenticels to the mechanical properties of cork in compression

DIC performs a strain field measurement of a sample surface by measuring the displacement of pixels in digital images after deformation.





Strain applied to the cork cube	Strain field measured on the cork surface (ε_{YY})	DIC image	Lenticels proportion (%)
0%			3.4
5%			2.6
15%			2.2

UFreckles V 2.0

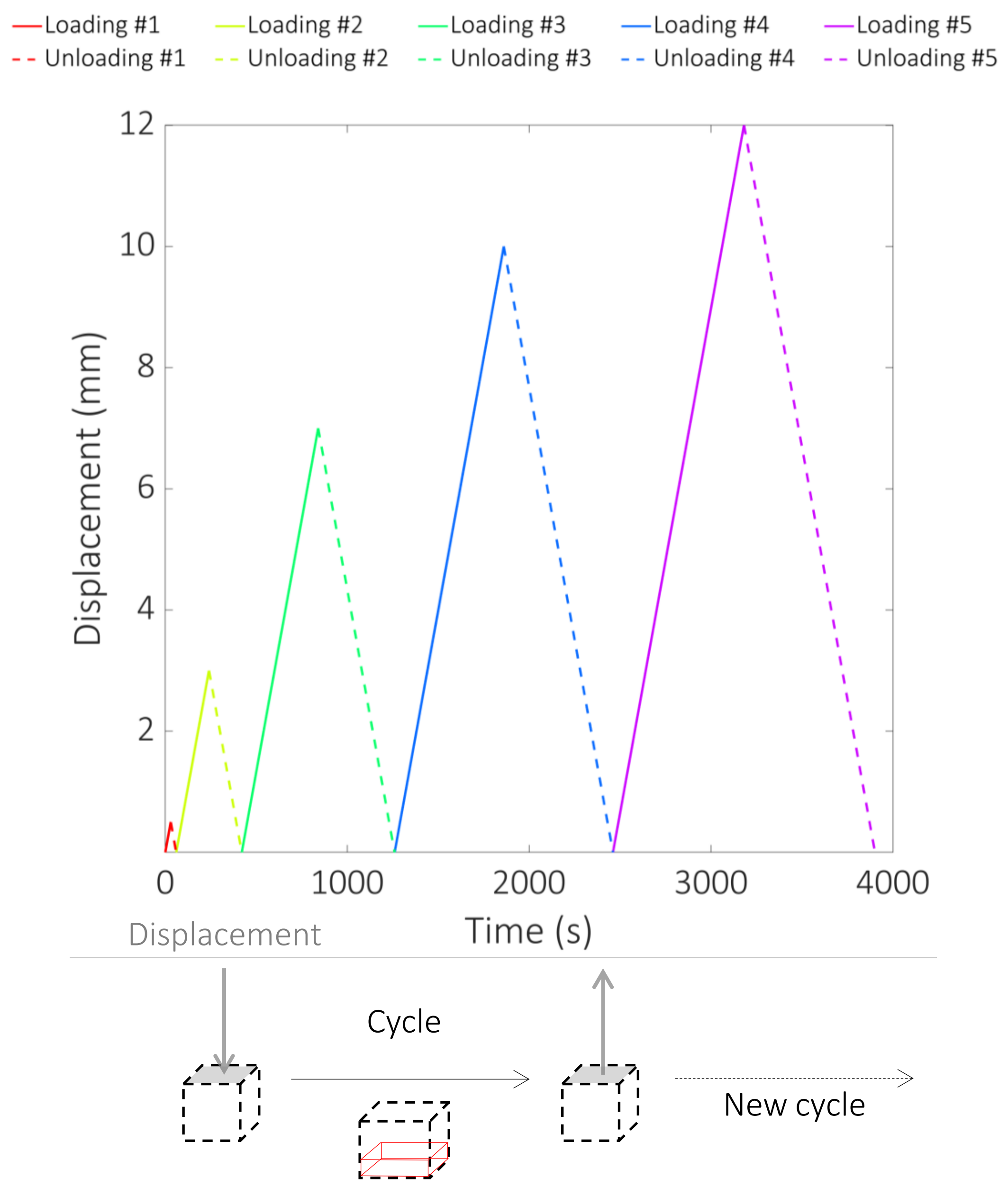
Heterogeneous strain distribution.

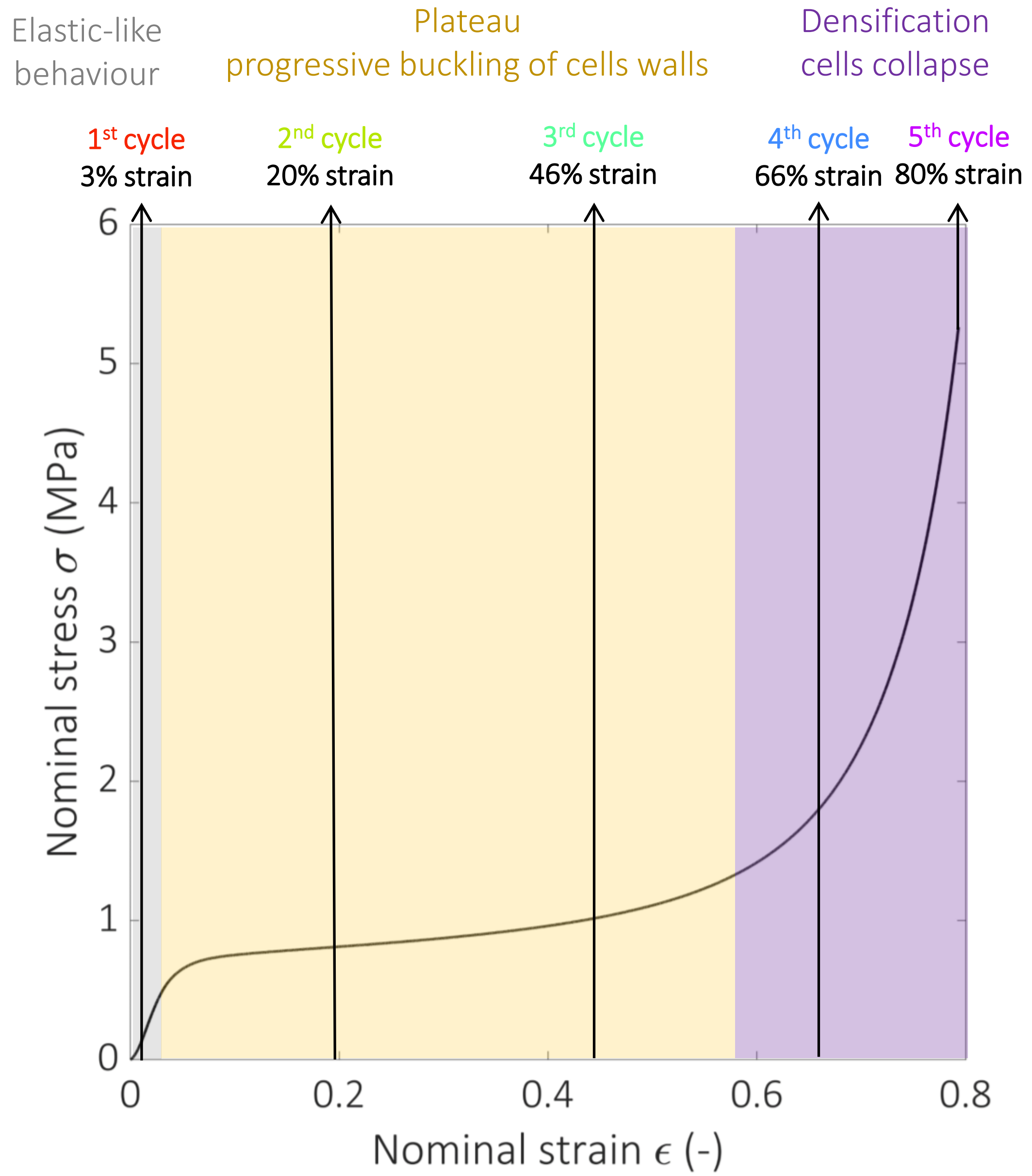
Lead to consider cork as composite material from the mechanical behaviour perspective.

Sasso et al. (2018) Application of DIC to static and dynamic testing of agglomerated cork material.

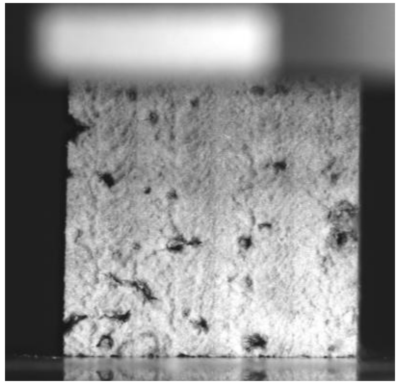
Le Barbenchon, et al. (2019) Multi-scale foam : 3D structure/compressive behaviour relationship of agglomerated cork.

PRL: Response of the cork material to Progressive Repeated Loading cycles





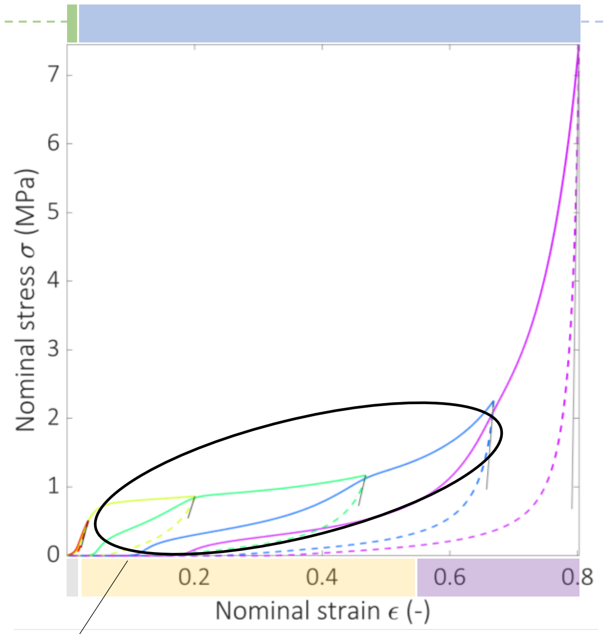
Cork subjected to small deformation



Nominal stress $\sigma_n = \frac{F}{A_0}$

Initial section of the sample

Nominal strain $\epsilon_n = \frac{L-L_0}{L_0}$

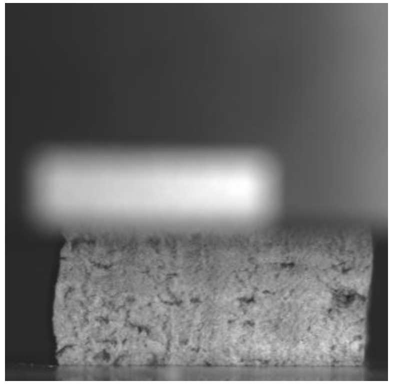


Elastic-like behaviour

Densification cells collapse

Plateau progressive buckling of cells walls

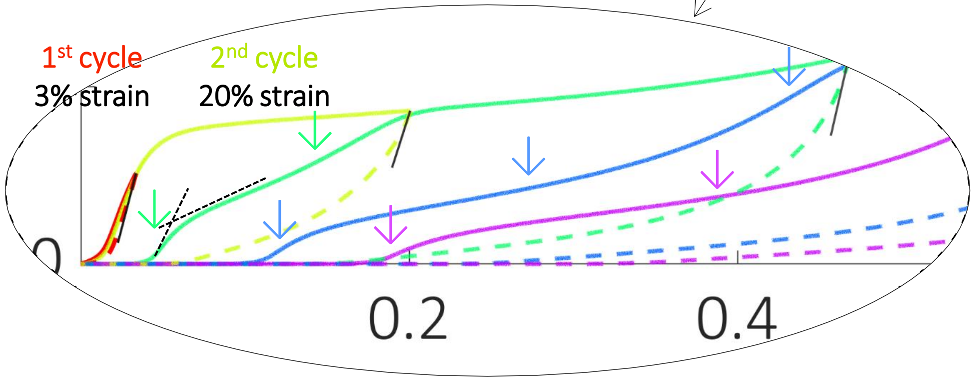
Cork subjected to high deformation



True stress $\sigma = \frac{F}{A} = \frac{F}{A_0} \cdot \frac{L}{L_o} = \sigma_n \cdot (1 + \epsilon_n)$

Instantaneous cross-sectional area of the sample

True strain $\epsilon = ln(1 + \epsilon_n)$



3rd cycle 46% strain

4th cycle 66% strain

5th cycle 80% strain

Which slope consider for the elastic modulus ?

From the 2^{nd} to the 5^{th} loading cycles different slopes are observed → modification in the material structure.

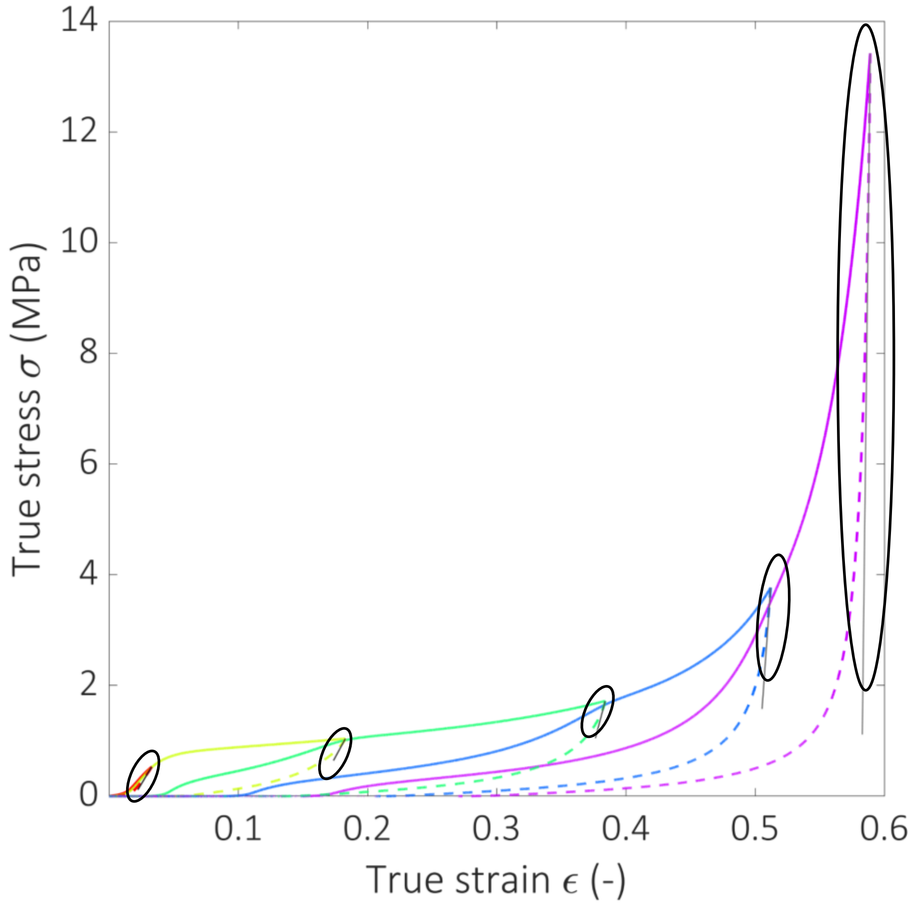
The tangent modulus is defined as the value of the tangent at the point of discharge

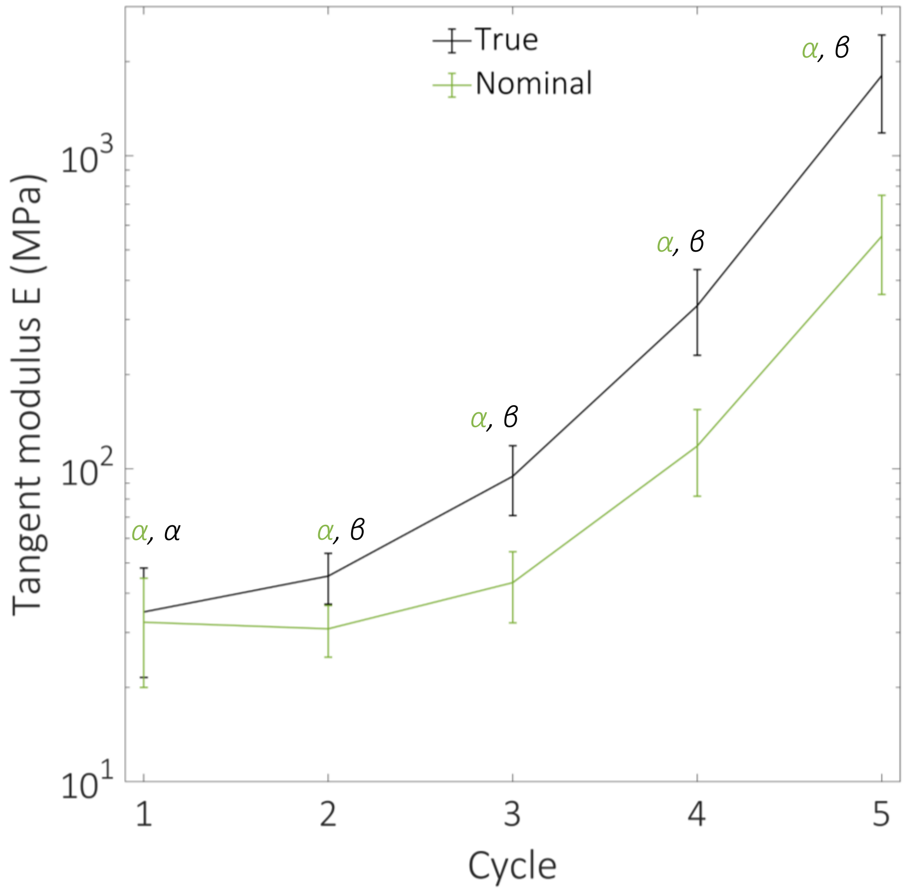
↓

3rd degree polynomial interpolation

↓

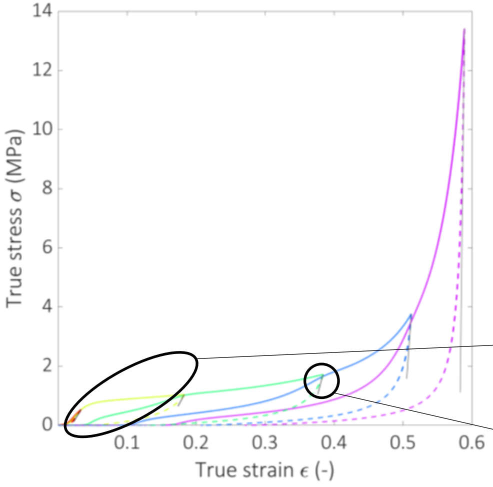
Derivative of the interpolated function



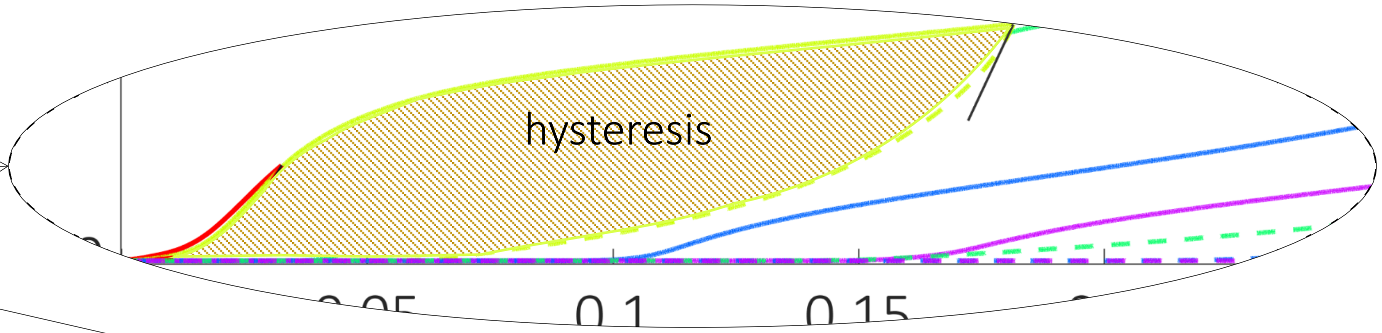


*$^{\alpha, \beta}$: *Statistics: One-way ANOVA ($p < 0.05$)*

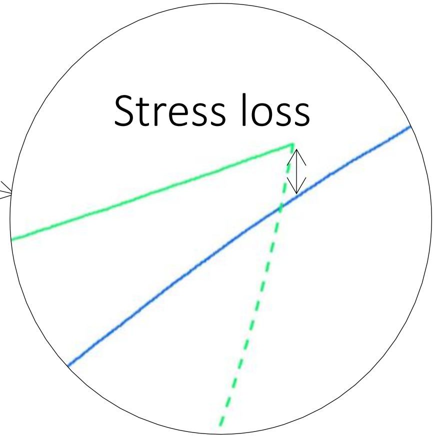
Stiffening of cork material at discharge → progressive cell wall contact



Reversible modifications in the cork structure (1st and 2nd cycles)
Irreversible modification (from 3rd to 5th cycles) after the application of high strain (up to 60 % true strain).

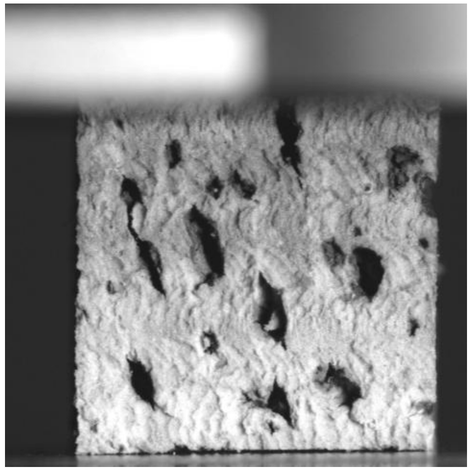


Between the loading and unloading part of the 2nd, 3rd,4th, 5th cycles

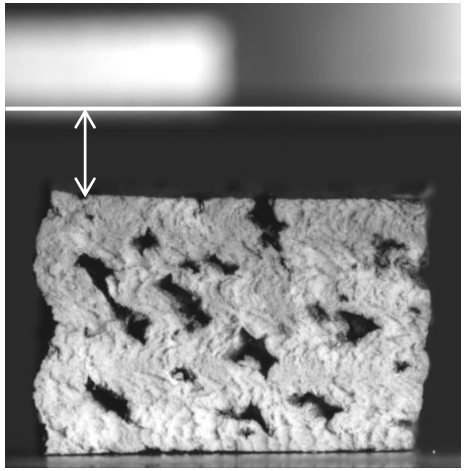


Between cycles:
2nd and 3rd → 3 %
3rd and 4th → 4 %
4th and 5th → 7 %

Crosshead – before PRL test



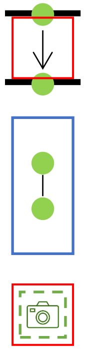
Following 5 cycles



Partial dimensional recovery → cellular damaged material
Time dependent behaviour → Viscous component characterized by several relaxation times

Conclusions

Quasi-static compression test

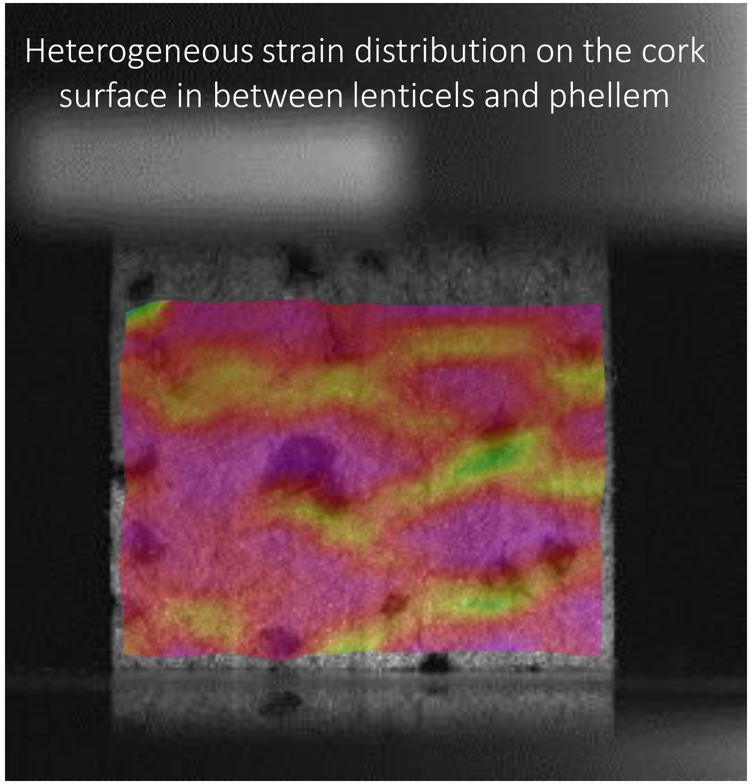


crosshead

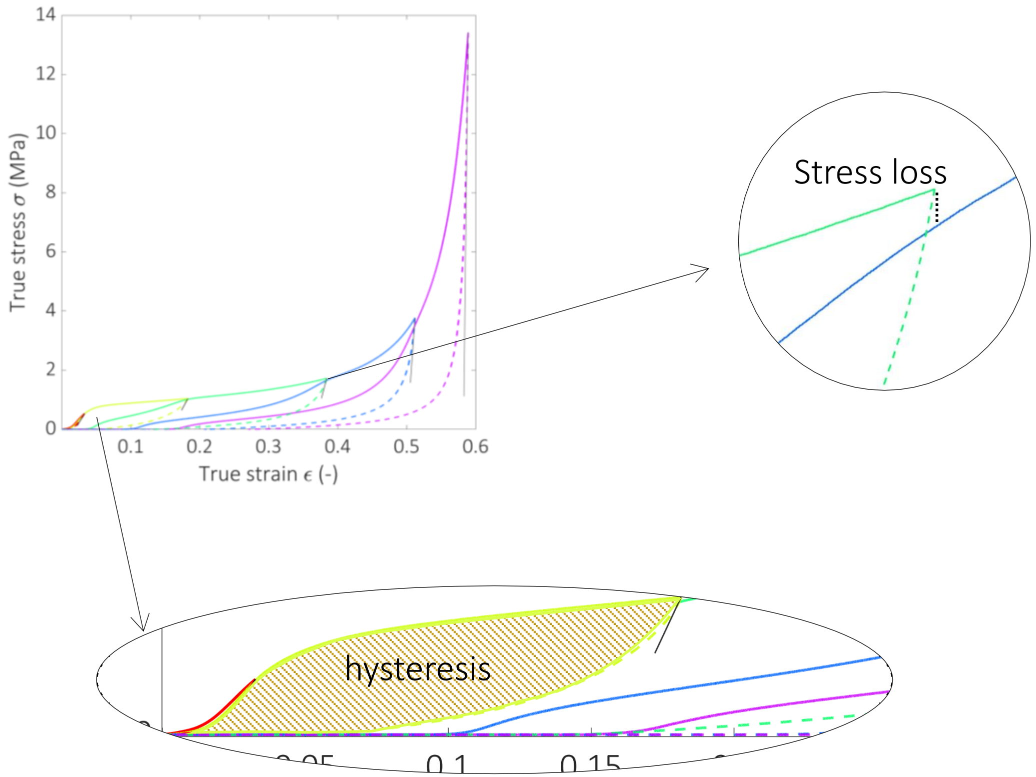
extensometer

DIC

E = 20 – 30 MPa
same order of magnitude



Progressive Repeated Loading cycles



Cork exhibit a **time dependant behaviour**.
The **viscous component** is characterised by several **relaxation times**.

Thanks for your attention