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Numerical yield surface determination of cemented rocks from digital microstructures

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Introduction

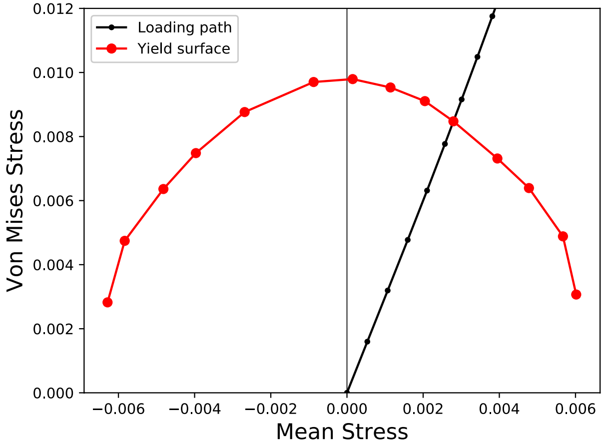
Digital rock physics: geomechanics

- **Started** with hydraulic properties (permeability)

- **Extending now** to mechanics with elastic properties

- Plastic properties should be the **new target** of homogenisation

This contribution presents the transition step, upscaling for the limit of elasticity (yield surface)



Introduction

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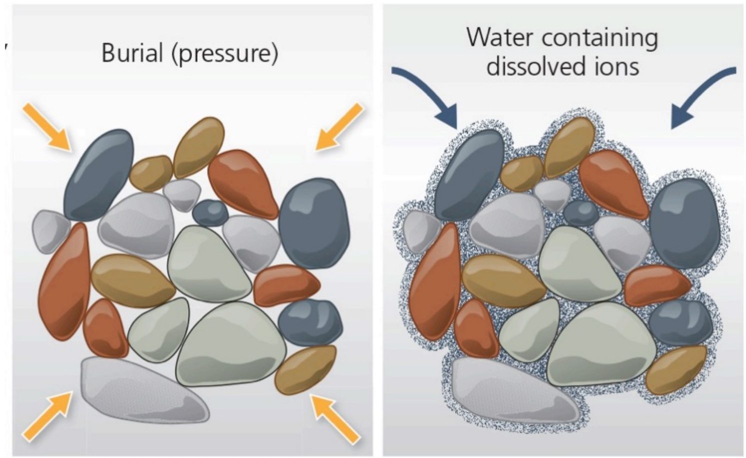
Cementation

Mineral matter precipitates at the pore-grain interface, during diagenesis

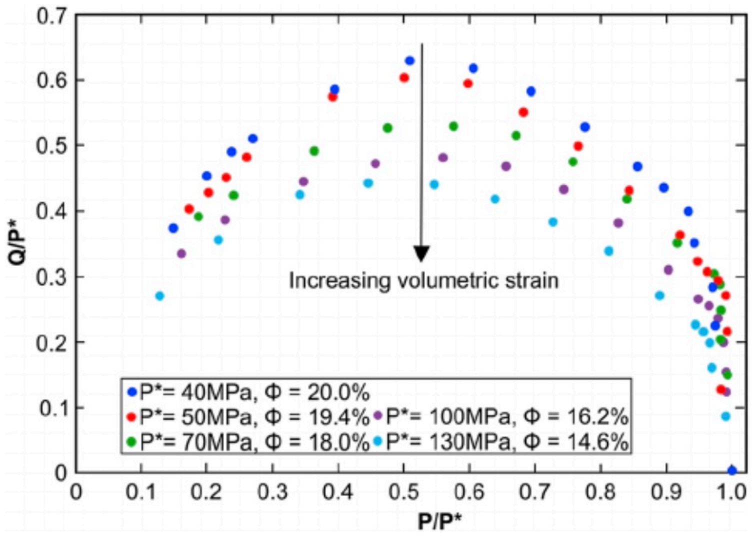


(b) Compaction (c) Cementation

Known to increase strength by creating a cohesion between the grains

⚠ Depends heavily on the microstructure

➢ No quantitative law between cementation and strength



Bedford et al. (2019) High-resolution mapping of yield curve shape and evolution for high-porosity sandstone. JGR

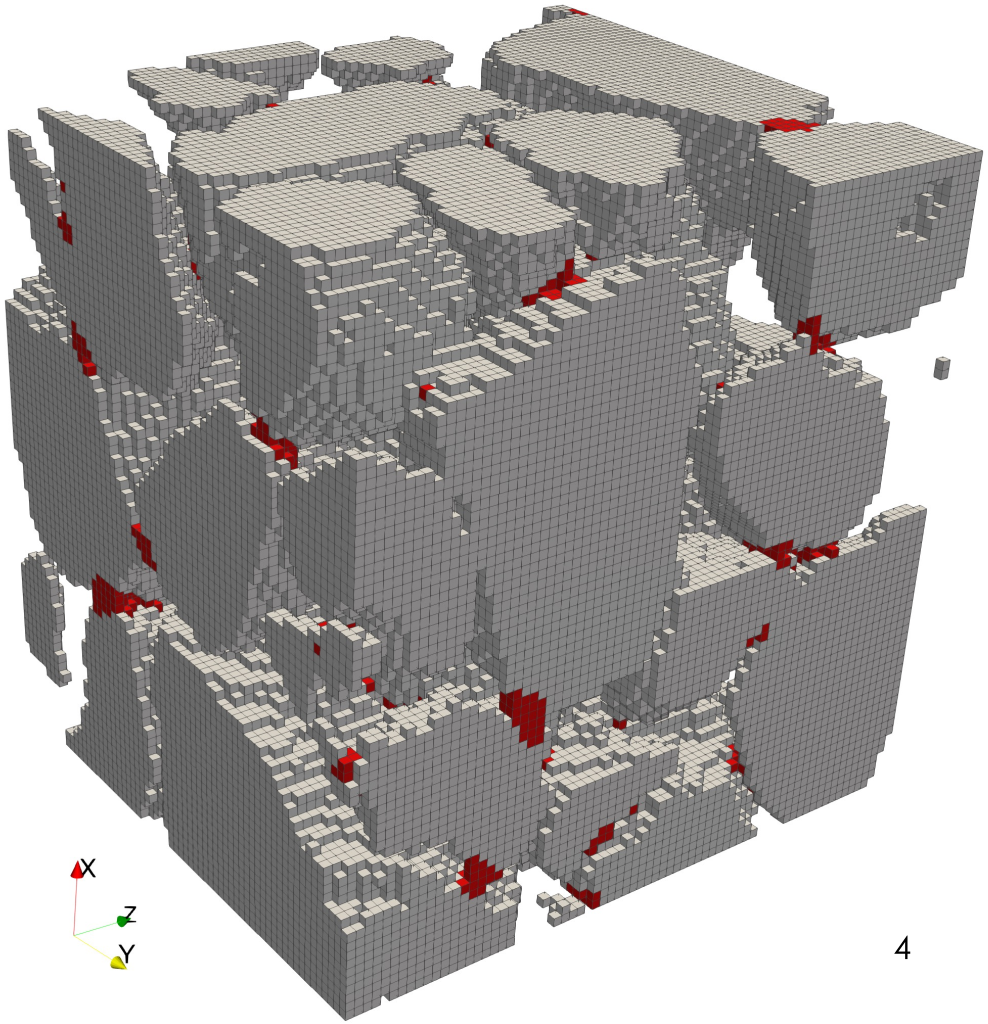
Numerical set-up

Model

Digital rock samples are reconstructed from a stack of 2D segmented microCT scans[1]

Mechanical loading solved with semi-discrete finite element method[1]

J2 plasticity assumed for the grain contacts



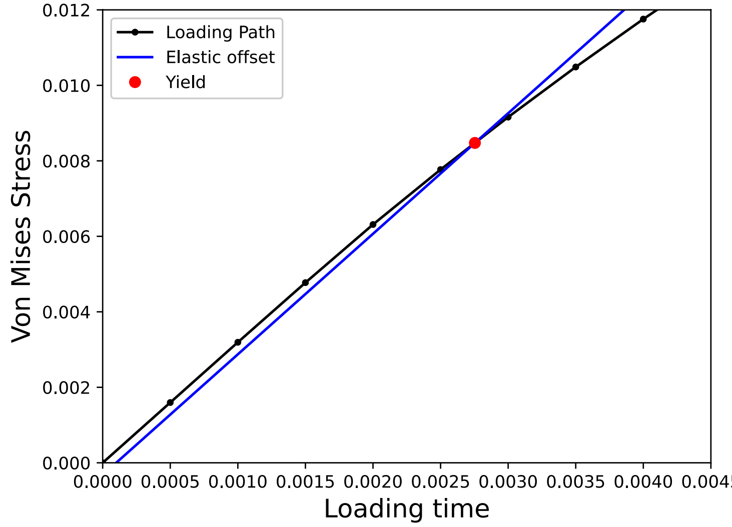
1. Lesueur et al. (2017) Modelling fluid-microstructure interaction on elasto-visco-plastic digital rocks. GETE

Homogenisation scheme

Proper homogenisation needs to respect the Hill-Mandel condition[1]

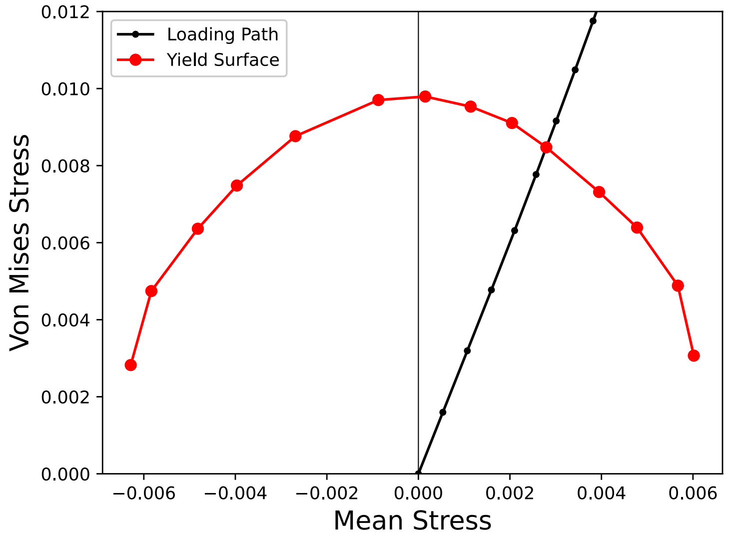
$$\overline{\sigma}_{ij}\overline{\varepsilon}_{ij} = \frac{1-\phi}{|\Omega|}\int_{\Omega}\sigma_{ij}\varepsilon_{ij}dV$$

Obtained by imposing homogeneous deformation rate $\overline{\varepsilon}_{ij} = D_{ij}t$



<u>Yield surface computation:</u>

1. Simulate loading until plasticity is reached
2. Yield stress measured with the offset method
   - One point of the yield surface
3. Repeat for different stress paths



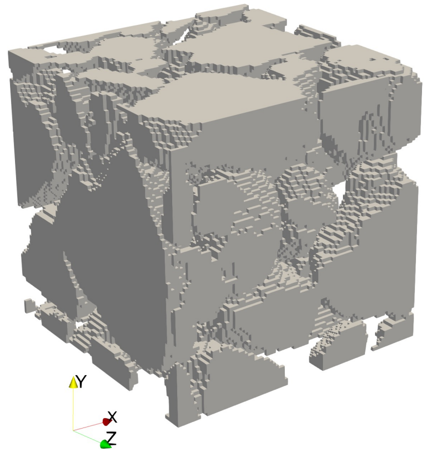
1. Hill, R. (1963). Elastic properties of reinforced solids: Some theoretical principles. J. Mech. Phys. Solids

REV convergence

Quantitative results obtained on Representative Elementary Volume (REV)

- Obtained when results converge

⚠ Qualitative behaviour can still be interpreted from statistical REV



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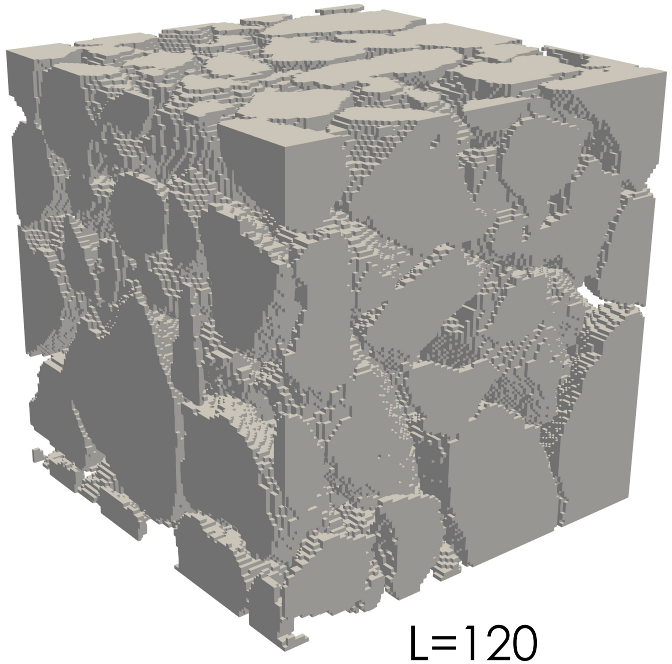

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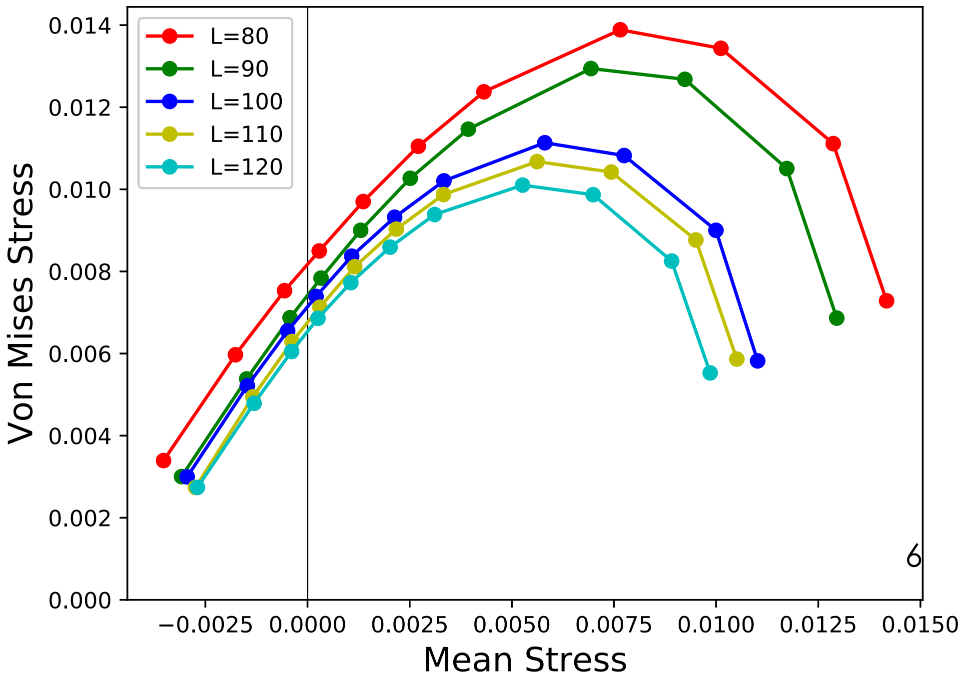


Cementation

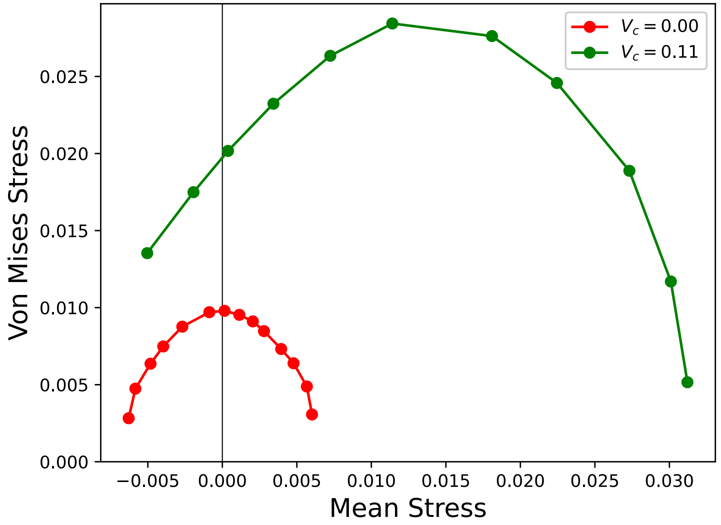
Assumed homogeneous

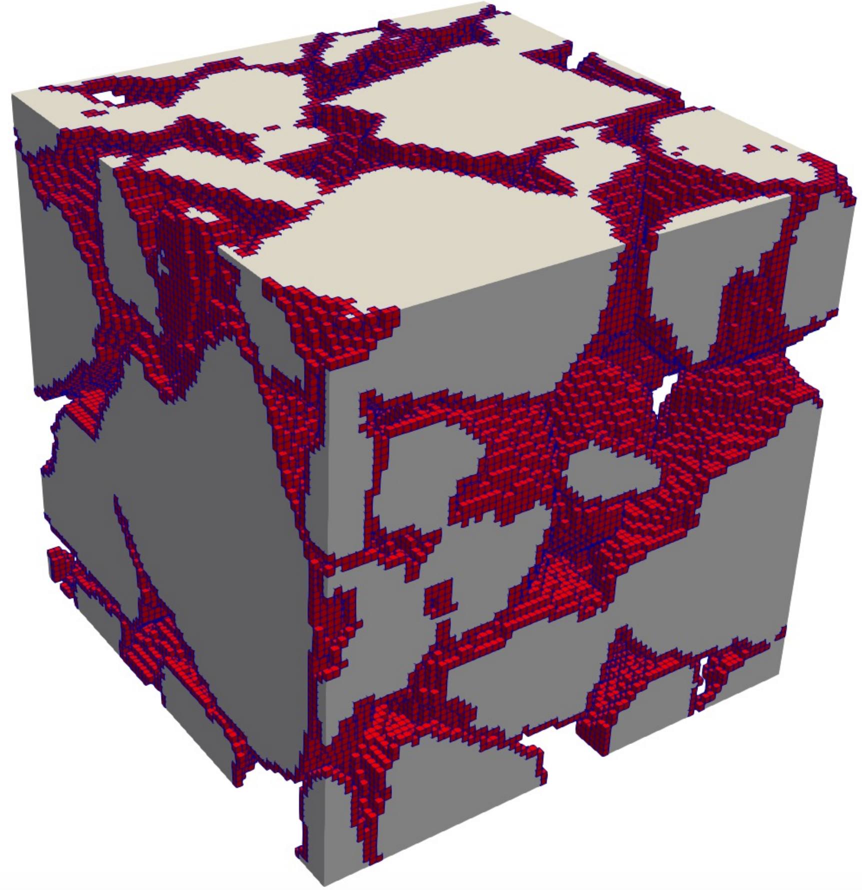
Implemented as an erosion algorithm[1]

- Adds layers of elements at the pore-grain interface

New layers corresponding to the cement phase are attributed different properties

- Drucker-Prager yield for pressure sensitivity





1. Lesueur et al. (2020) Three-scale multiphysics finite element framework (FE^3) modelling fault reactivation. CMAME

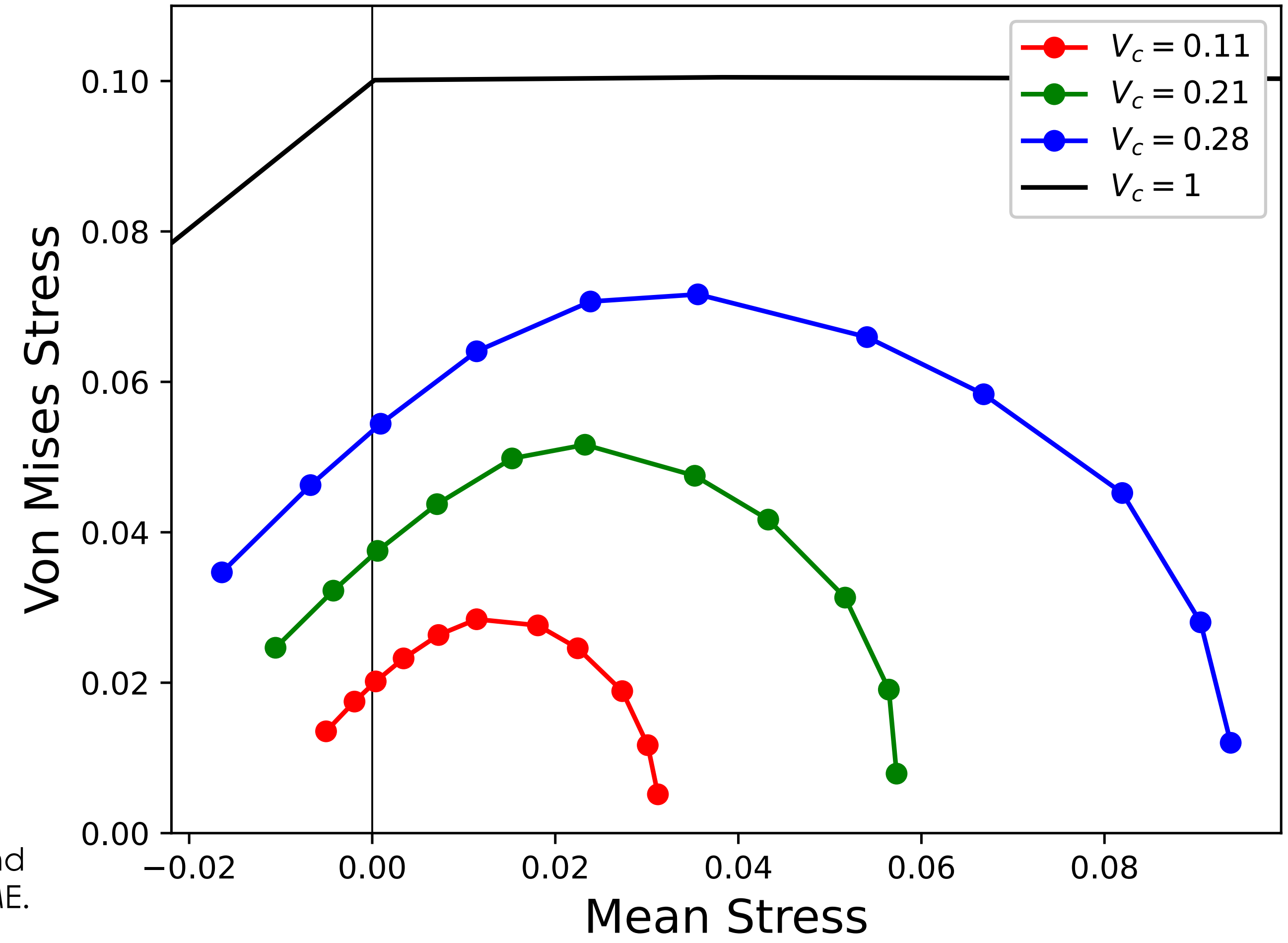
Parametric study

Cementation Volume

Strength increases with cementation volume, as expected

At full cementation, surface follows the minimum of the model input

Yield surface stretches open towards null porosity[1]



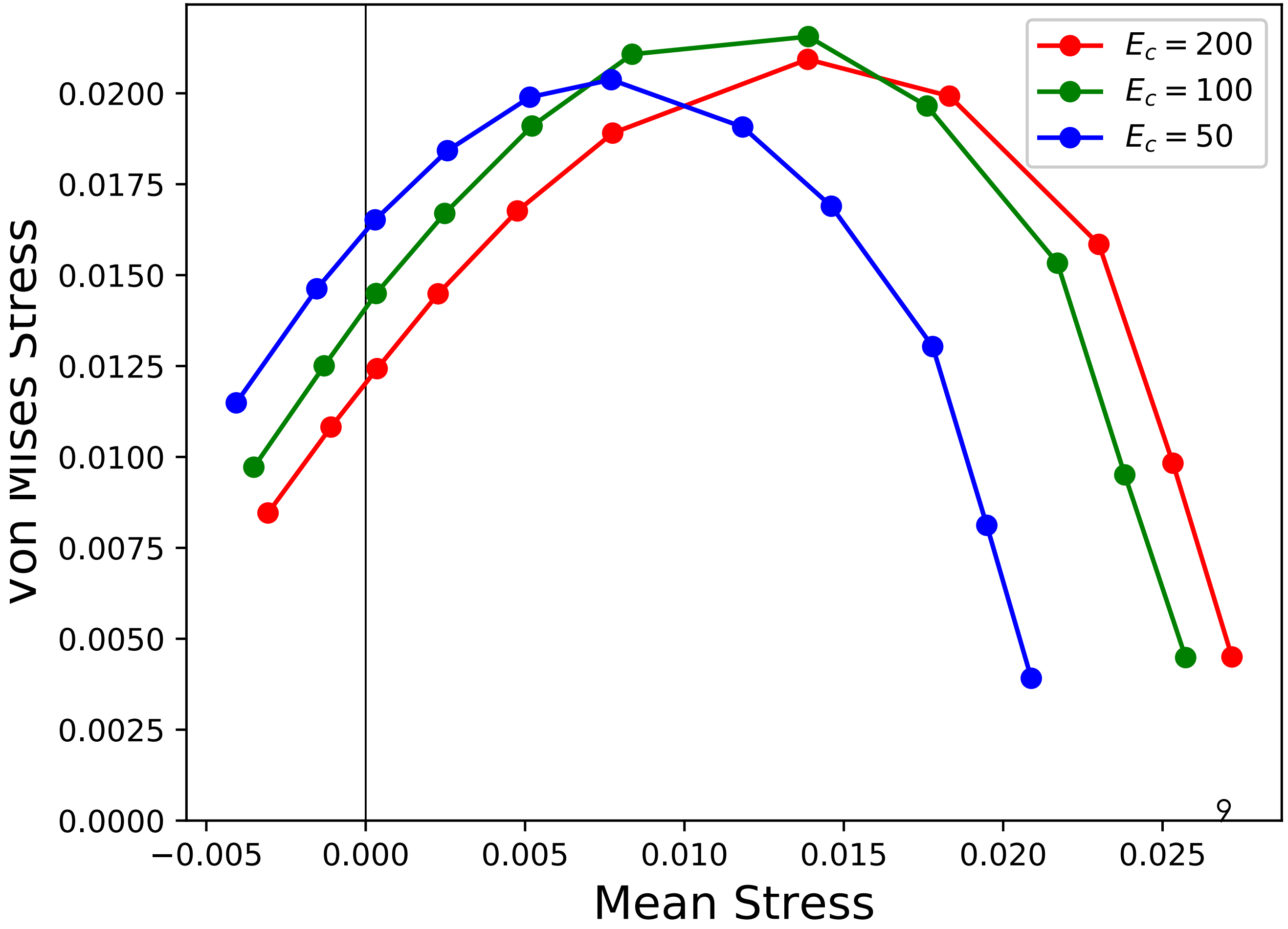
1. Gurson (1977) Continuum Theory of Ductile Rupture by Void Nucleation and Growth: Part I—Yield Criteria and Flow Rules for Porous Ductile Media. ASME. J. Eng. Mater. Technol.

Parametric study

Elastic properties: Cement Young's modulus

Yield surface does not change shape

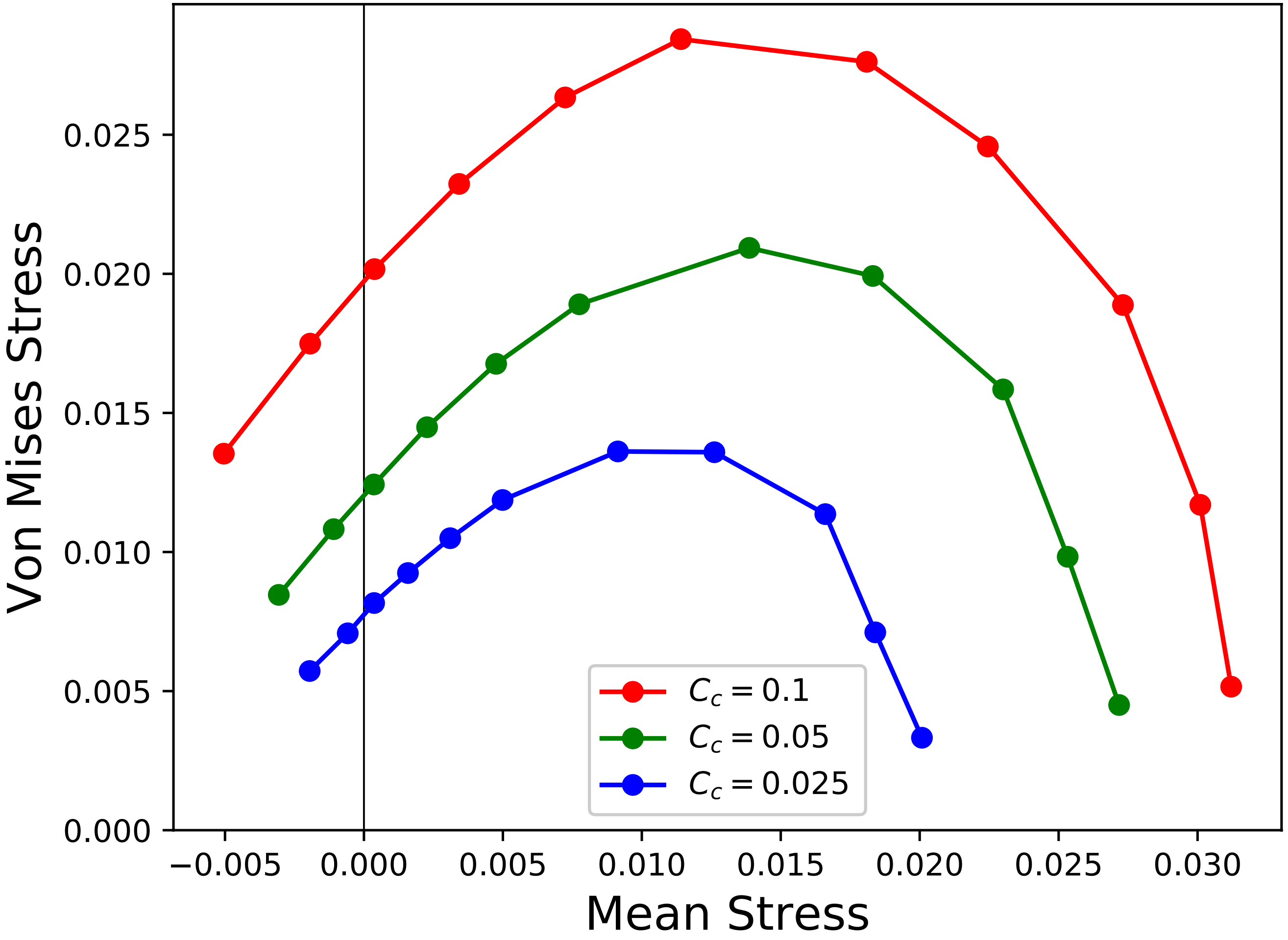
Mostly translated in mean stress



Parametric study

Plastic properties: Cohesion

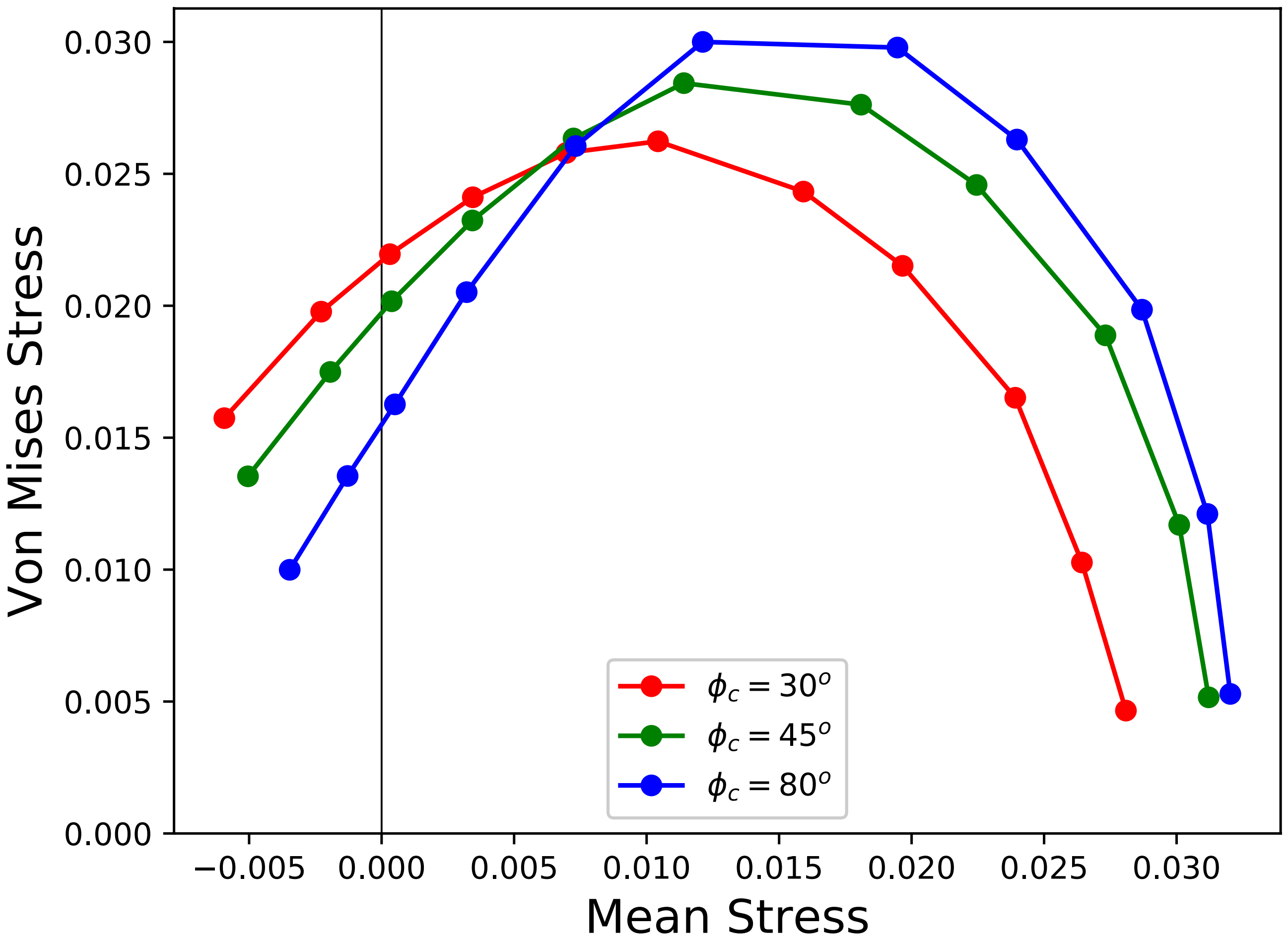
Strength increases with cement's cohesion



Parametric study

Plastic properties: Friction

Friction increases with cement's cohesion



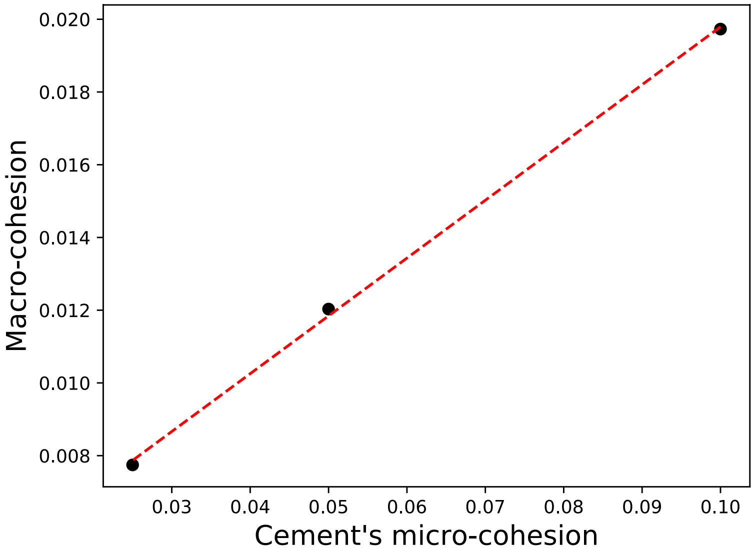
Results interpretation

Frictional part

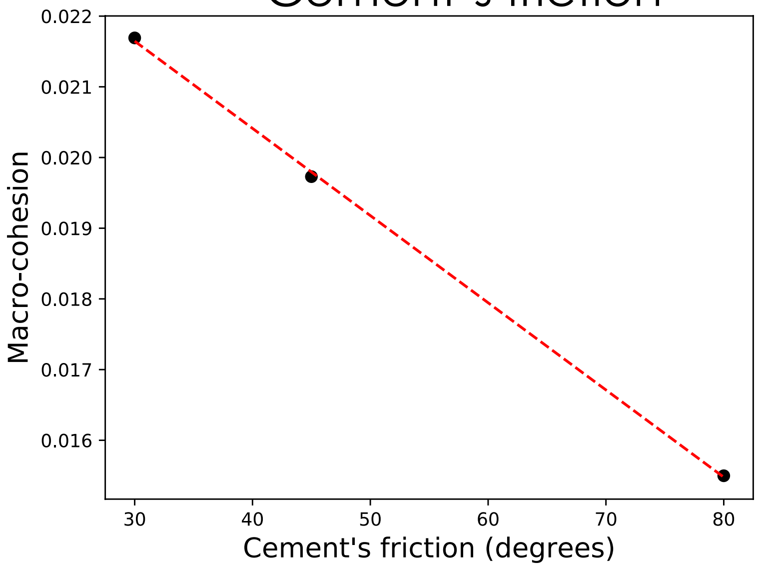
Quantitative analysis show that

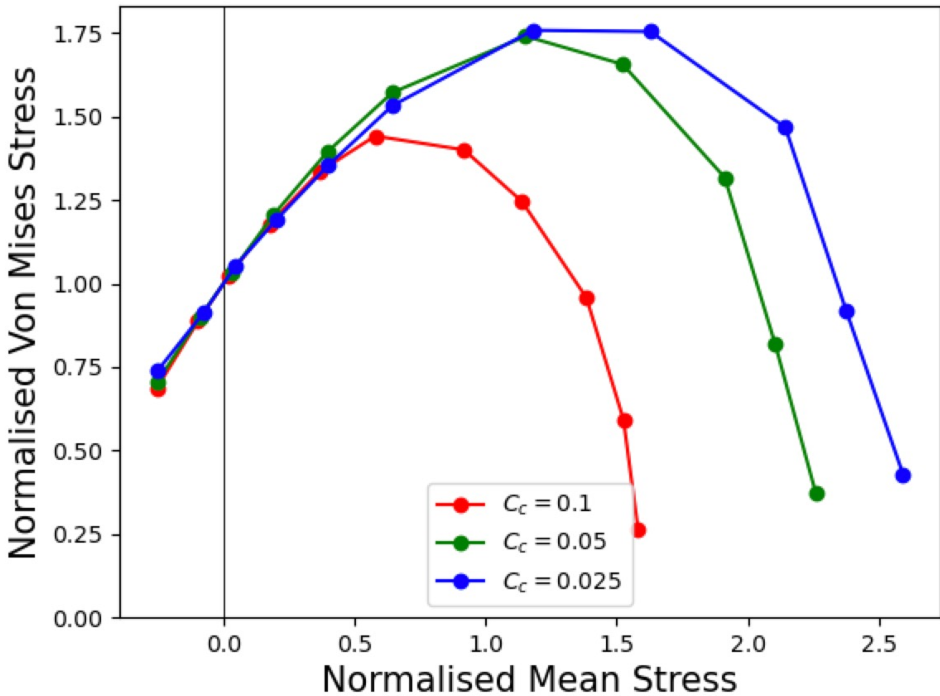
- Cement's cohesion and friction have a linear influence on the macro-cohesion
- The macro-friction is unchanged

Cement's cohesion



Cement's friction



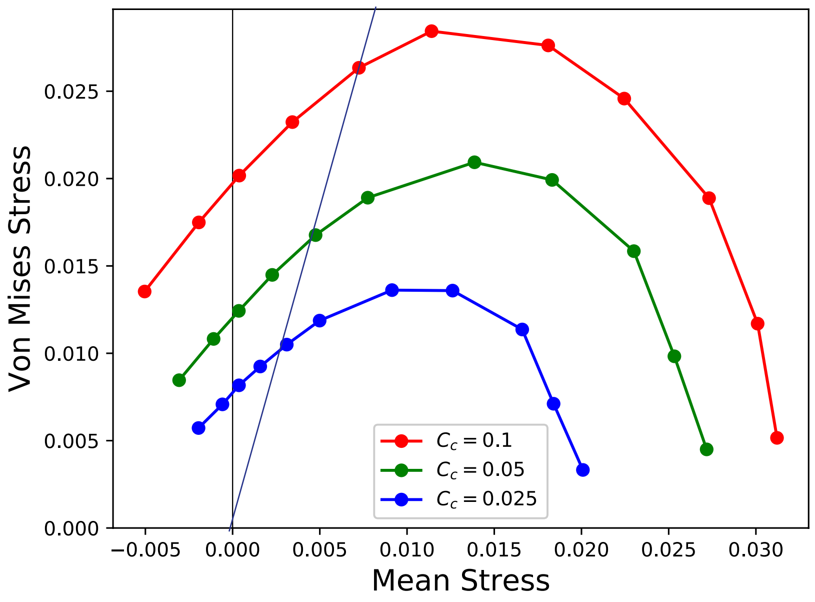


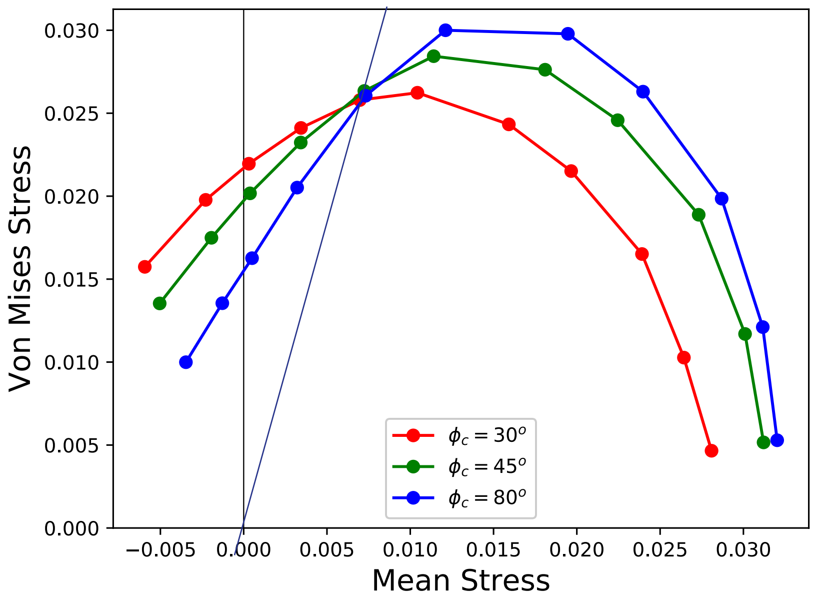
Results interpretation

Critical state line[1]

Results show clear change of behaviour at angle of ~70deg

➢ Transition from frictional part to compaction cap





1. Wood (1990). Soil behaviour and critical state soil mechanics. Cambridge university press.

Results interpretation

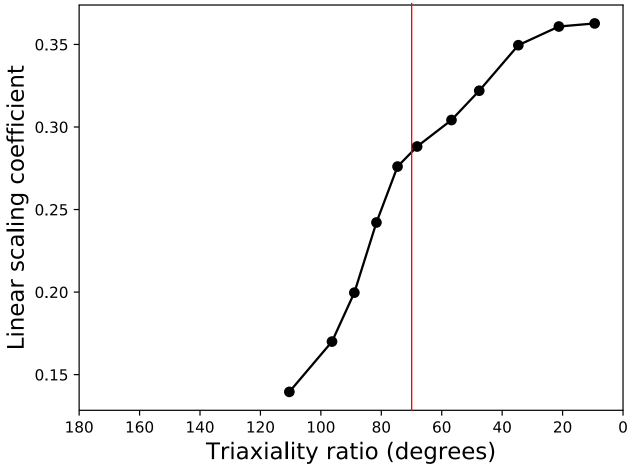
Critical state line[1]

Results show clear change of behaviour at angle of ~70deg

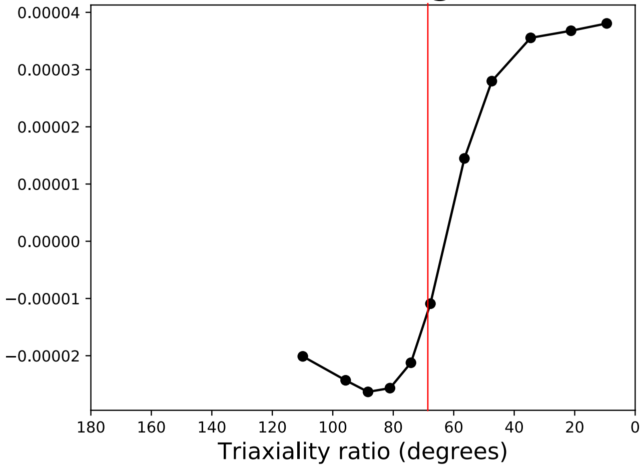
- ➢ Transition from frictional part to compaction cap

Quantified by observing the variation of the slope of the radial yield stress evolution per triaxial ratio angle

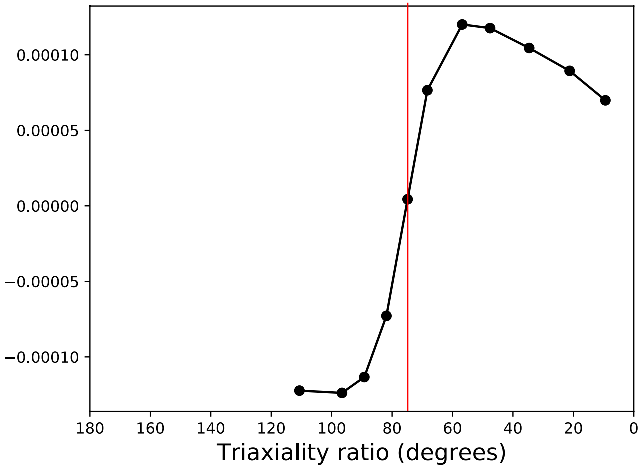
Cementation volume



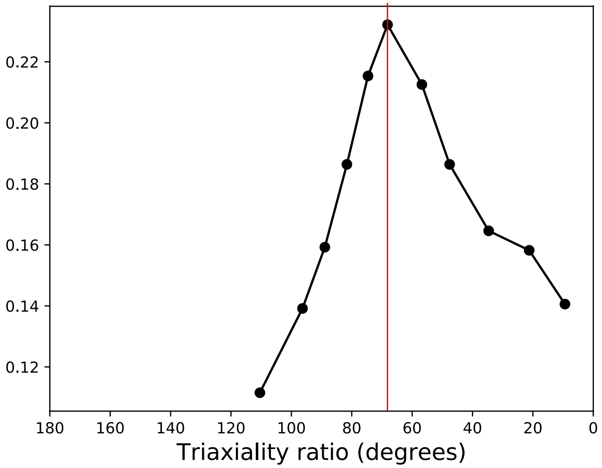
Cement's Young modulus



Cement's cohesion



Cement's friction



Results interpretation

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Compaction cap

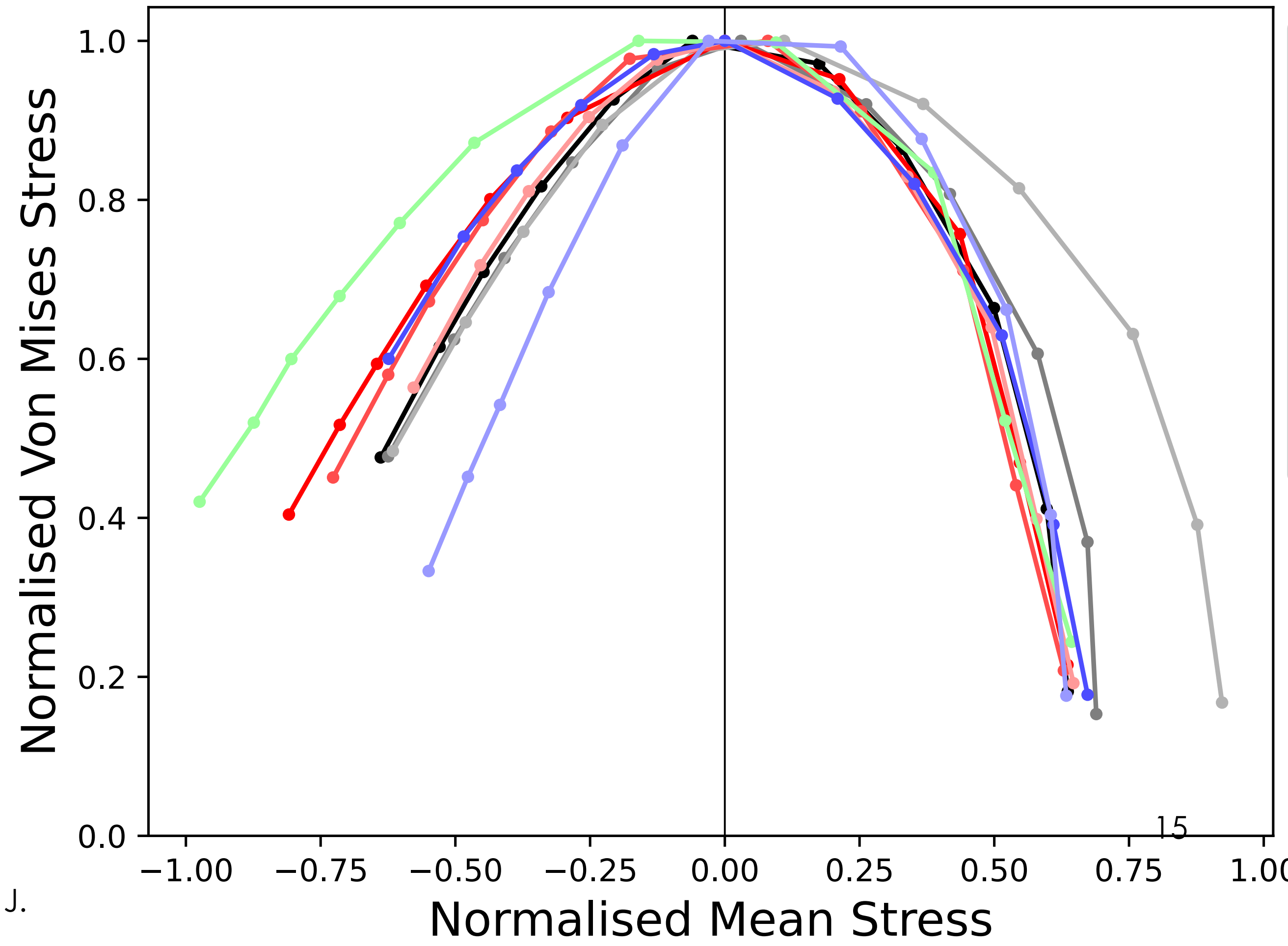
Normalisation of all the realisations at the peak stress show that the compaction cap always has the same shape

Except for cementation volume,

That opens up the envelope

Compaction cap depends only on the microstructure[1]

➢ Only changes with cementation volume



1. Gurson (1977) Continuum Theory of Ductile Rupture by Void Nucleation and Growth: Part I—Yield Criteria and Flow Rules for Porous Ductile Media. ASME. J. Eng. Mater. Technol.

Model & experiments fit

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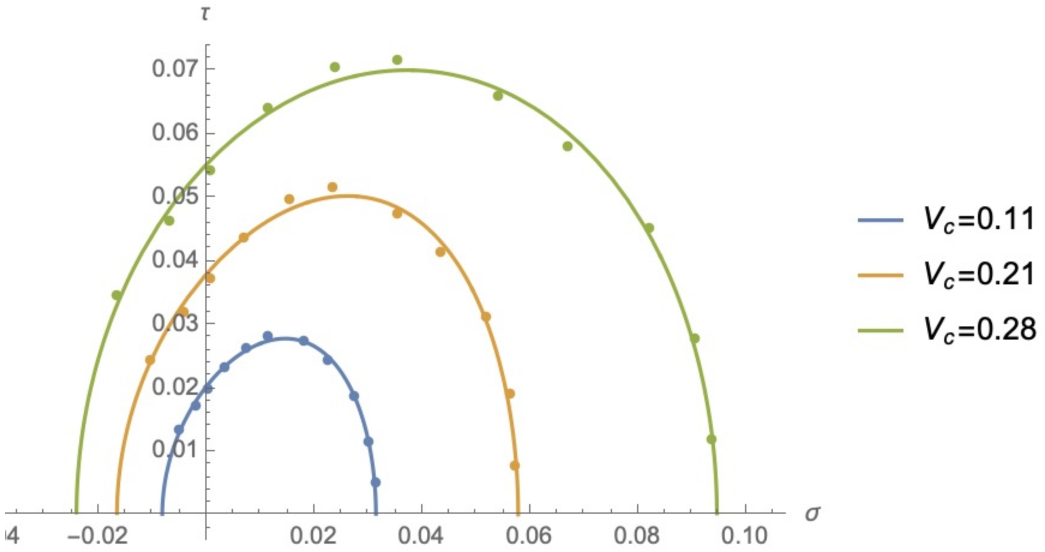
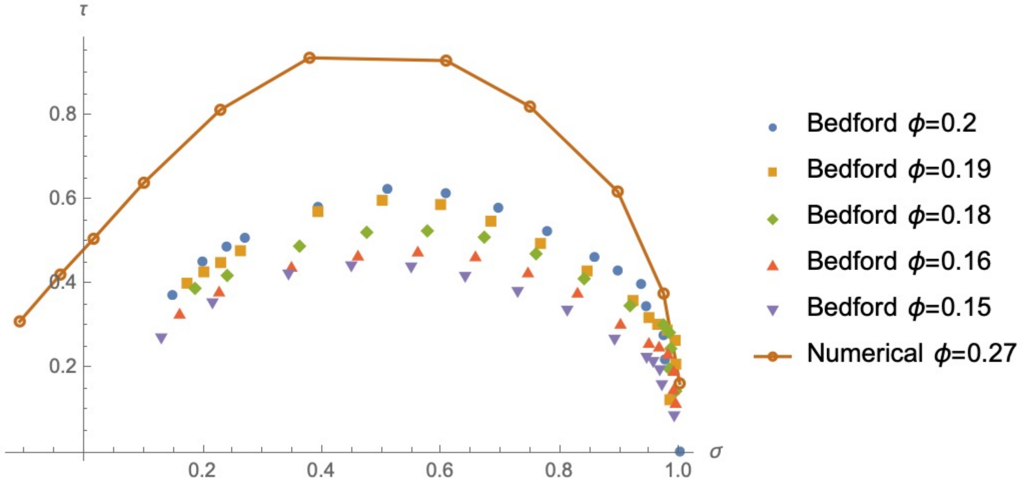
Samudio yield surface model[1]:

- Asymmetric Cam-Clay model, unifying frictional part and compaction cap
- ➢ Fits our data sets



Comparison with Bedford's normalised experimental data[2]:

Coherence of shape and scale relative to porosity



1. Samudio (2017) Modelling of an oil well cement paste from early age to hardened state : hydration kinetics and poromechanical behaviour. PhD thesis - Université Paris-Est
2. Bedford et al. (2019) High-resolution mapping of yield curve shape and evolution for high-porosity sandstone. JGR

Conclusions

Method to homogenise yield surface of digital rock and look at its evolution with various parameters

- opens the door further to geomechanics in digital rock physics

- Produces similar yield surfaces compared to experimental observations

- Linear relationship of cement's plastic parameters in frictional regime
- Existence of critical state line
- Compaction cap shape solely linked to rock microstructure

Future work: Study the influence of microstructure morphology on the yield surface

Consider pressure solution (stress-dependent cementation)[1]

1. Guével et al. (2020). Viscous phase-field modeling for chemo-mechanical microstructural evolution: application to geomaterials and pressure solution. International Journal of Solids and Structures