Powder flowability at low stresses: ball indentation

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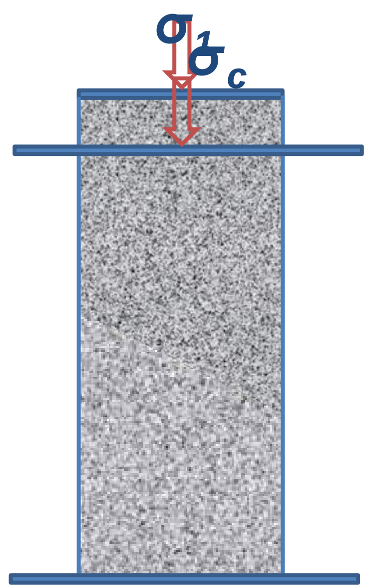
Powder flowability

- Uniaxial compression test



σ_1: pre-consolidation stress

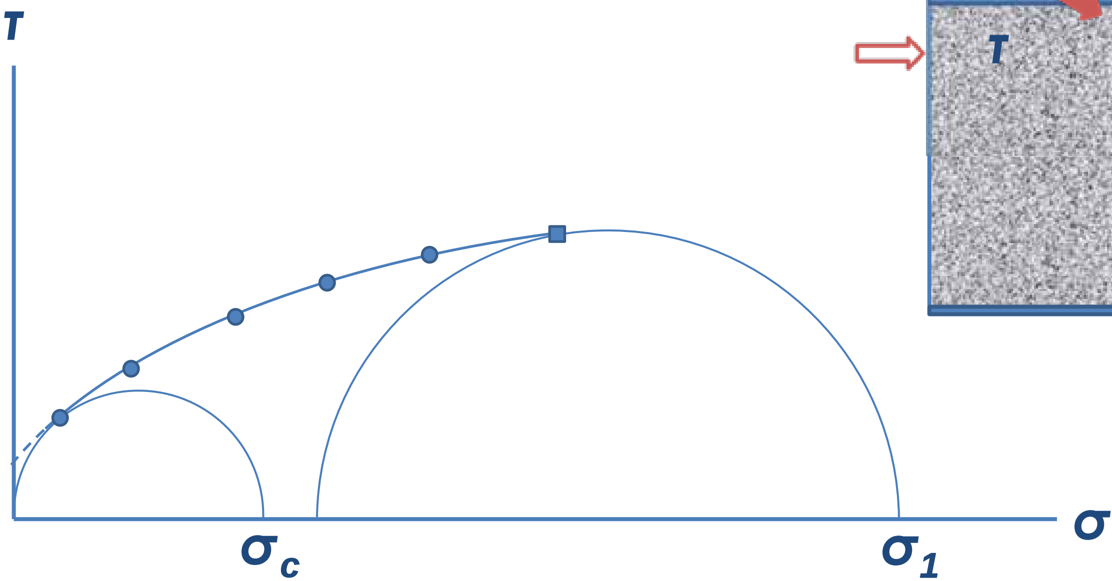
σ_c: unconfined yield stress

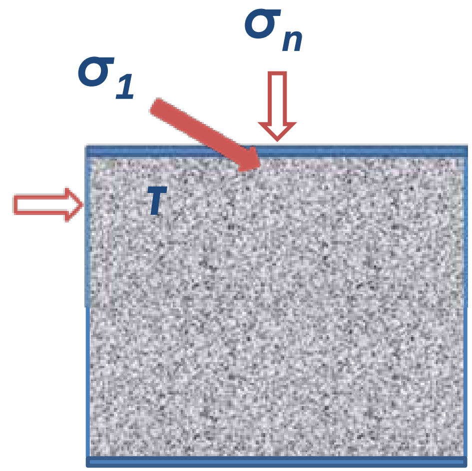
$\frac{\sigma_1}{\sigma_c}$ = flow function, ff_c

[1} Schulze, D., 2007 "Powders and bulk solids: behaviour, characterization, storage and flow", *Springer*

Flowability measurement

- Ø More commonly measured with shear cells



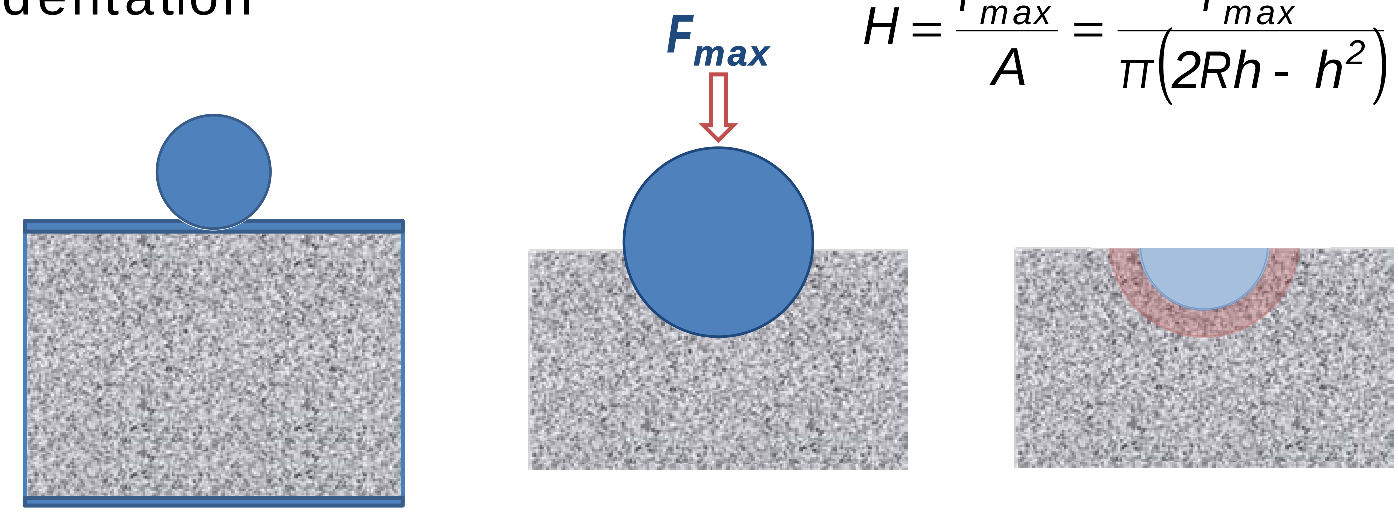


[1} Schulze, D., 2007 “Powders and bulk solids: behaviour, characterization, storage and flow”, *Springer*

Proposed method

- Ball indentation[2]

$$H = \frac{F_{max}}{A} = \frac{F_{max}}{\pi\left(2Rh - h^2\right)}$$



- Elastically deforming region provides additional constraint:

$$H = C.\sigma_c$$

[2] Hassanpour, A., Ghadiri, M., 2007 "Characterisation of flow of loosely compacted cohesive powders by ball indentation", *Particle & Particle Systems Characterization* 24, 117-123

Ball indentation

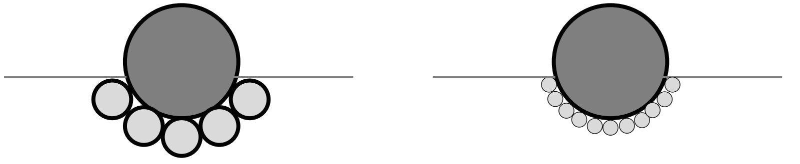
- Routinely used for characterising hardness of continuum solids
  - *C* is known for metals (~3)[3]
  - *C* can be calculated from material properties for organics & polymers[4]

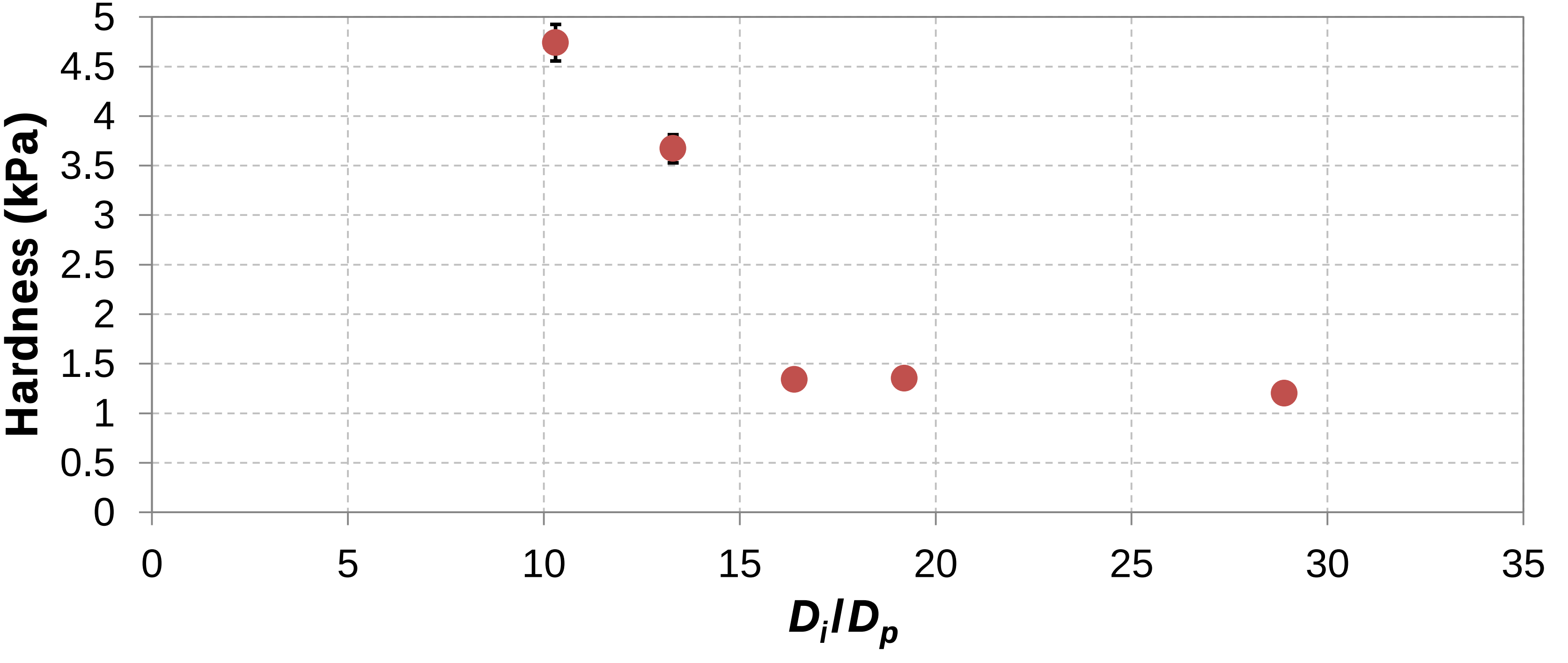
- Indentation procedure has been established[5]:
  - Indenter size to be used for a given particle size
  - Minimum amount of powder needed
    - Bed diameter
    - Bed height
  - To what depth the indent should be made

[3] Tabor, D., 1951 "The hardness of metals", *Clarendon* Press
[4] Johnson, K.L., 1985 "Contact mechanics", *Cambridge University Press*
[5] Zafar, U., Hare, C., Hassanpour, A., Ghadiri, M., 2017 "Ball indentation on powder beds for assessing flowability: Analysis of operation window", *Powder Technology* 310, 300-306.

Indenter size

Minimum:

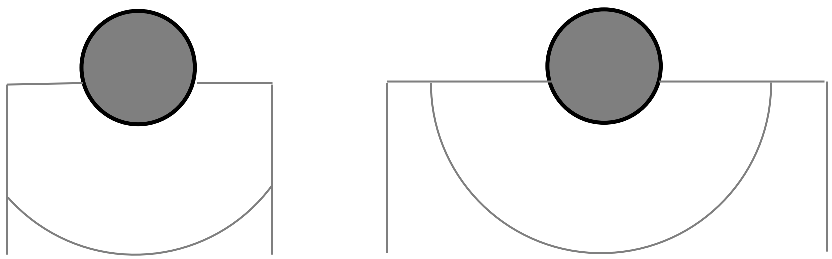


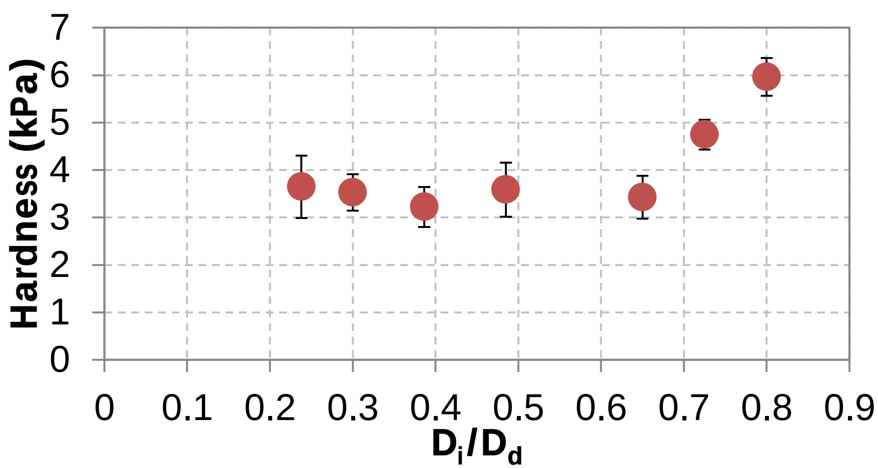


[5] Zafar, U., Hare, C., Hassanpour, A., Ghadiri, M., 2017 “Ball indentation on powder beds for assessing flowability: Analysis of operation window”, *Powder Technology* 310, 300-306.

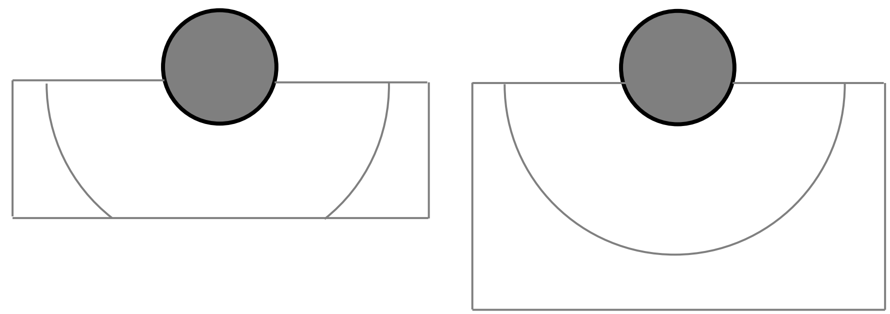
Minimum amount of powder

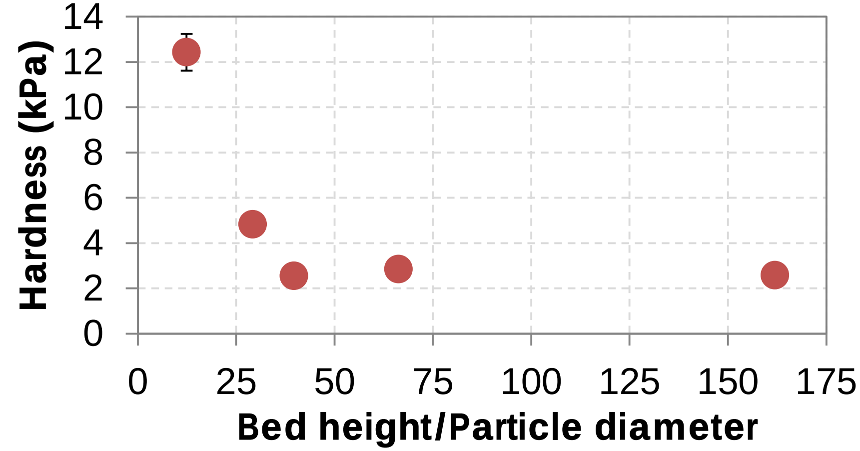
Bed diameter





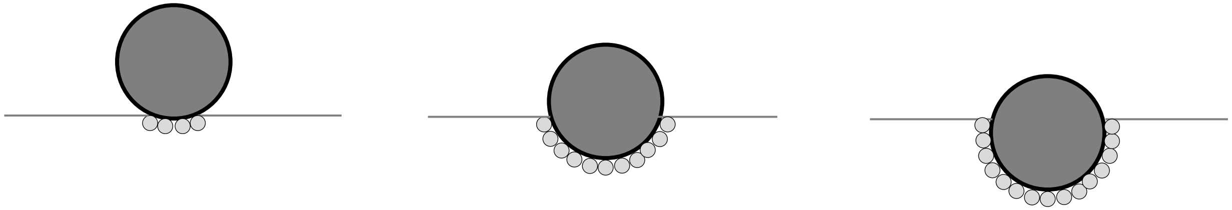
Bed height

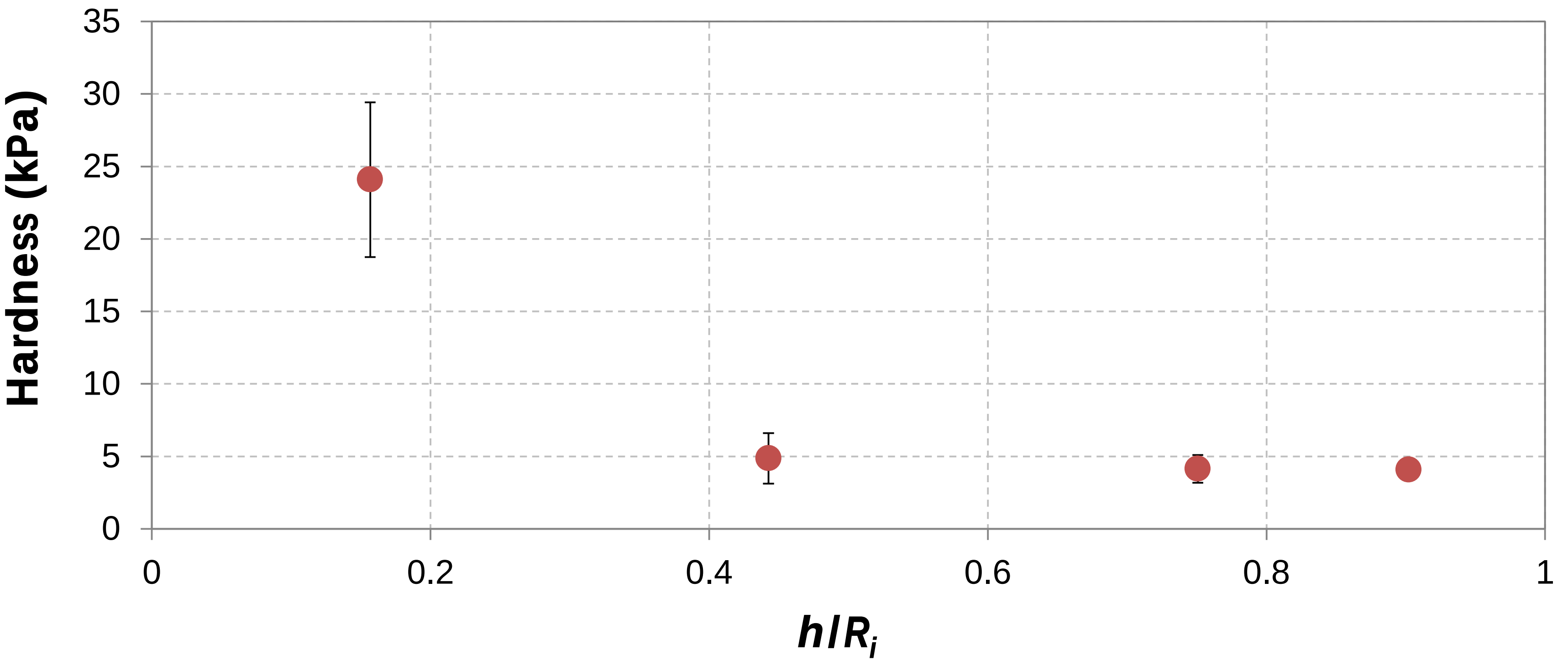




[5] Zafar, U., Hare, C., Hassanpour, A., Ghadiri, M., 2017 “Ball indentation on powder beds for assessing flowability: Analysis of operation window”, *Powder Technology* 310, 300-306.

Indentation depth





[5] Zafar, U., Hare, C., Hassanpour, A., Ghadiri, M., 2017 "Ball indentation on powder beds for assessing flowability: Analysis of operation window", *Powder Technology* 310, 300-306.

Indentation procedure

- Indenter diameter ≥ 17 d_p
- Bed diameter ≥ 1.5 D_{Ind}
- Bed height ≥ 40 d_p

Size d_{50} (μm)	Diameter (mm)		Bed height (mm)	Bed Volume (mm³)
	Indenter	Bed		
50	0.85	1.7	2	5
100	1.7	3.4	4	40
200	3.4	6.8	8	300
500	8.5	17	20	4500

- Dimensionless penetration depth (h/R_i) ≥ 0.4

[5] Zafar, U., Hare, C., Hassanpour, A., Ghadiri, M., 2017 "Ball indentation on powder beds for assessing flowability: Analysis of operation window", *Powder Technology* 310, 300-306.

Determining constraint factor

- Generally we want to know the unconfined yield stress
  - Need to know constraint factor
- How does constraint factor vary with particle properties?
- Can shear cell data be reliably extrapolated to low stress?

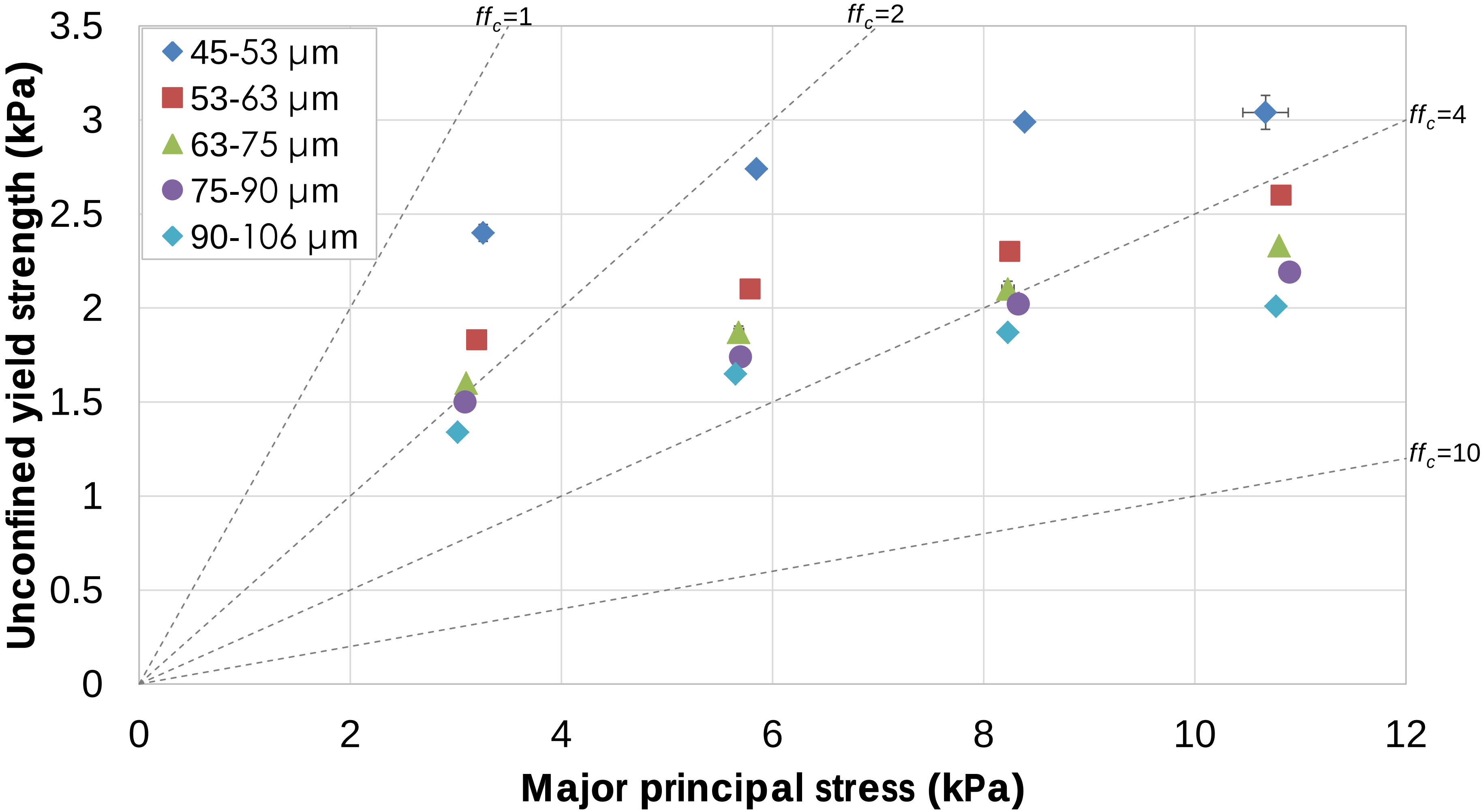
Materials

- Indentation tested for wide range of powders
  - Silanised glass beads (varying size distributions)
  - Food powders – sweetener, maize starch, pea protein
  - Inorganic powders – limestone, titania, talc, copper

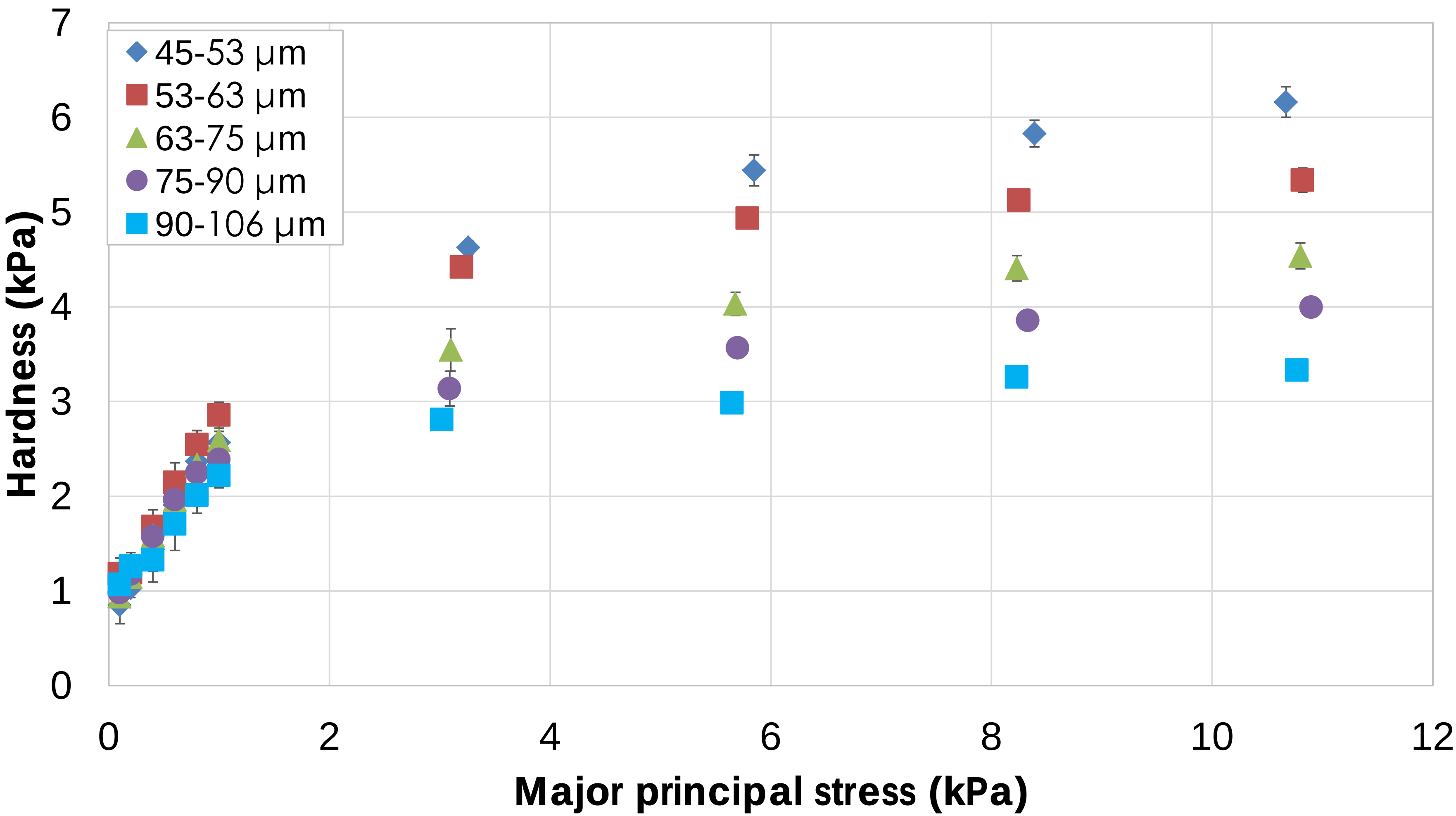
Methods

- FT4 shear cell
- Ball indentation

Unconfined Yield Strength

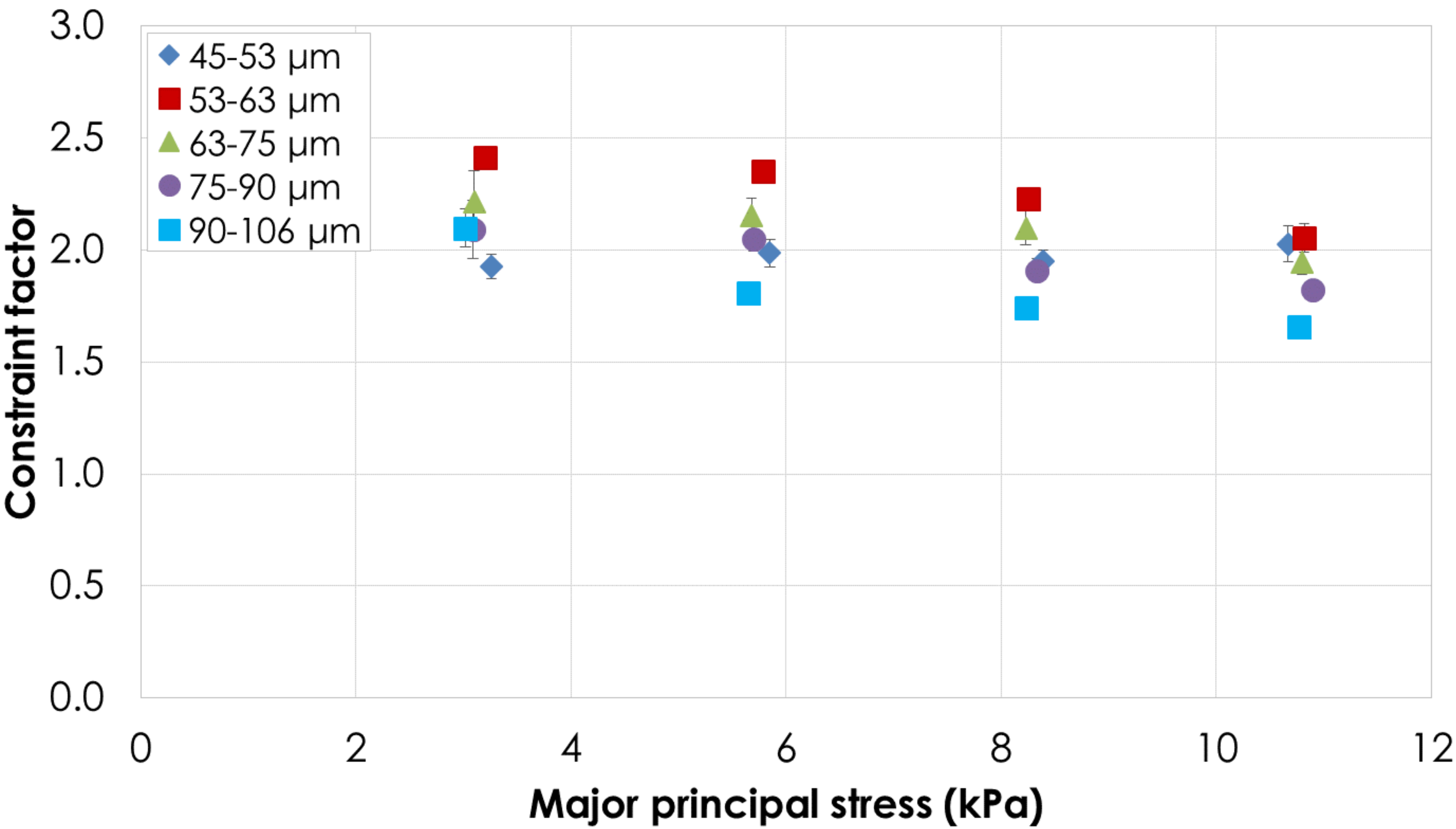


Hardness

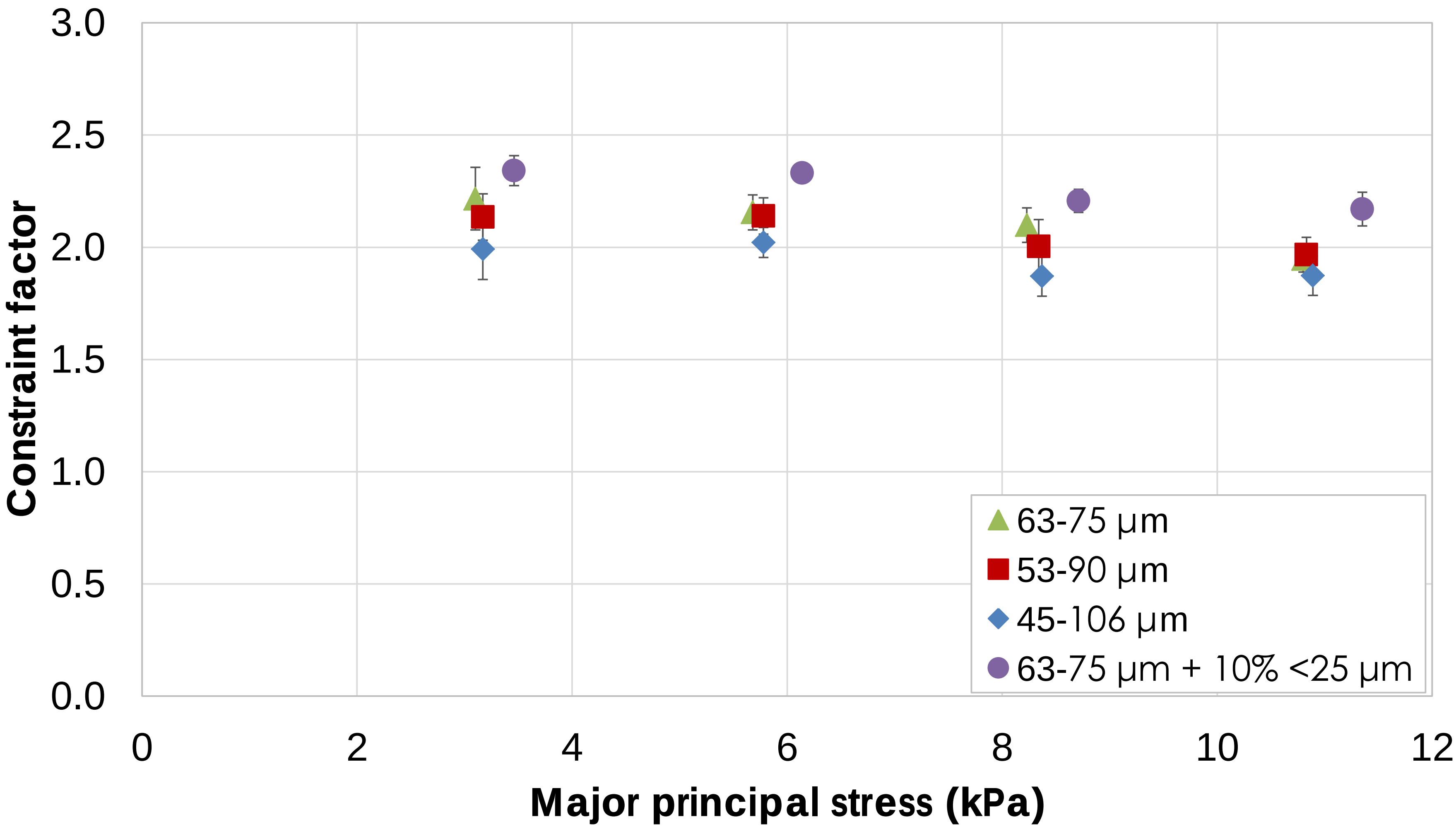


7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
45-53 µm
53-63 µm
63-75 µm
75-90 µm
90-106 µm
Hardness (kPa)
Major principal stress (kPa)

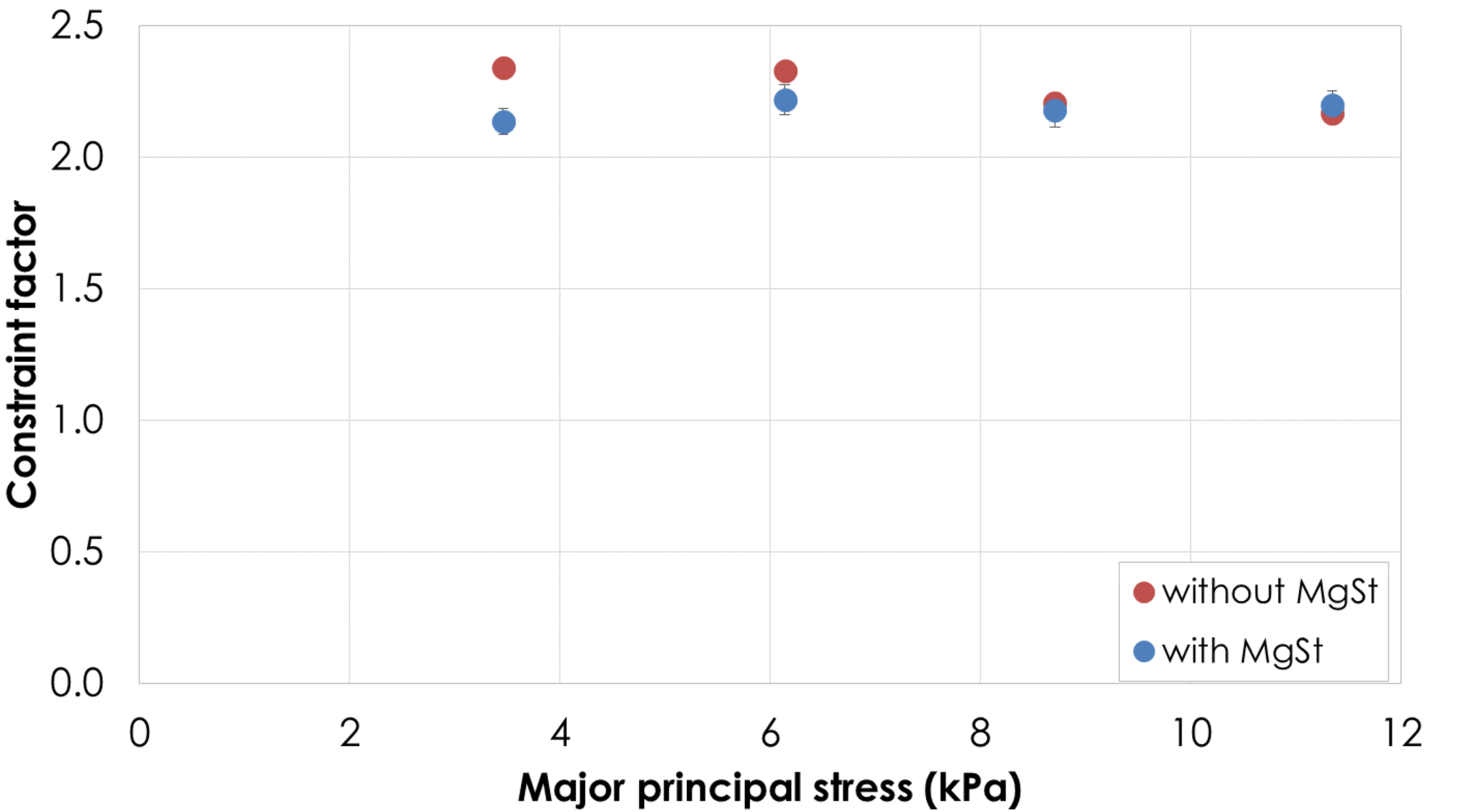
Constraint factor



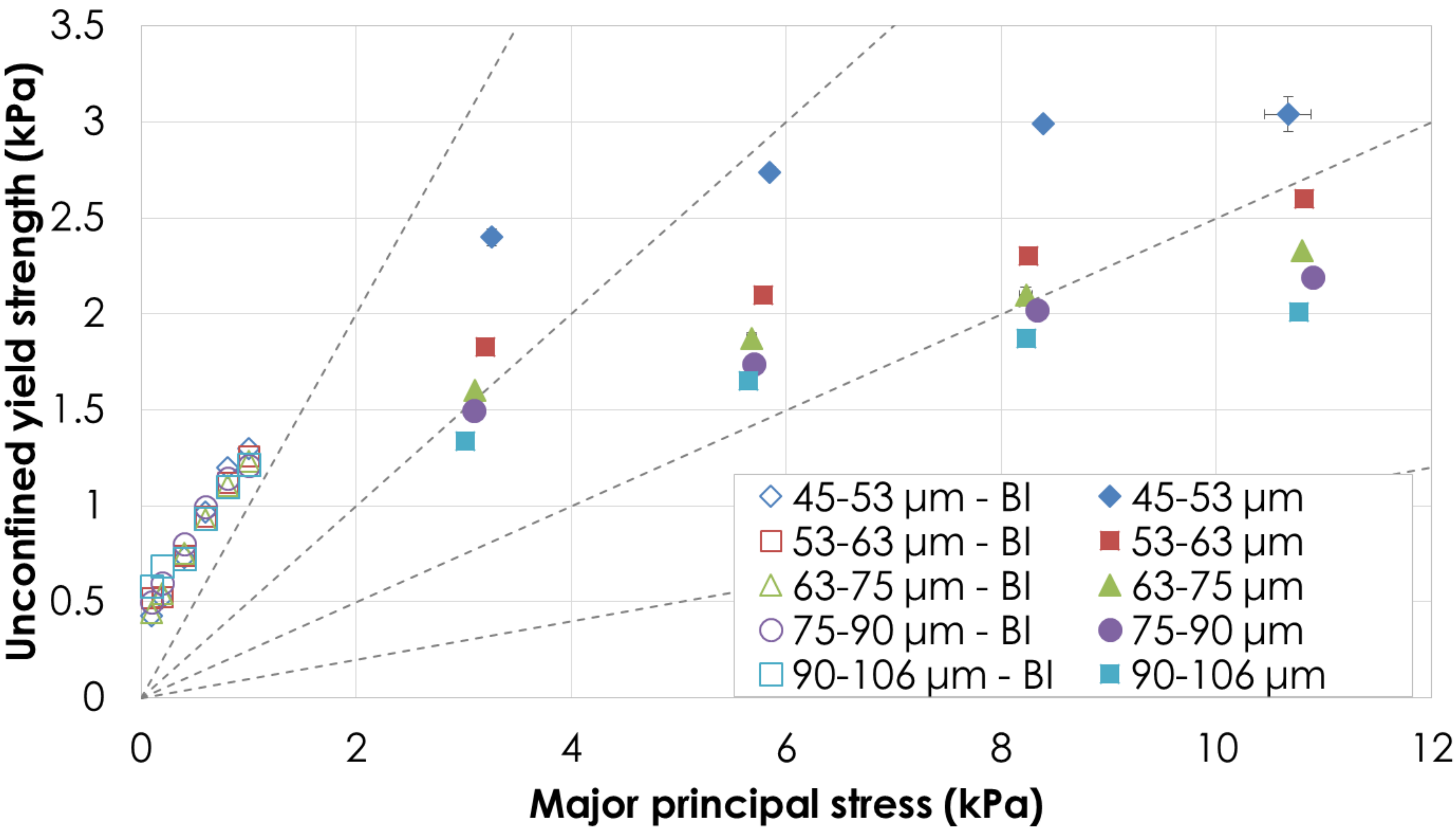
Size distribution effect



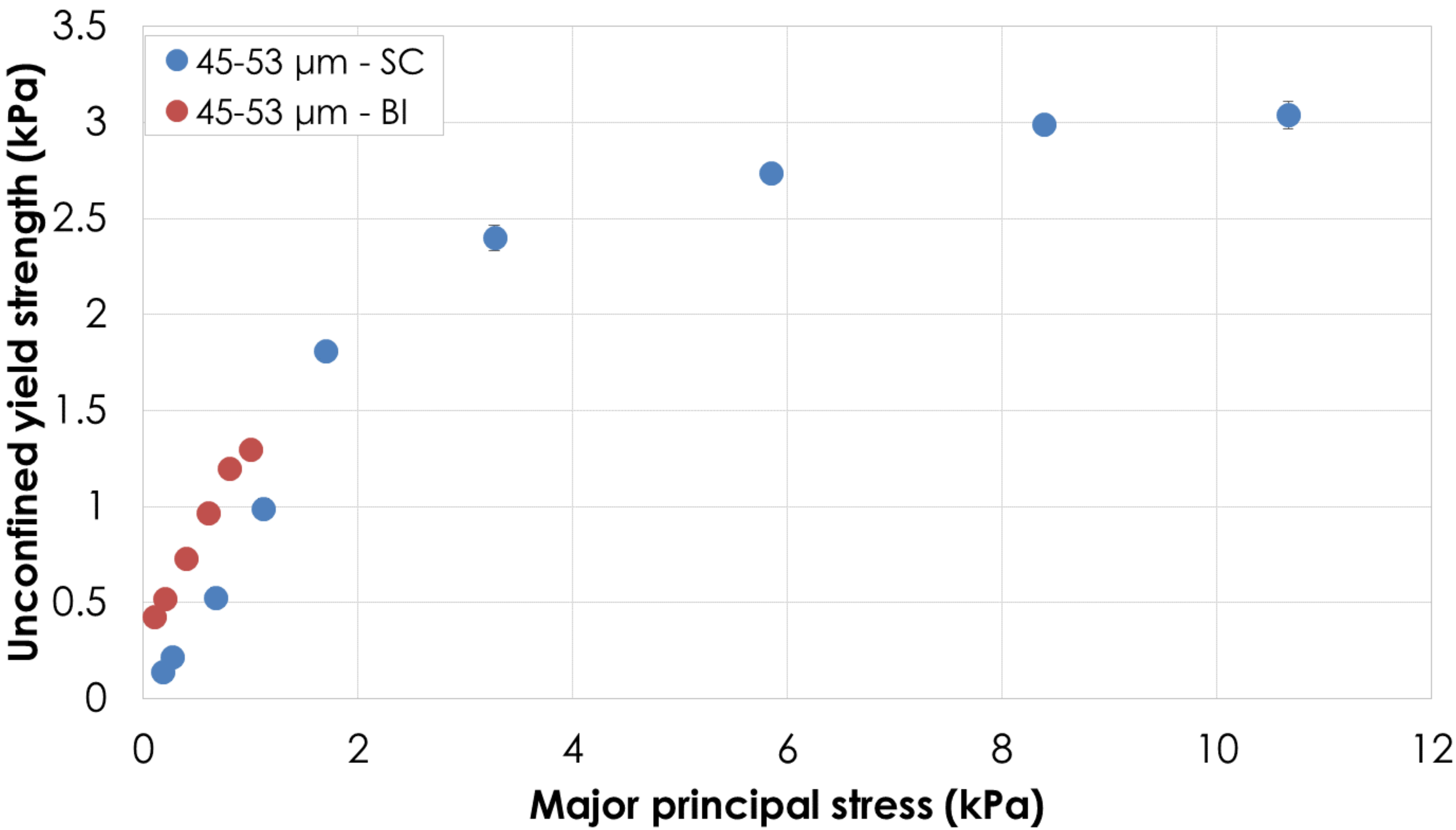
Adhesion to the piston



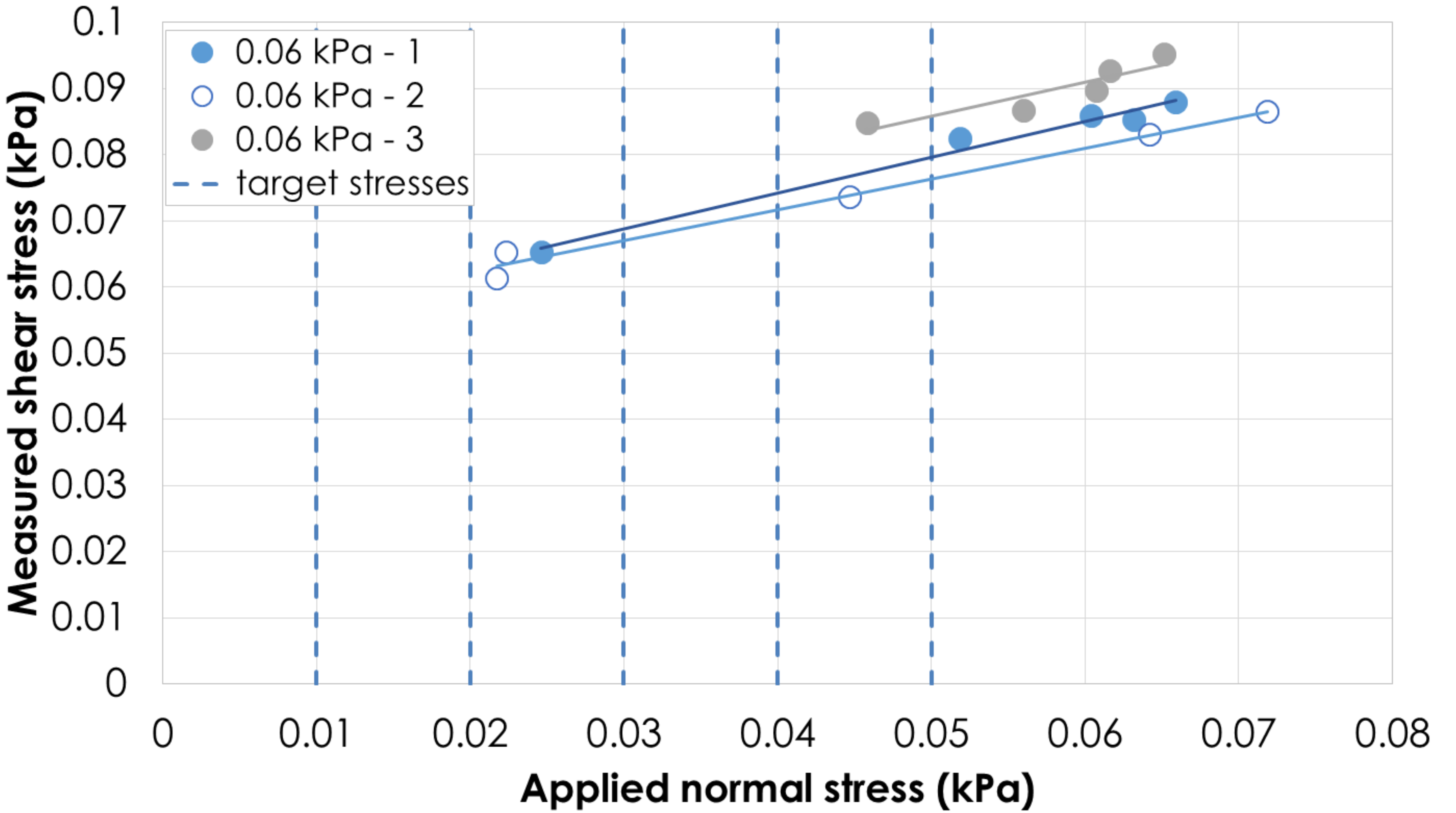
Low stress behaviour



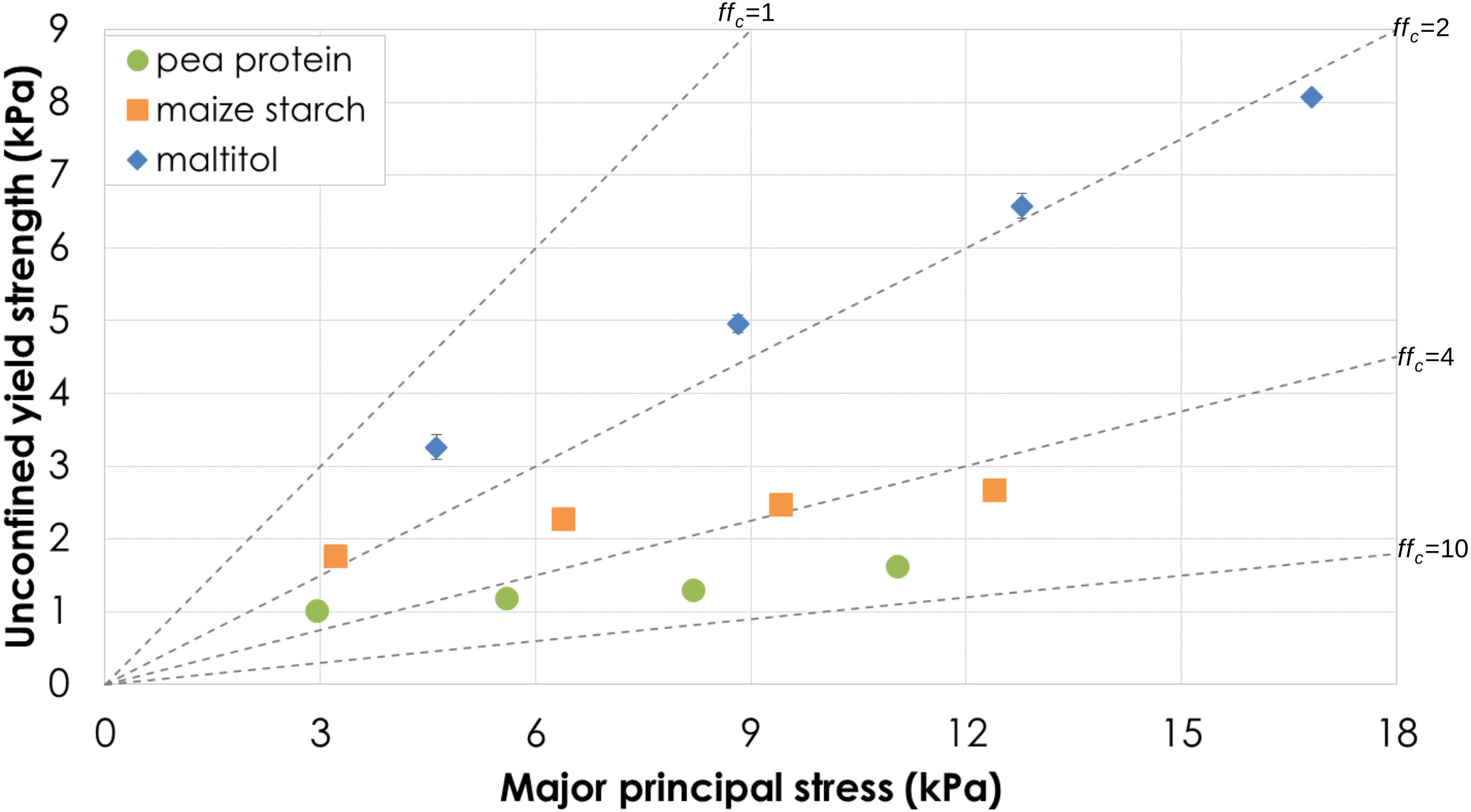
Comparison of techniques



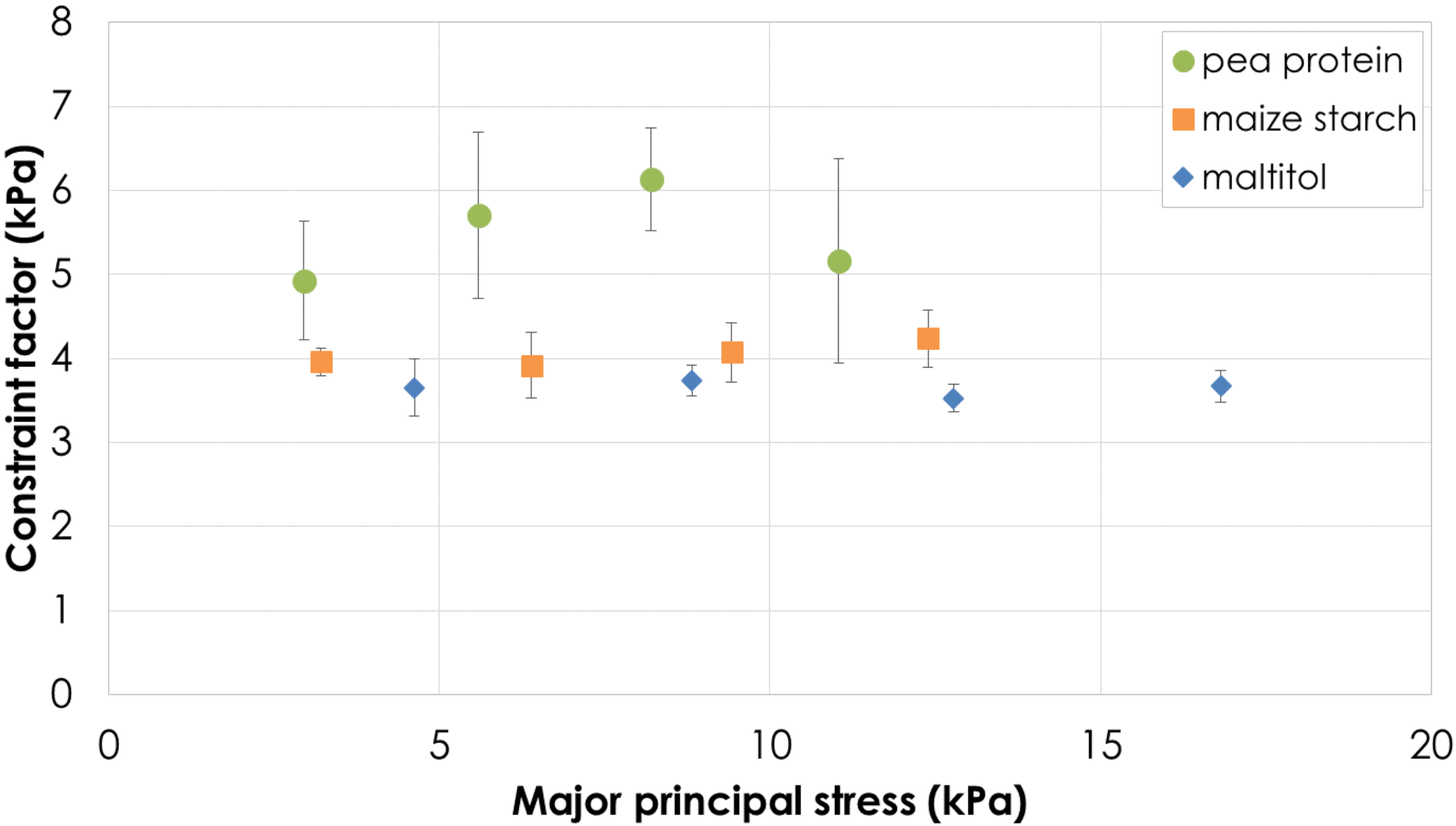
Shearing at low stresses



Food powders – shear cell



Constraint factor



Slip-stick behaviour: pea protein

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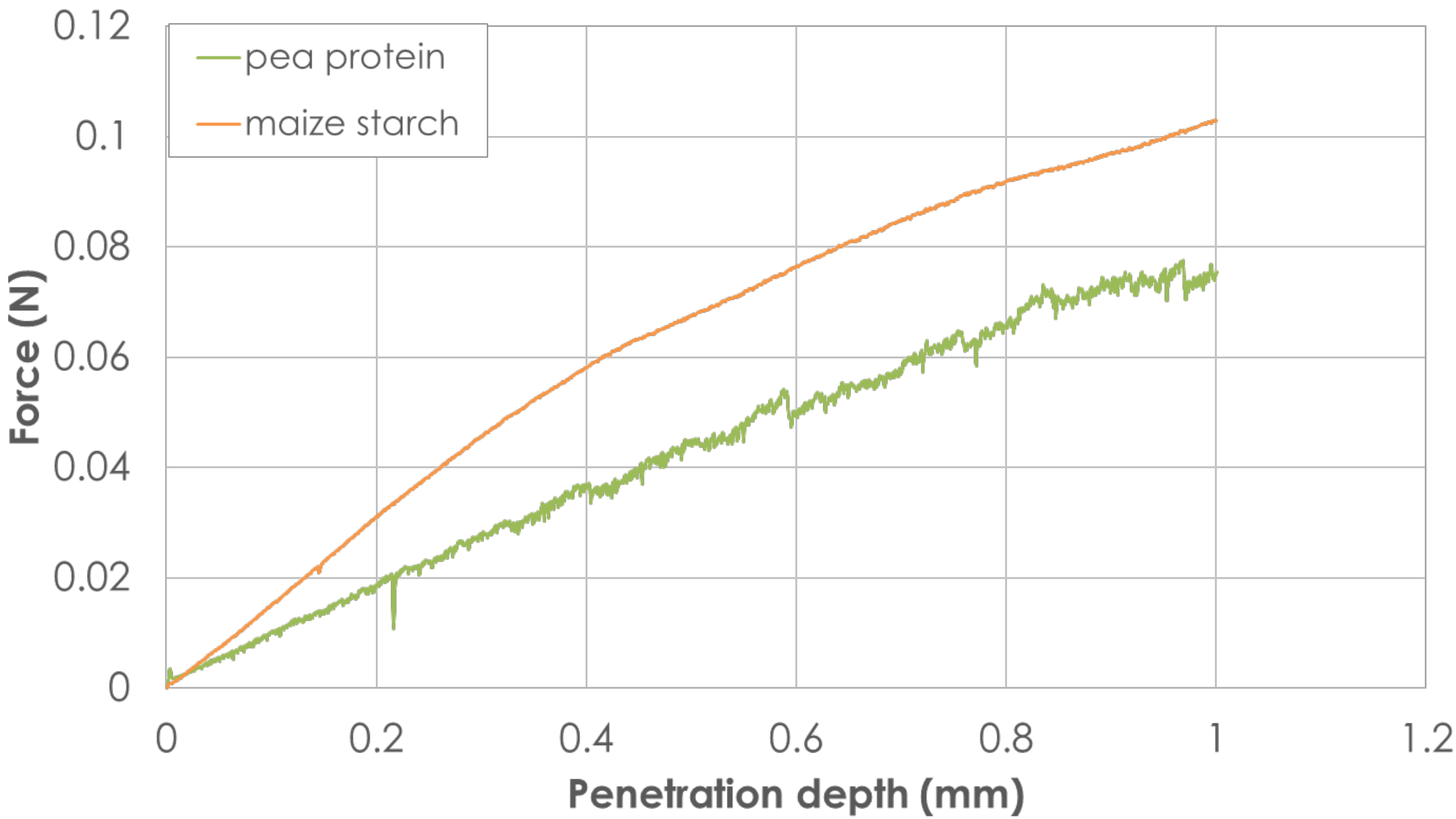
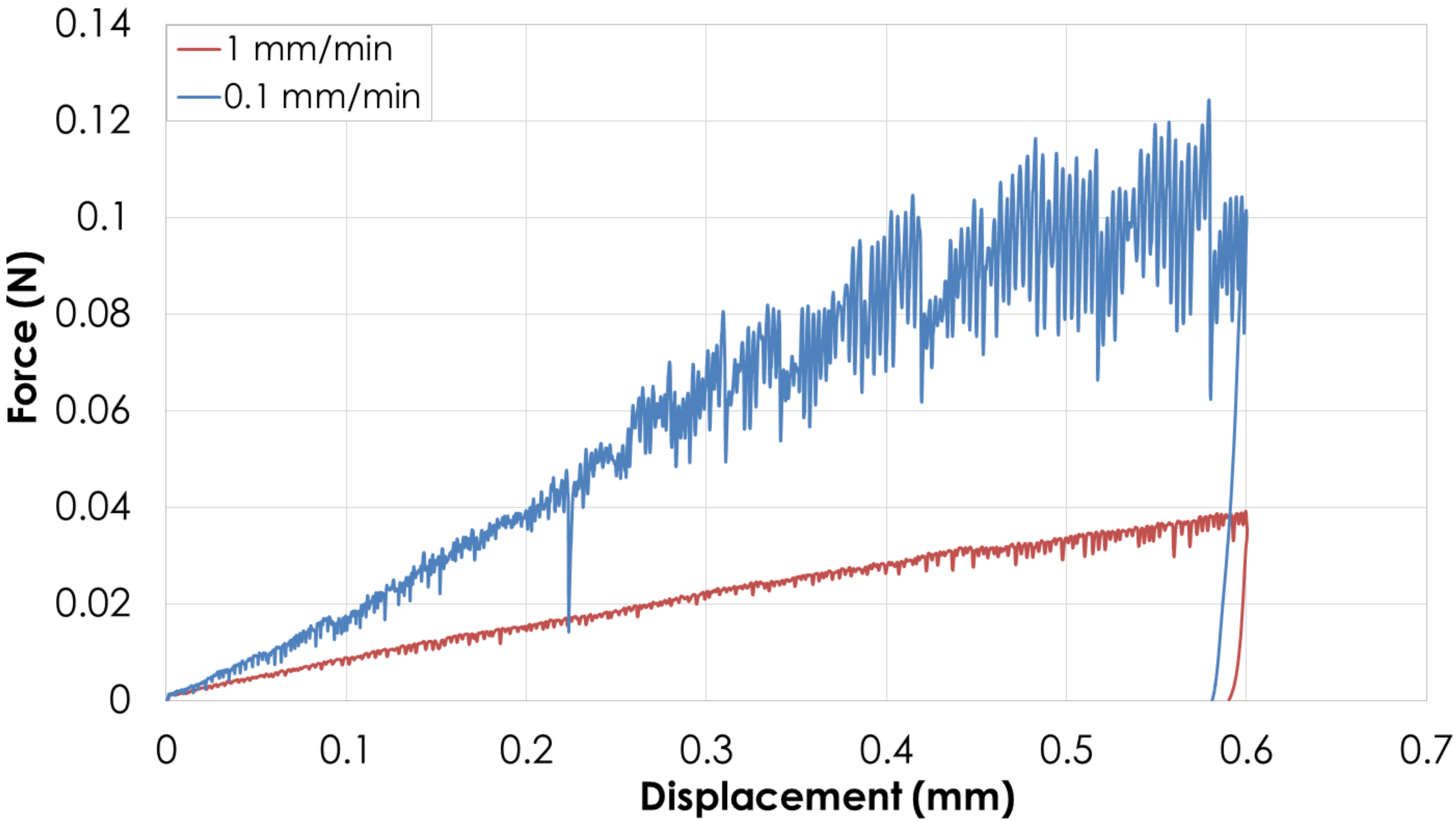
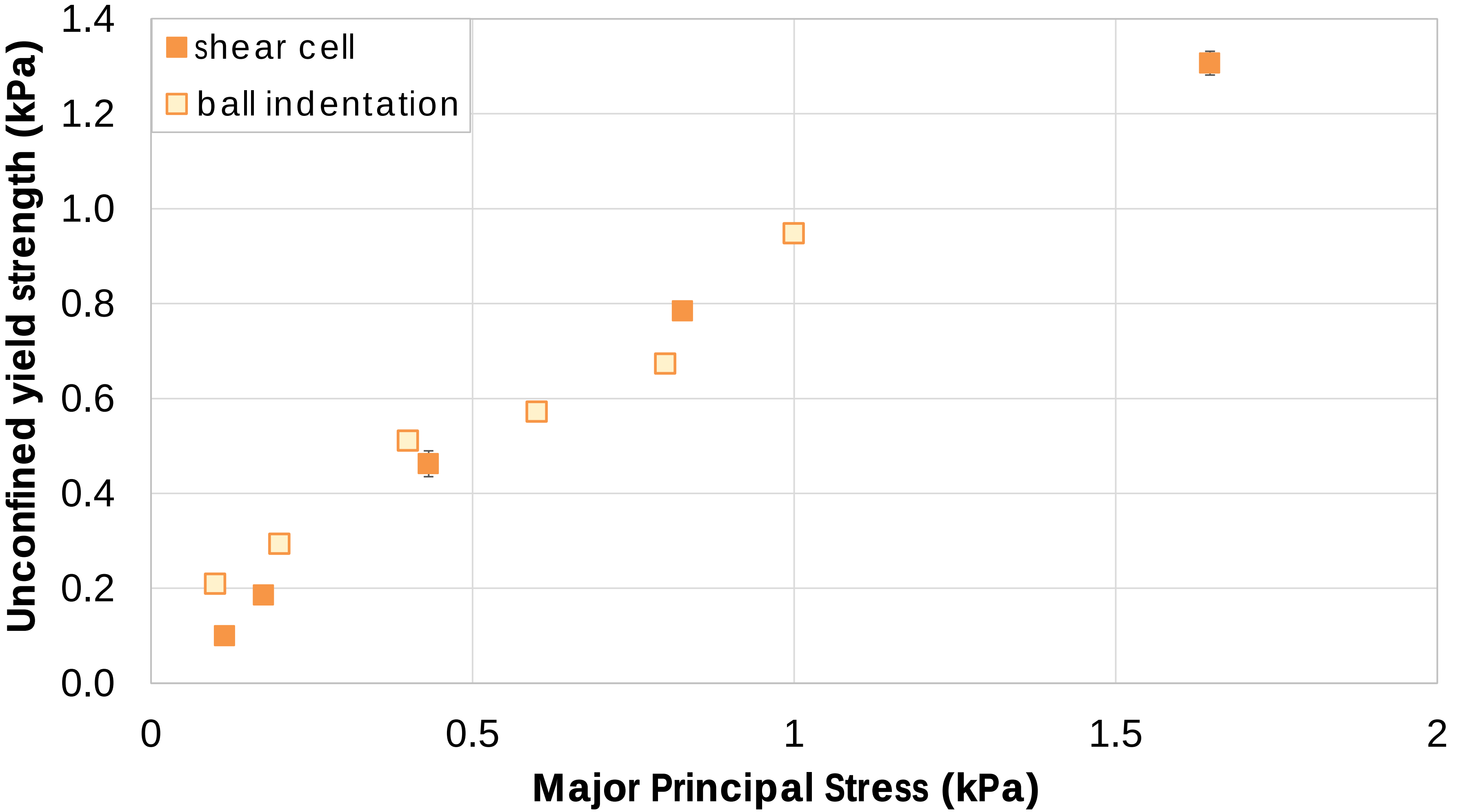


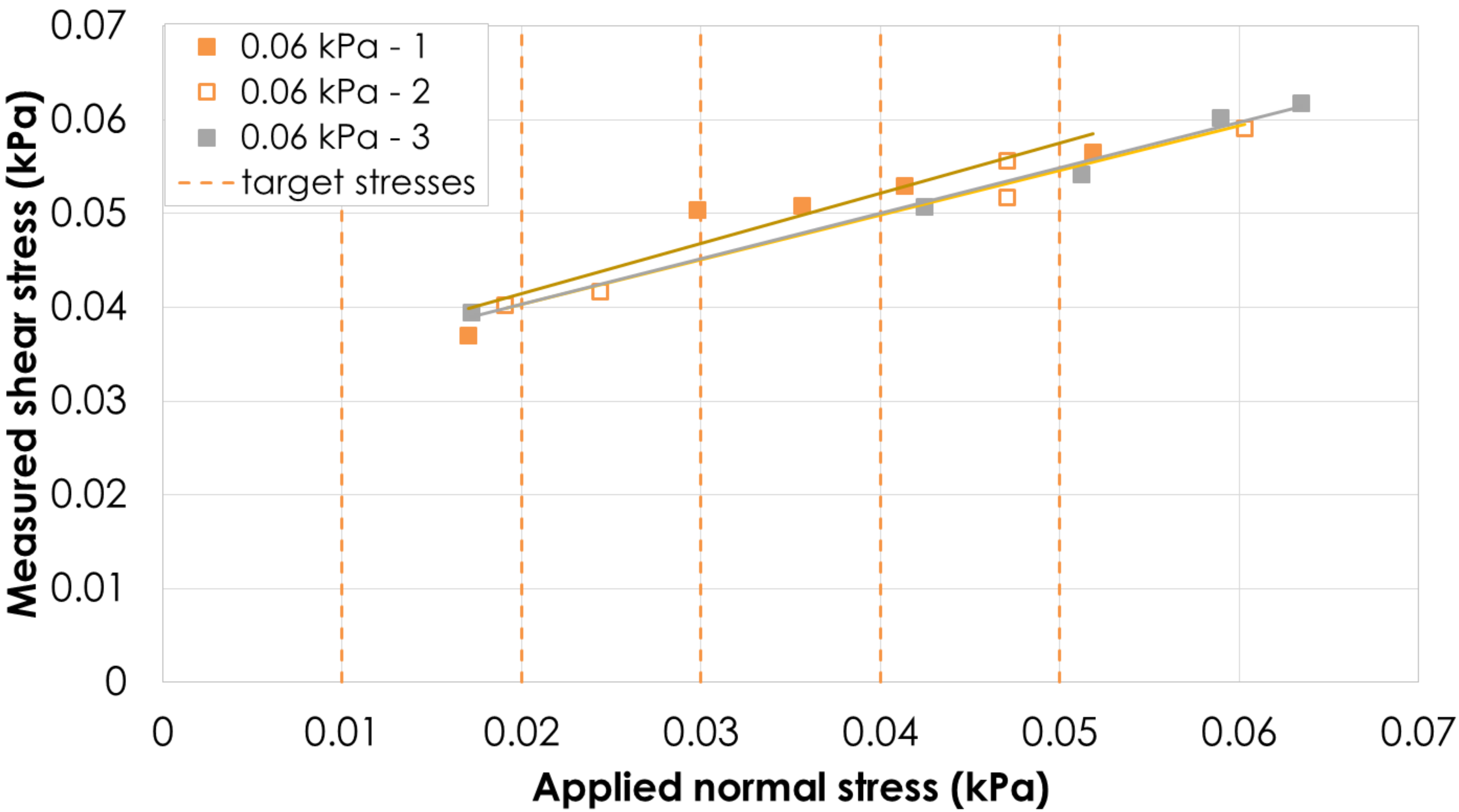
Slip-stick: strain rate effect



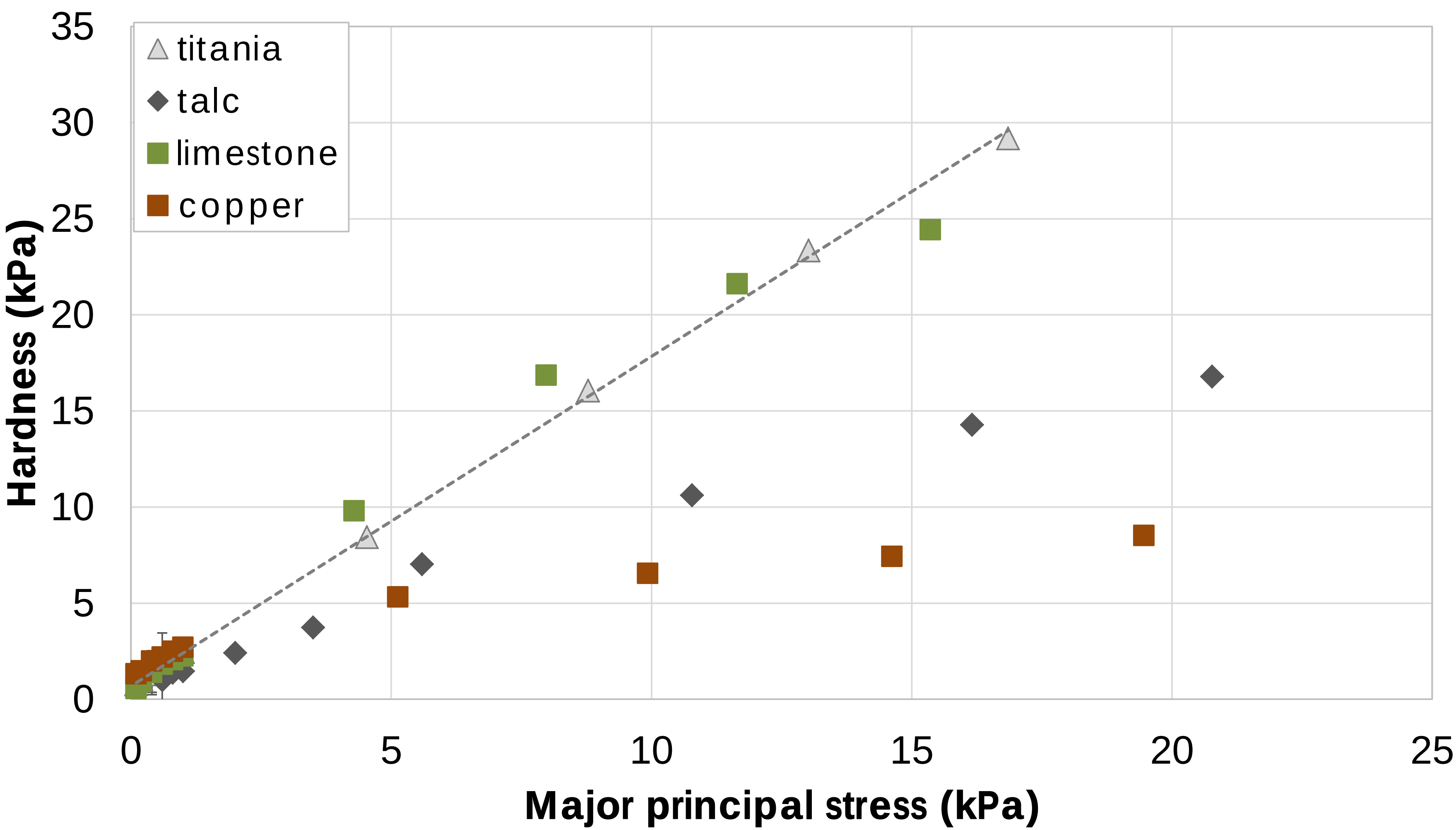
Comparison of techniques - maize



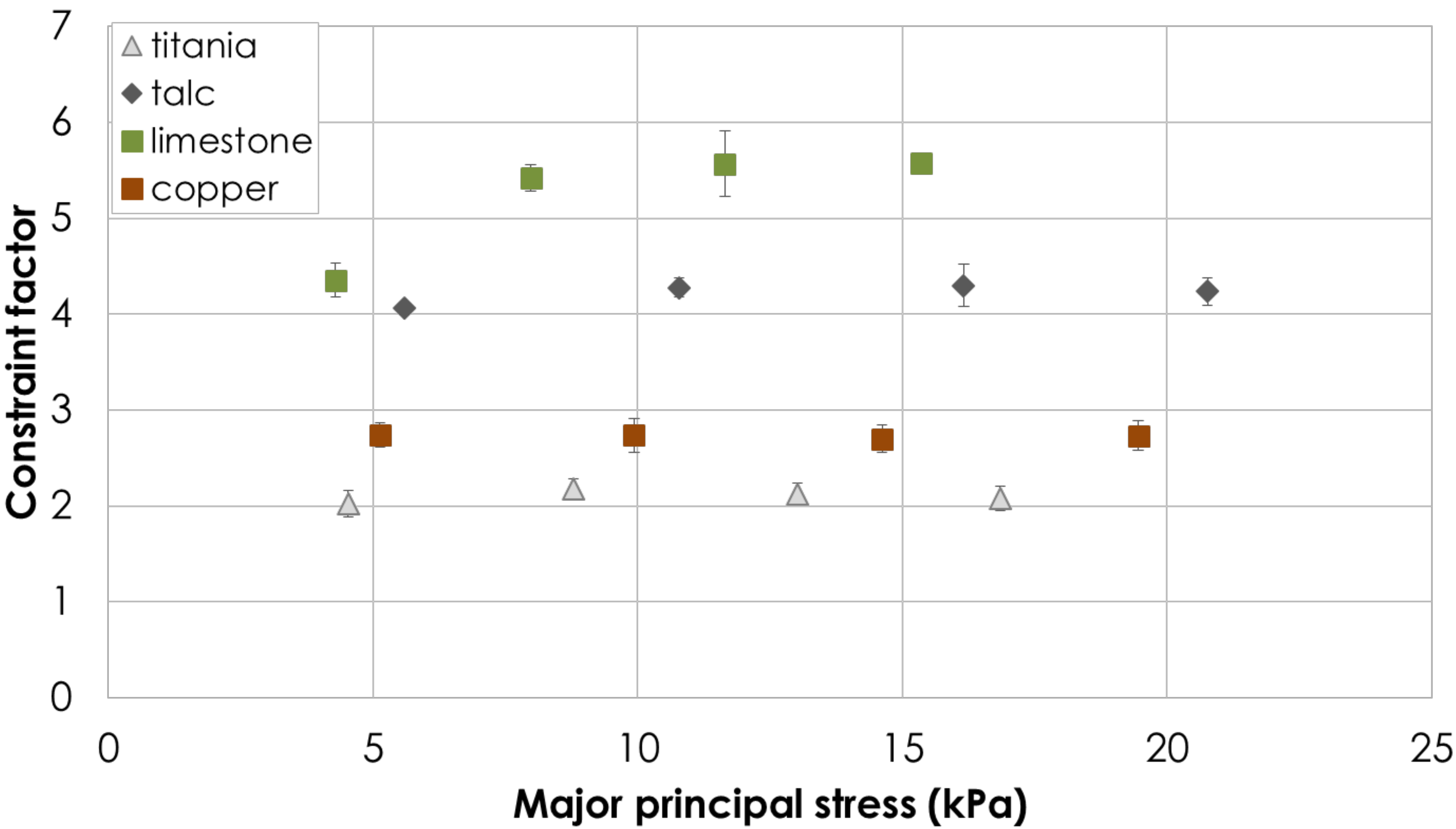
Shearing at low stresses



Inorganic powders



Inorganic powders



Conclusions

- Flowability cannot be easily measured at low stresses using shear cells
  - Target stresses often not obtained
  - Determined yield locus may be inconsistent

- Ball indentation can provide reproducible measurements of flowability at low stresses
  - Requires constraint factor to be known (or determined)

- Constraint factor found to be independent of applied stress
  - Though varies (~ 2 – 6) for different materials
  - Reduces slightly with d_{50}, though increases with fines addition

- Several powders exhibit sharp reduction in shear stress at lower stresses
  - Behaviour at higher stresses cannot be reliably extrapolated

Future work

- DEM will be used to analyse *C* at low stresses
  - And influence of particle shape on *C*

- Experimentally assess dependency of *C* on surface energy
  - A range of coatings applied to different batches

- Investigate indentation at high-strain rates

- Optimisation of shear cell procedure at low stresses
  - Number of pre-shear steps applied
  - Defined end point – i.e acceptable deviation to define steady state
  - Required agreement between consecutive pre-shears

Acknowledgements

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IFPRI
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