



Measurement of powder flow properties and relation with interparticle properties

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Joint IFPRI/T--MAPPP Workshop
Hotel Schiphol, Rijksweg A4 3, 2132 MA Hoofddorp, Netherlands
23 January 2017

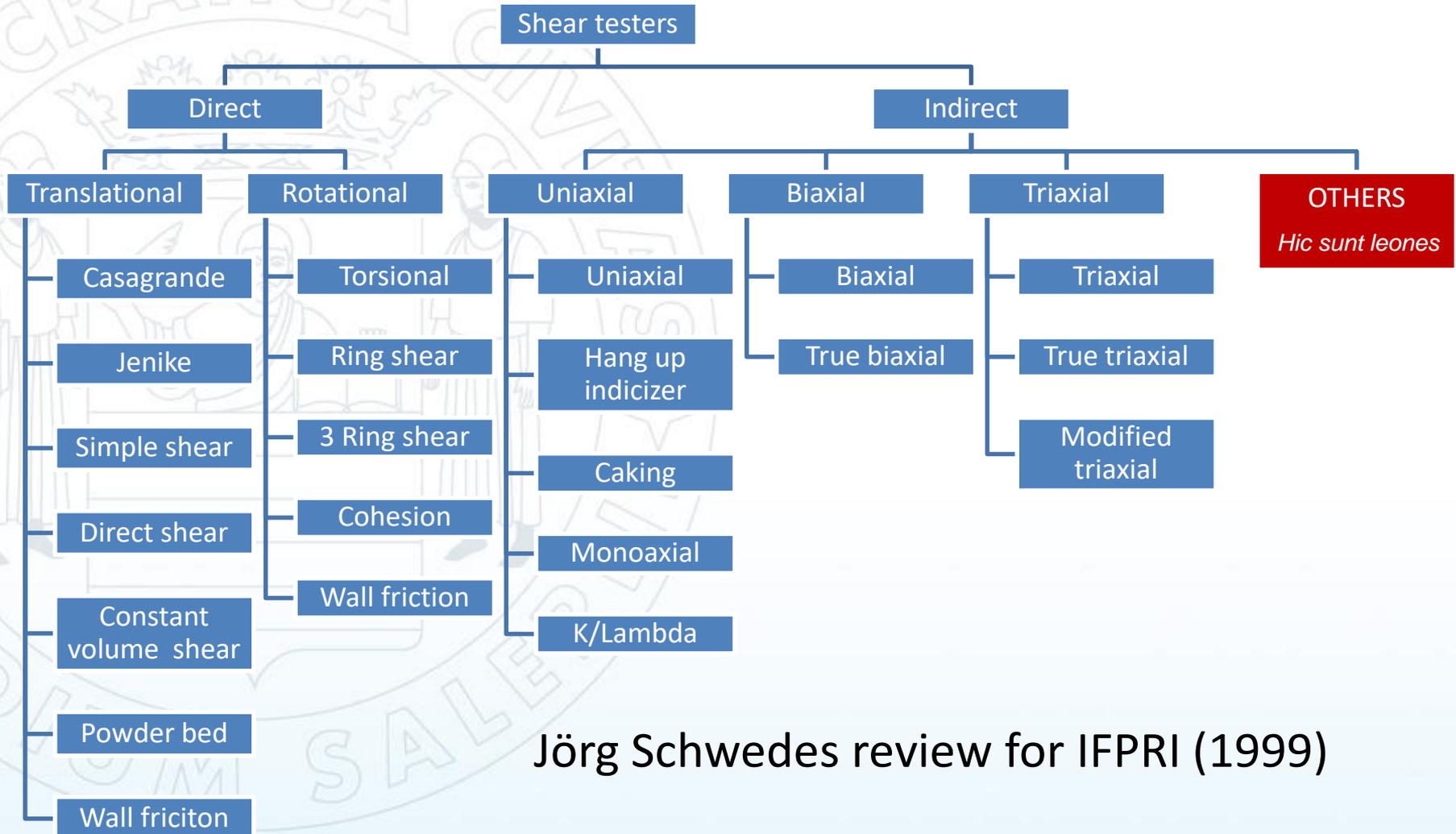
Talk content

- Characterization of the history and state-of-the-art in powder flow
- Confront the "grand challenge" to relate particle properties and bulk flow behaviour
- Define three scientific questions that IFPRI and other funding sources should promote



HISTORY AND STATE-OF-THE-ART IN POWDER FLOW

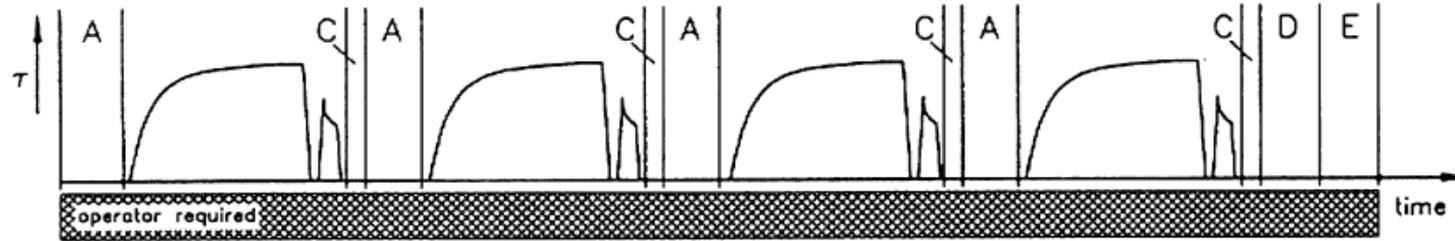
The starting point



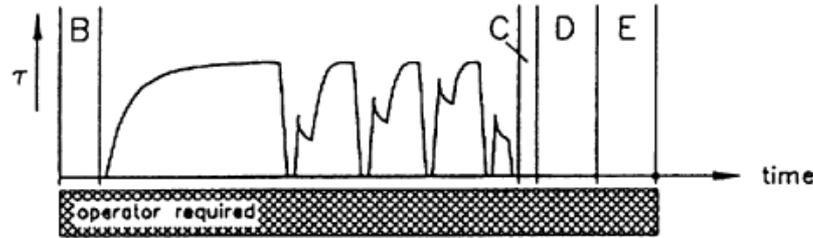
Jörg Schwedes review for IFPRI (1999)

Automation of direct shear testers

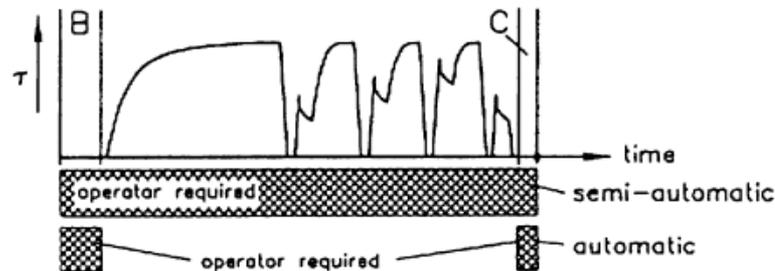
Translational shear tester (one sample per measurement point)



Ring shear tester (manual operation; one sample per yield locus)



Ring shear tester (semi-automatic and automatic mode)



- A: preparation of shear cell (filling, preconsolidation, set-up)
- B: preparation of ring shear cell (filling, set-up)
- C: clean shear cell
- D: read data from chart recorder
- E: type data into PC, evaluate yield locus

Automated shear tester

Schulze Testers
RST-01.pc



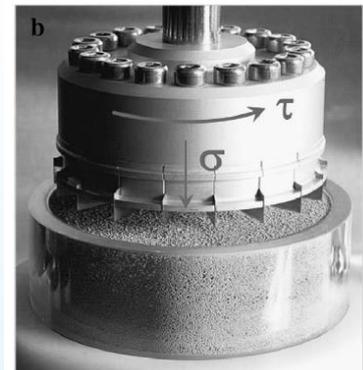
Brookfield
Powder Flow Tester (PFT)



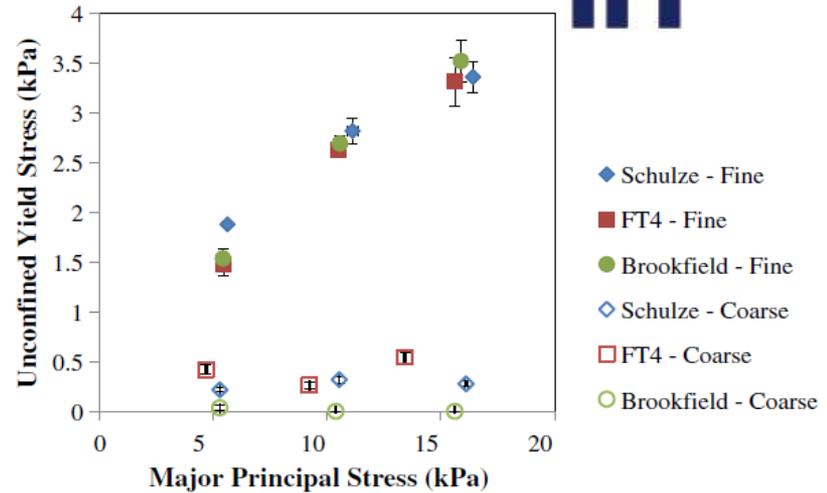
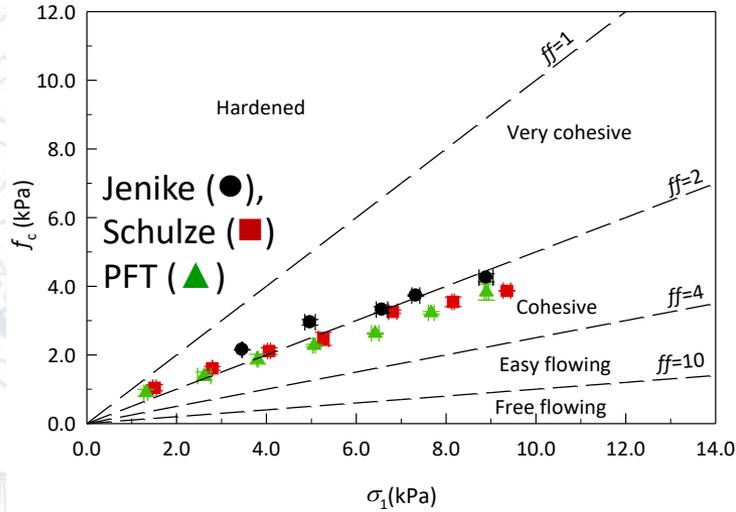
Freeman FT4
Shear tester set up



RST-XS.s

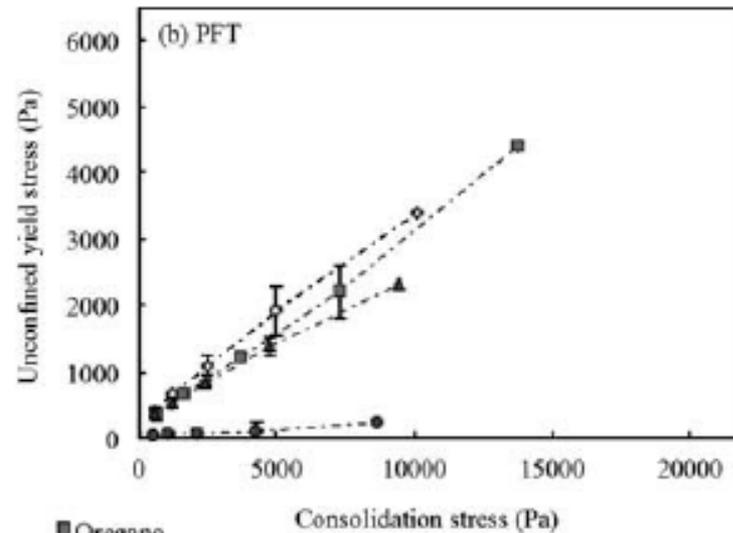
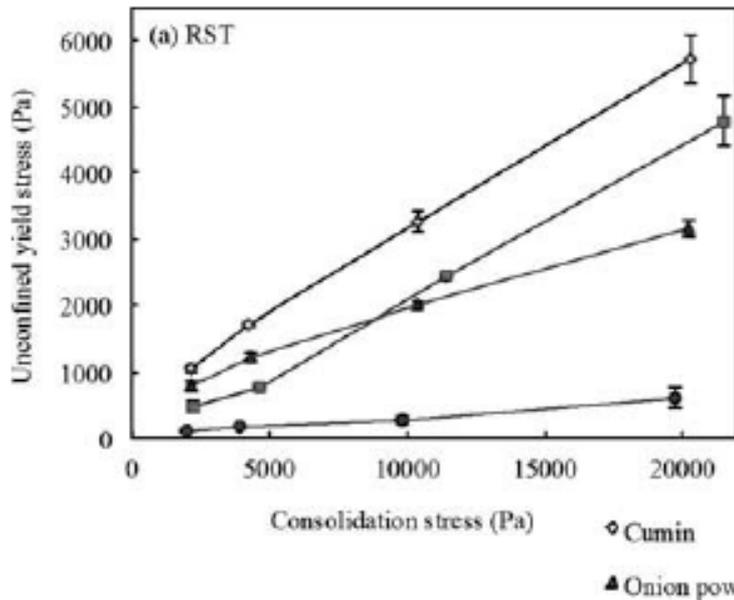


Comparison between testers



Salehi, Hamid, Diego Barletta, and Massimo Poletto. "A Comparison between Powder Flow Property Testers." *Particuology*, January 2017. doi:10.1016/j.partic.2016.08.003.

Koynov, Sara, Benjamin Glasser, and Fernando Muzzio. "Comparison of Three Rotational Shear Cell Testers: Powder Flowability and Bulk Density." *Powder Technology* 283 (2015): 103–12. doi:10.1016/j.powtec.2015.04.027.

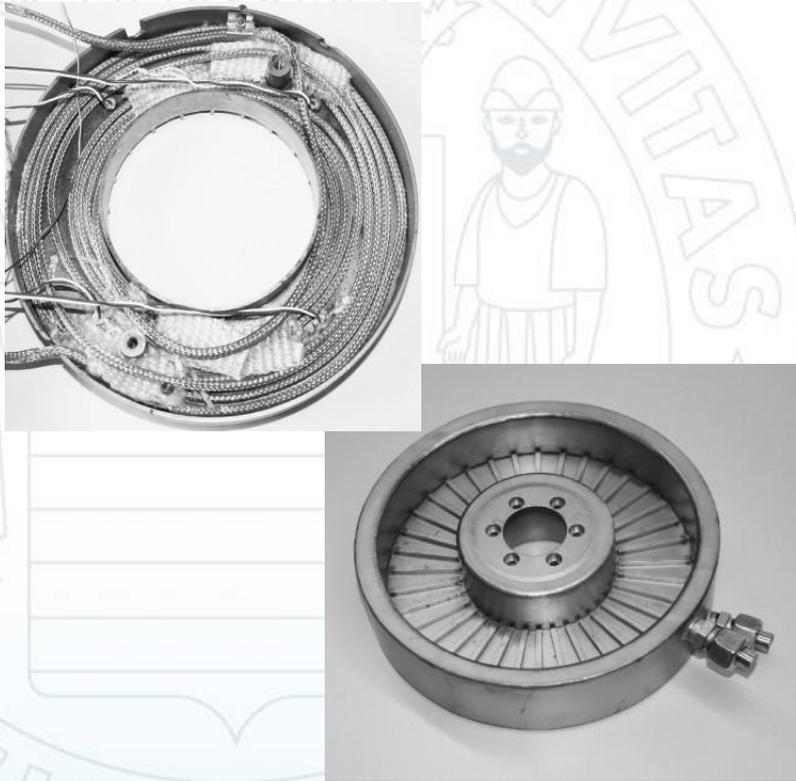


Slettengren, Katarina, Epameinondas Xanthakis, Lilia Ahmé, and Erich J. Windhab. "Flow Properties of Spices Measured with Powder Flow Tester and Ring Shear Tester - XS." *International Journal of Food Properties* 2912, no. September (2015): 150911191058007. doi:10.1080/10942912.2015.1083576.

Special direct shear testers

High Temperature RST

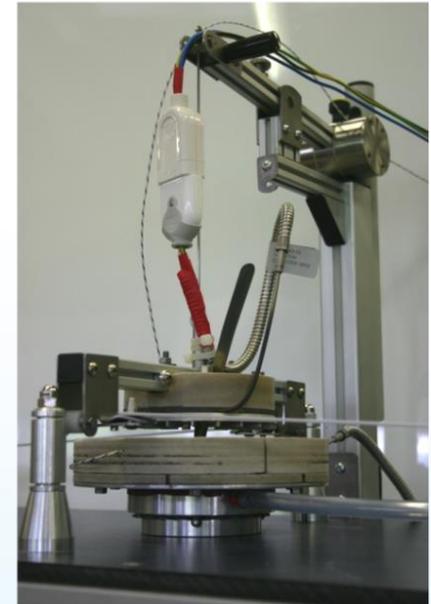
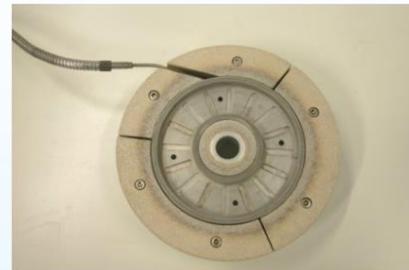
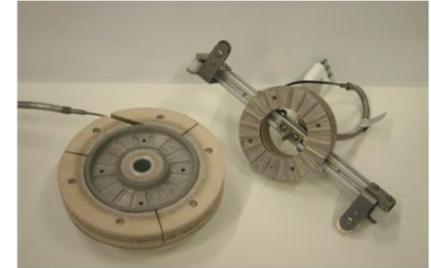
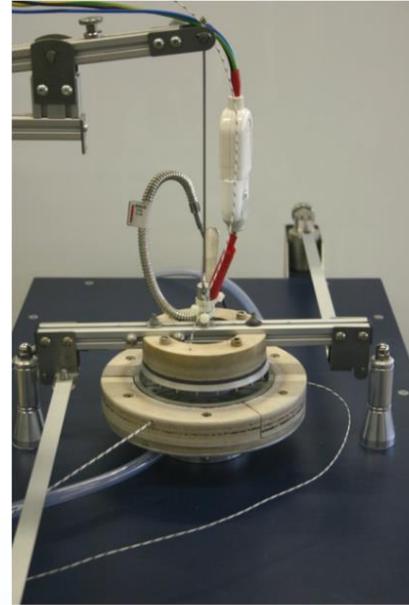
TU Kaiserslautern



-80 to 200°C

UNISA

Ambient to 500°C



Ripp, Marcus, and Siegfried Ripperger. "Influence of Temperature on the Flow Properties of Bulk Solids." *Chemical Engineering Science* 65, no. 13 (July 2010): 4007–13. doi:10.1016/j.ces.2010.03.046.

Tomasetta, Iginio, Diego Barletta, and Massimo Poletto. "The High Temperature Annular Shear Cell: A Modified Ring Shear Tester to Measure the Flow Properties of Powders at High Temperature." *Advanced Powder Technology* 24, no. 3 (2013): 609–17. doi:10.1016/j.appt.2012.11.007.

Special direct shear testers

Aerated shear



Uniaxial testing

Edinburgh tester



Freeman Technology



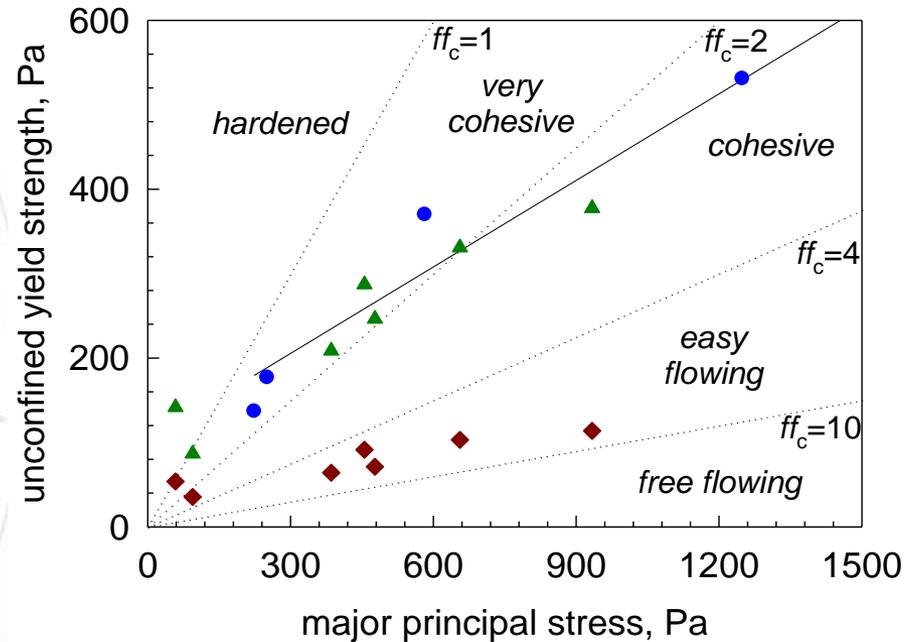
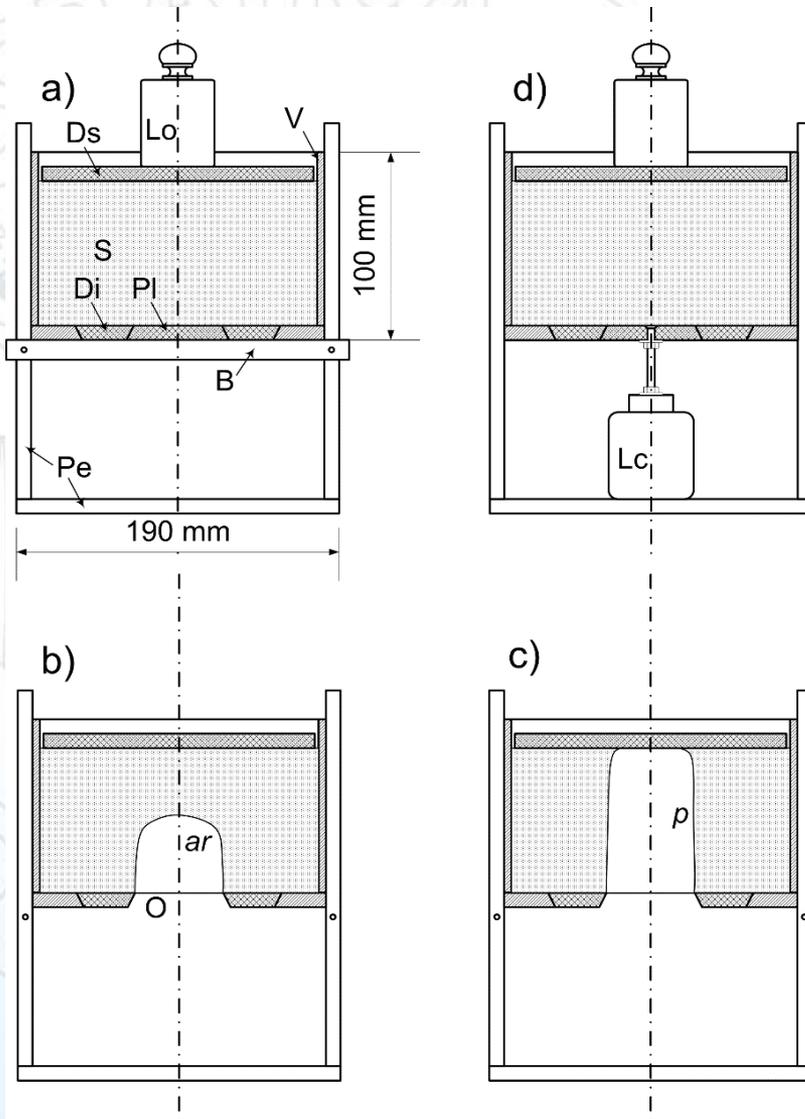
UNISA



Bell, T. A., E. J. Catalano, Z. Zhong, Jin Y. Ooi, and J. M. Rotter. "Evaluation of the Edinburgh Powder Tester." In PARTEC 2007 - Congress on Particle Technology <http://edinburghpowdertest.wixsite.com/edinburghpowdertest>

Parrella, L., D. Barletta, R. Boerefijn, and M. Poletto. "Comparison between a Uniaxial Compaction Tester and a Shear Tester for the Characterization of Powder Flowability." *KONA Powder and Particle Journal* 26, no. March (2008): 178–89. doi:10.14356/kona.2008016.

Modified hang up

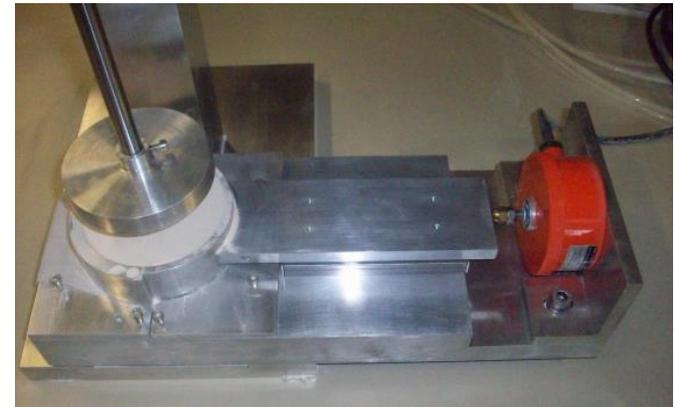
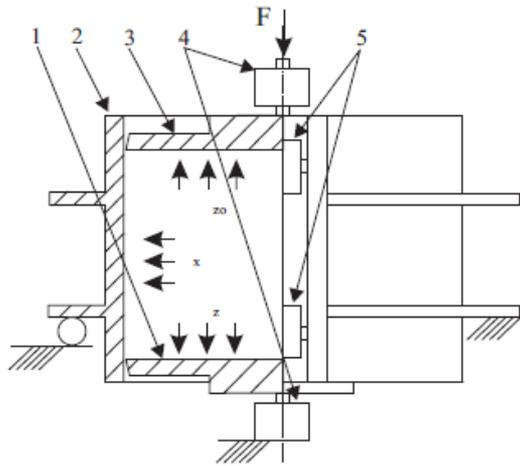


Miccio, Francesco, Diego Barletta, and Massimo Poletto. "Flow Properties and Arching Behavior of Biomass Particulate Solids." Powder Technology 235 (February 2013): 312–21. doi:10.1016/j.powtec.2012.10.047.

Split lambda tester

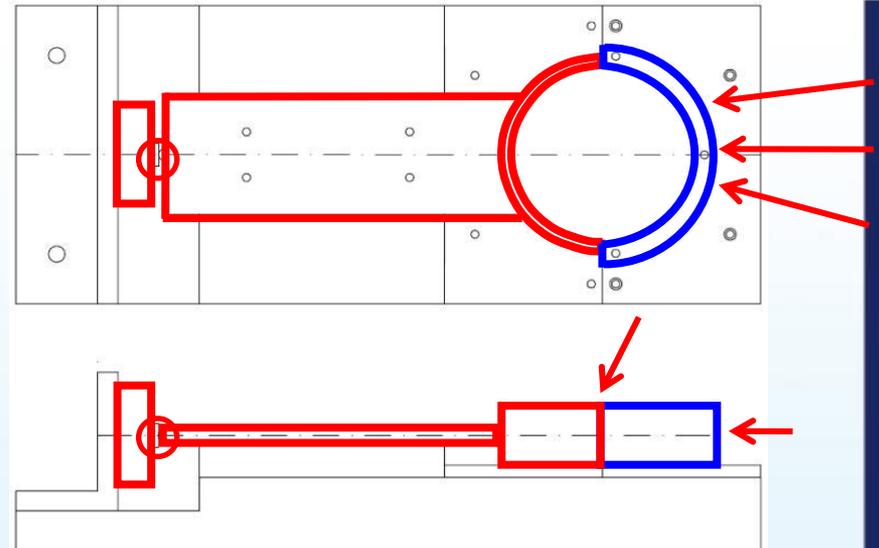
Polish Academy of Sciences

UNISA

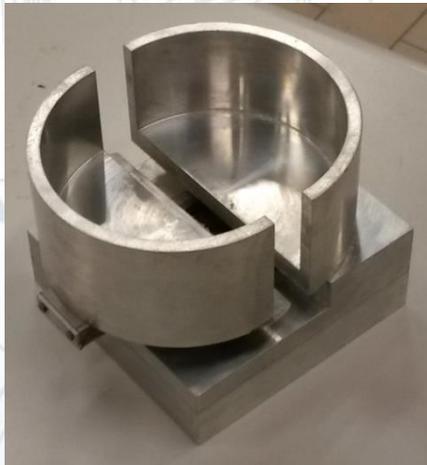


Horabik, J., and R. Rusinek. "Pressure Ratio of Cereal Grains Determined in a Uniaxial Compression Test." *International Agrophysics*, no. 5 (2002): 23–28. <http://lgm.ipan.lublin.pl/pdf/HORABIK13.pdf>.

Poletto and Barletta. WPMP5 K/Lambda project presentations (2009-2012)

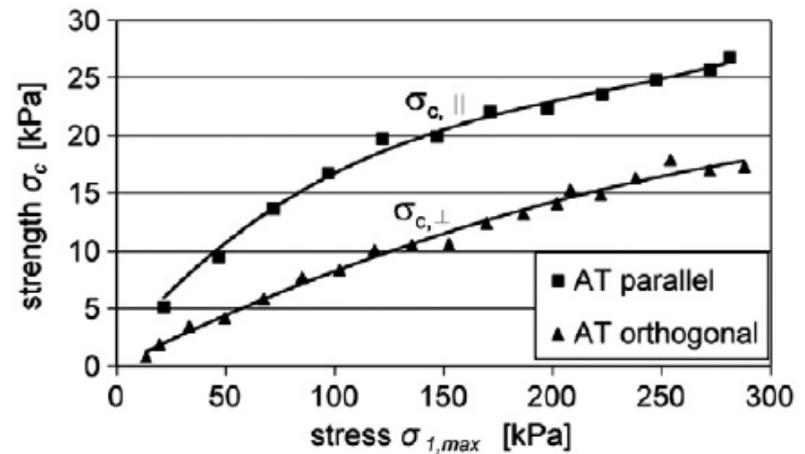
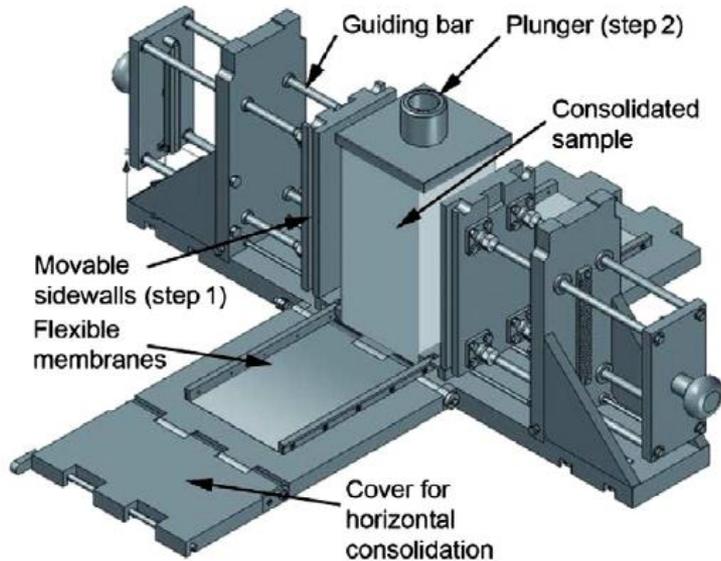


Fully split lambda tester



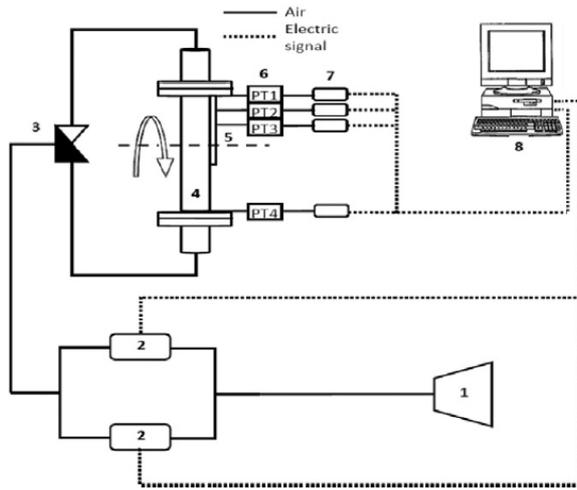
Biaxial testing: Anisotropy

TU Braunschweig

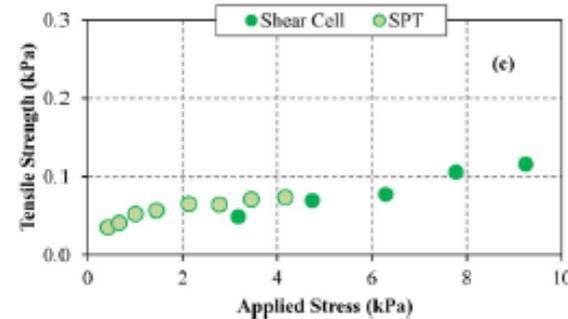
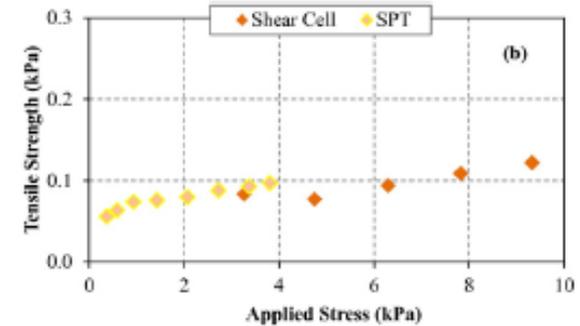
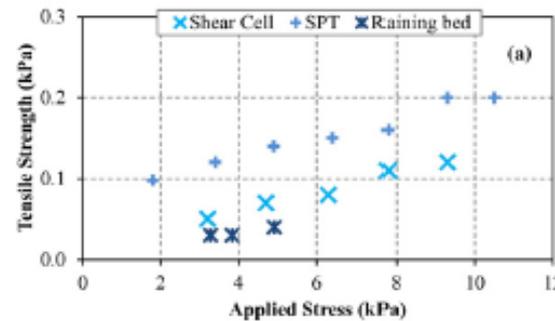
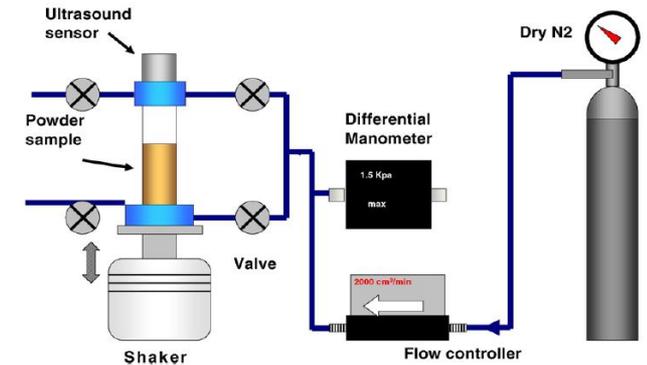


Ittershagen, T, J Schwedes, and A Kwade. "A New Powder Tester to Investigate the Anisotropic Consolidation Behaviour." Powder Technology 211, no. 1 (July 1, 2011): 85–89.

OTHERS: Direct tensile strength testing



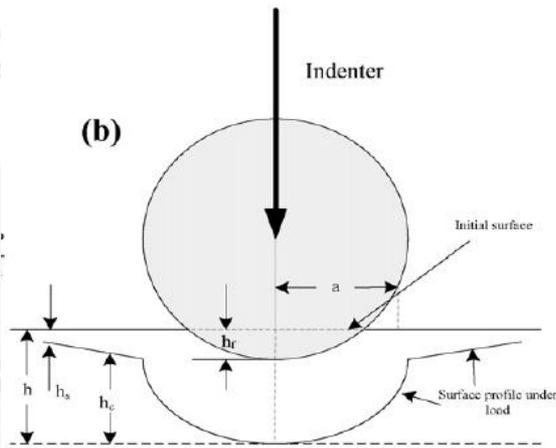
- | | |
|---|-----------------------|
| 1 | Compressor |
| 2 | Mass flow controllers |
| 3 | Three-ways valve |
| 4 | Fluidization column |
| 5 | Pressure taps |
| 6 | Graduate scale |
| 7 | Pressure transducers |
| 8 | Personal computer |



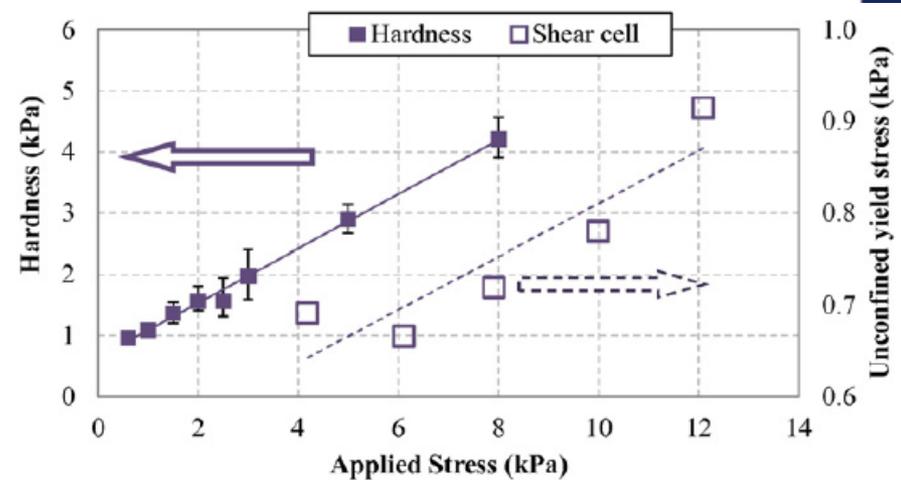
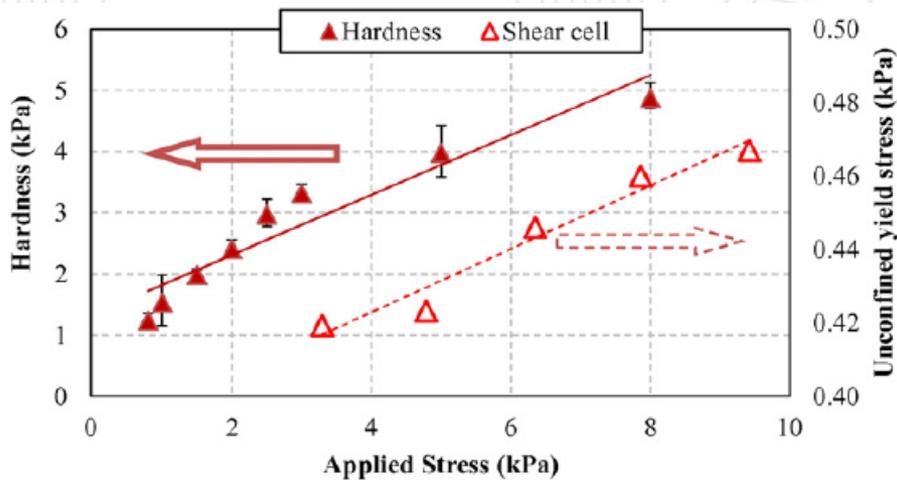
Zafar, U., C. Hare, G. Calvert, M. Ghadiri, R. Gimonte, B. Formisani, M.A.S. Quintanilla, and J.M. Valverde. "Comparison of Cohesive Powder Flowability Measured by Schulze Shear Cell, Raining Bed Method, Sevilla Powder Tester and New Ball Indentation Method." Powder Technology 286 (December 2015): 807–16. doi:10.1016/j.powtec.2015.09.010.

Fig. 14. Comparison between techniques for (a) FCC 45-63 μm, (b) FCC 63-75 μm and (c) FCC 75-90 μm.

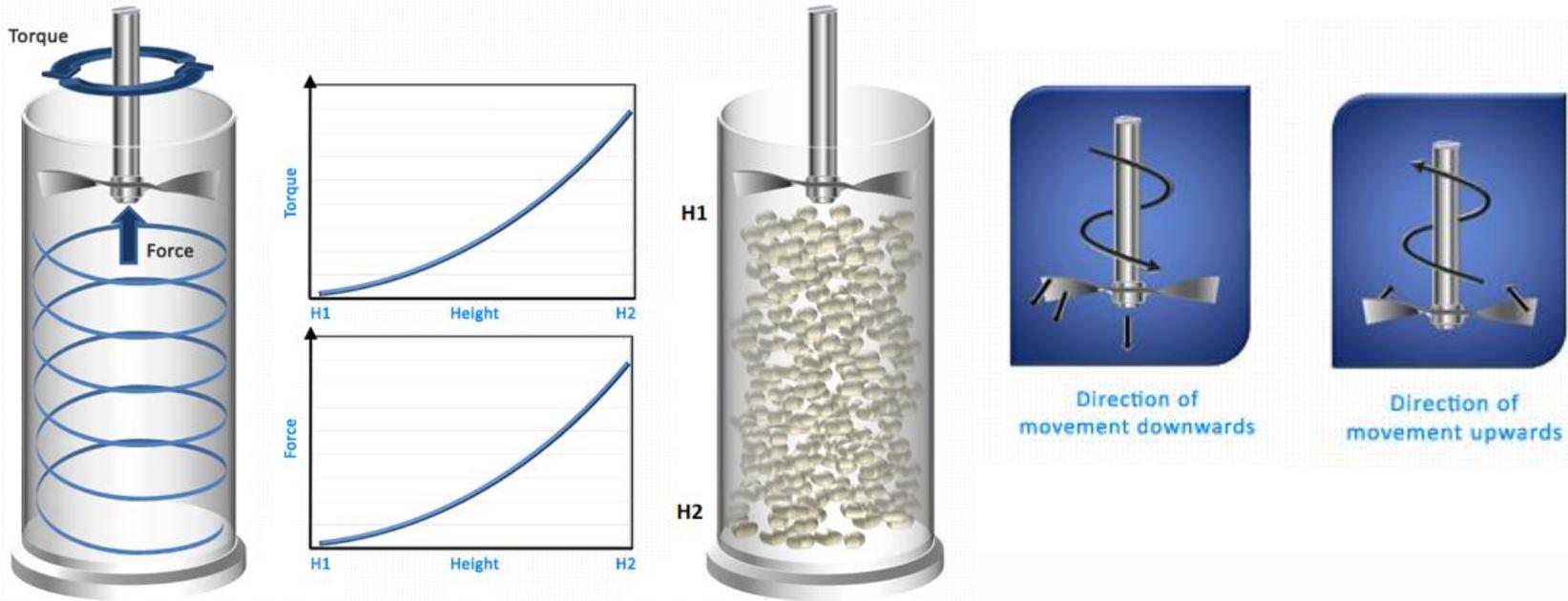
OTHERS: Ball indentation



Zafar, U., C. Hare, G. Calvert, M. Ghadiri, R. Girimonte, B. Formisani, M.A.S. Quintanilla, and J.M. Valverde. "Comparison of Cohesive Powder Flowability Measured by Schulze Shear Cell, Raining Bed Method, Sevilla Powder Tester and New Ball Indentation Method." *Powder Technology* 286 (December 2015): 807–16. doi:10.1016/j.powtec.2015.09.010.



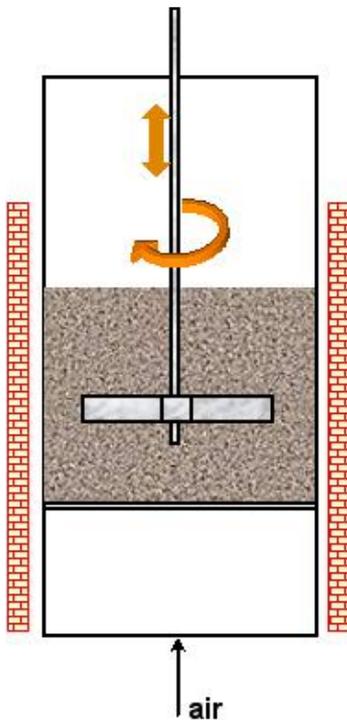
OTHERS: FT4 Rheometer



- A single test includes the record of the torque and force in a downward compressing movement and an upward releasing movement
- Allows to experience powder compression and tension
- Very flexible and multipurpose equipment

OTHERS: msFBR @ UCL

The mechanically stirred Fluidized-Bed Rheometer @ University College London



Aerated column sizes

Internal diameter D 14 cm

Vessel height 30 cm

Agitating system

Steel shaft height 16.5 cm

Impeller height h 7 mm

Impeller horizontal dimension d 36 mm

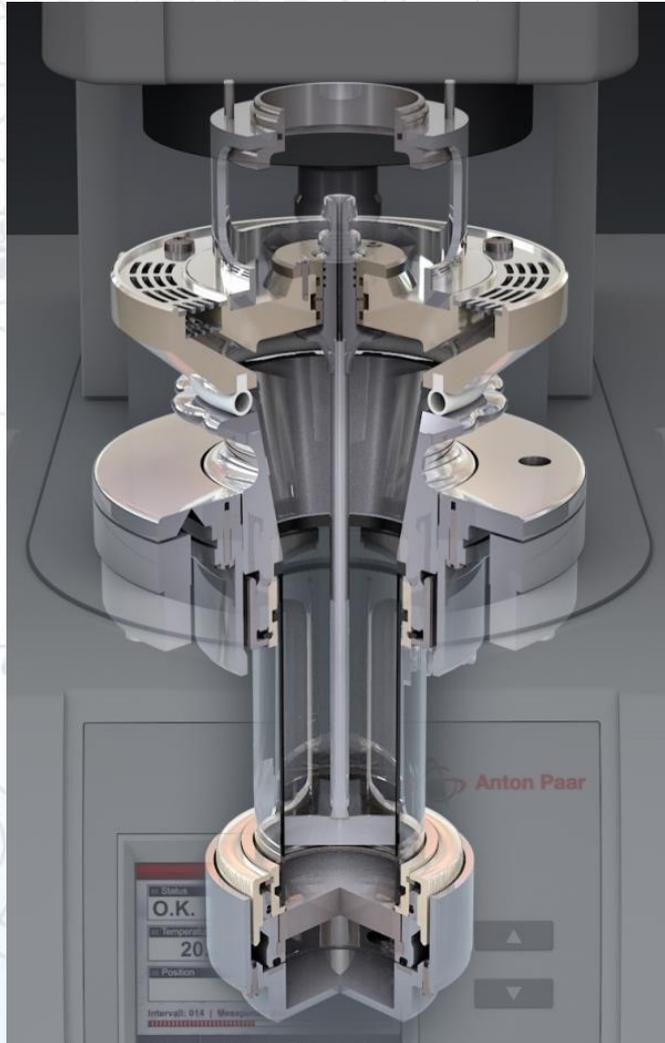
The measured variables are:

- the braking torque of the rotating impeller;
- the pressure drop across the bed.

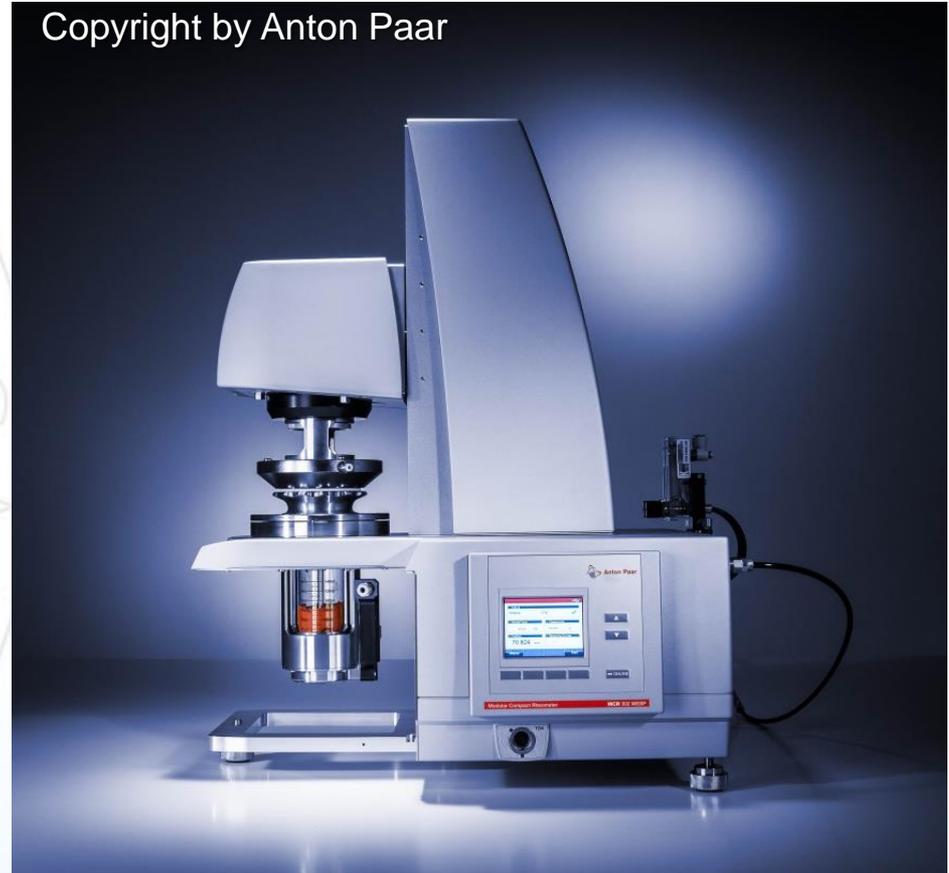
G. Bruni, D. Barletta, M. Poletto and P. Lettieri. A rheological model for the flowability of aerated fine powders. *Chemical Engineering Science*, 62, 397 – 407 (2007). ISSN: 0009-2509. doi:10.1016/j.ces.2006.08.060.

I. Tomasetta, D. Barletta, P. Lettieri and M. Poletto. The measurement of powder flow properties with a mechanically stirred aerated bed. *Chem. Eng. Sci.*, 69, 373–381 (2012). ISSN: 0009-2509. doi:10.1016/j.ces.2011.10.056

OTHERS: Anton Paar Powder Cell



Copyright by Anton Paar

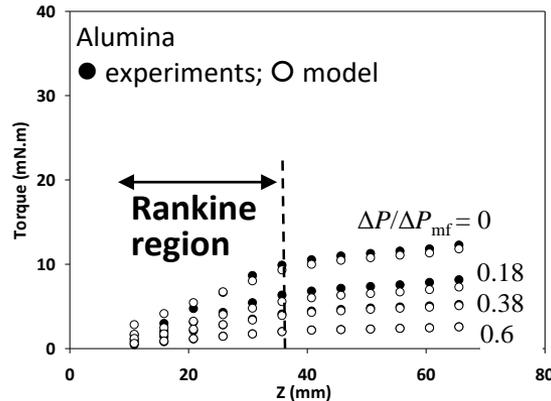
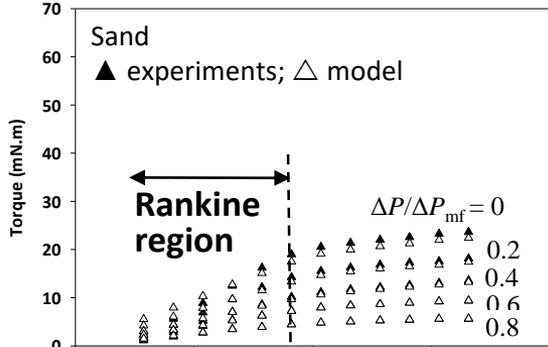
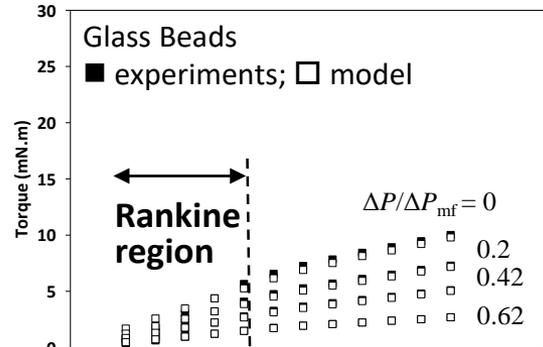


- Torque measures between 10^{-8} - 0.3 Nm
- Impeller rotational speeds 0.1 - 500 rpm.

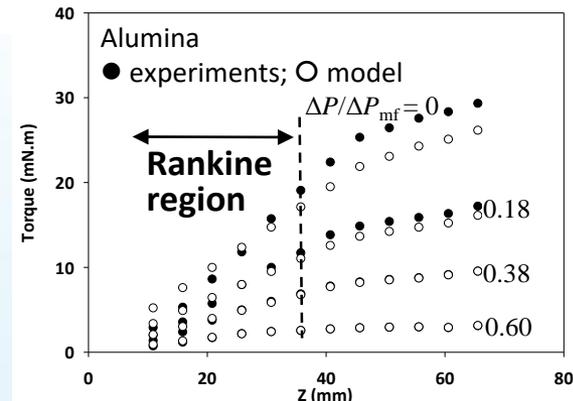
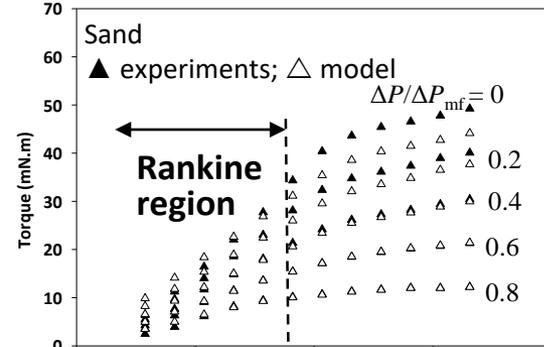
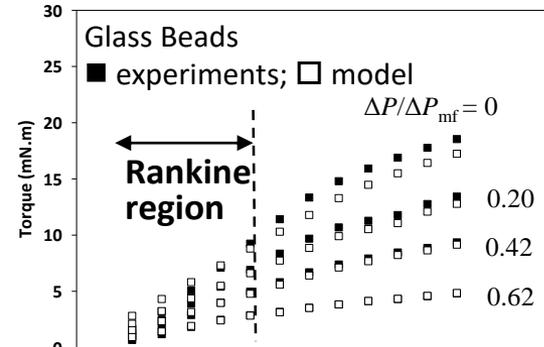
OTHERS: Torque shear based model

η values fitted in the Rankine region

$h' = 05 \text{ mm}$

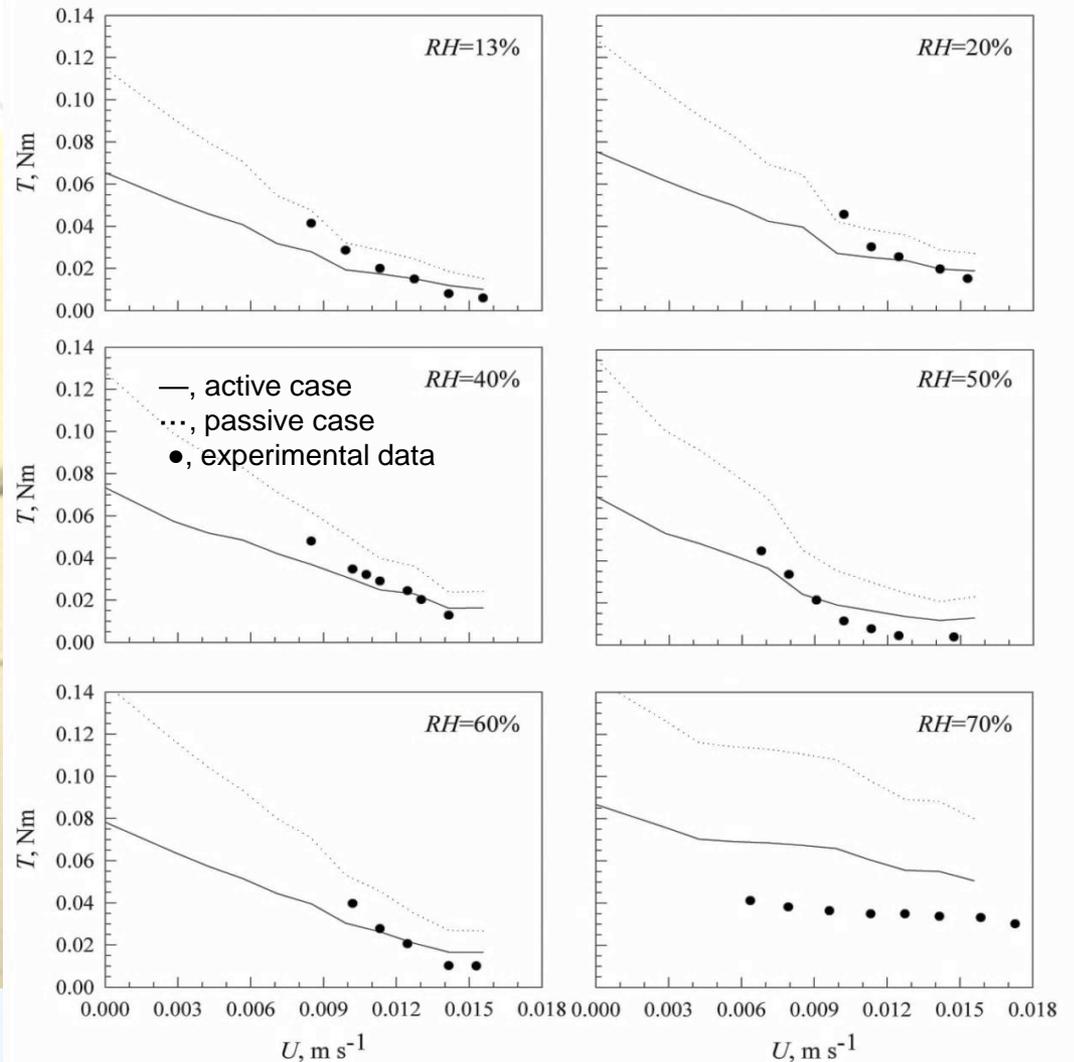
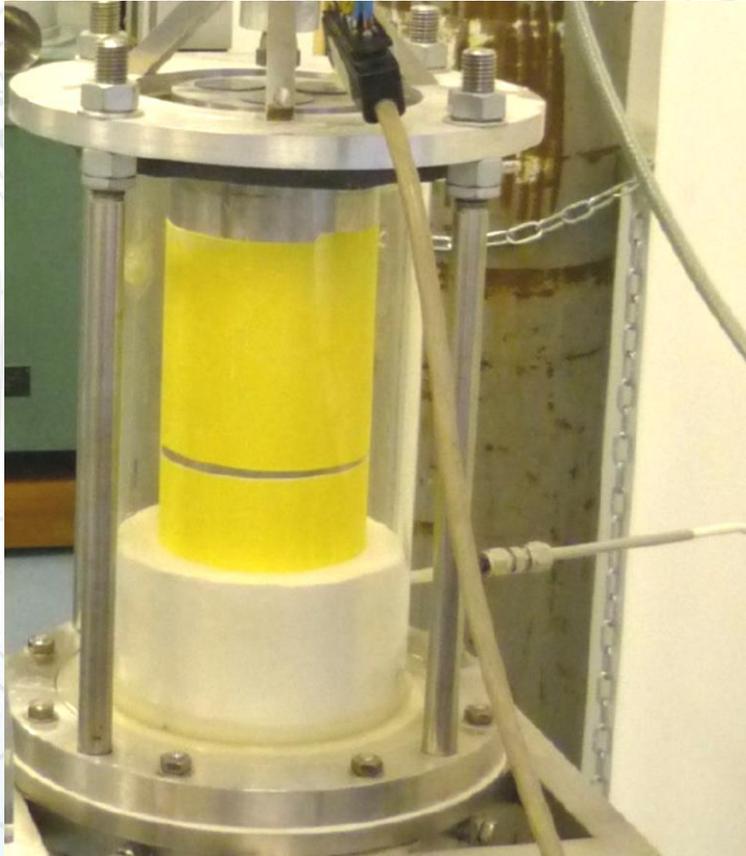


$h'' = 10 \text{ mm}$



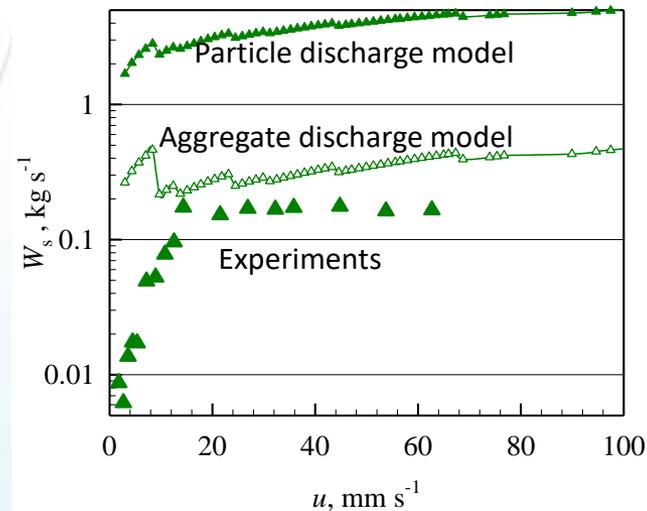
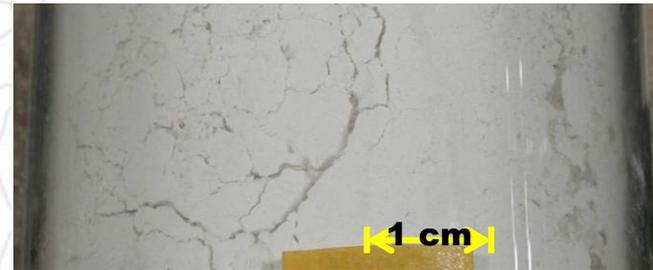
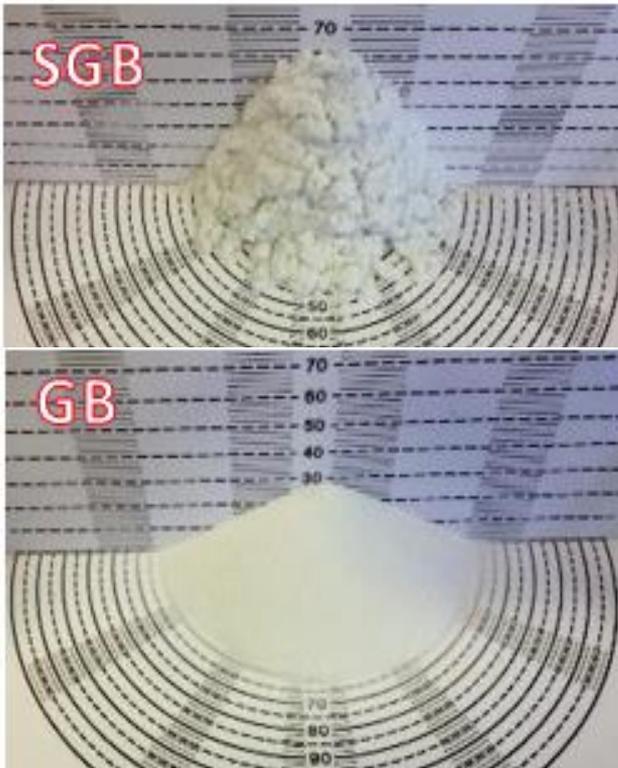
OTHERS: Couette rheometer@UCL

Glass beads in humid air



Why powder rheometers

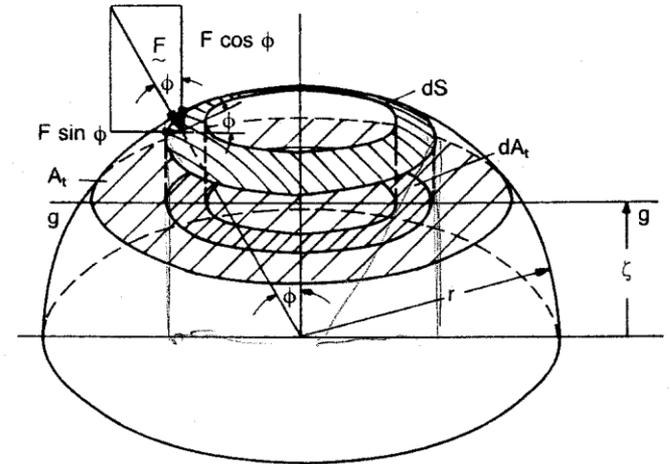
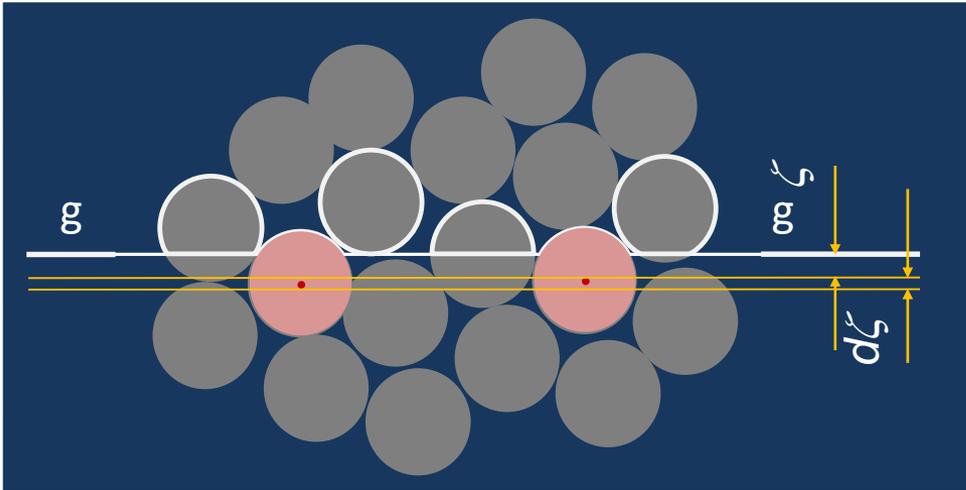
- Cohesive powders at low consolidation self-organize in aggregates
- Preshear alters this state of powders
- Rheometers do not need preshear





CONFRONT THE "GRAND CHALLENGE" TO RELATE PARTICLE PROPERTIES AND BULK FLOW BEHAVIOUR

The particle-particle approach by Rumpf (1970) and Molerus (1975)



Hypotheses

- randomly packed assembly
- spherical and monodisperse particles
- the contact areas between particles are small
- the contact points are equally distributed over the particle surface with a total number k
- the packing structure is isotropic
- isostatic state of stress.

where: σ = stress

F = interparticle force

ε = particle volume fraction

k = particle coordination number

d_p = particle diameter

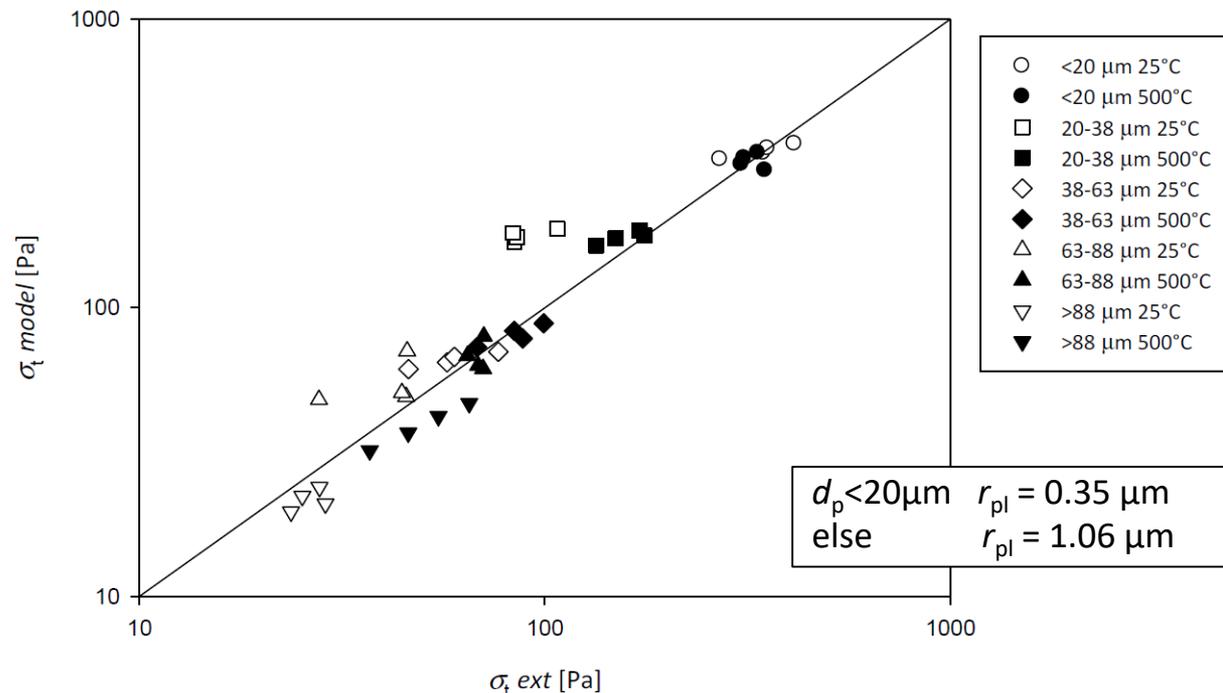
$$\sigma = \frac{\int_{-r}^r \left(\frac{k}{4\pi r^2} \int_s F \cos \phi dS \right)}{\frac{1}{(1-\varepsilon)} \int_{-r}^r \pi (r^2 - \zeta^2) n \frac{d\zeta}{r}}$$

$$\int_s \cos \phi dS = \pi (r^2 - \zeta^2) \quad k \cong \frac{\pi}{\varepsilon} \quad (\text{Rumpf, 1958 from data of Smith et al., 1929})$$

$$\sigma = \frac{F}{4r^2} \frac{k(1-\varepsilon)}{\pi} = \frac{F}{d_p^2} \frac{(1-\varepsilon)}{\varepsilon}$$

Pure ceramic powders many sizes at 25 and 500°C

- Tensile strength predicted with Rumpf model
- van der Waals interparticle forces predicted with the Molerus model for pure plastic deformation of contact
- 1 fitting value for the equivalent radius at the contact, same for almost all

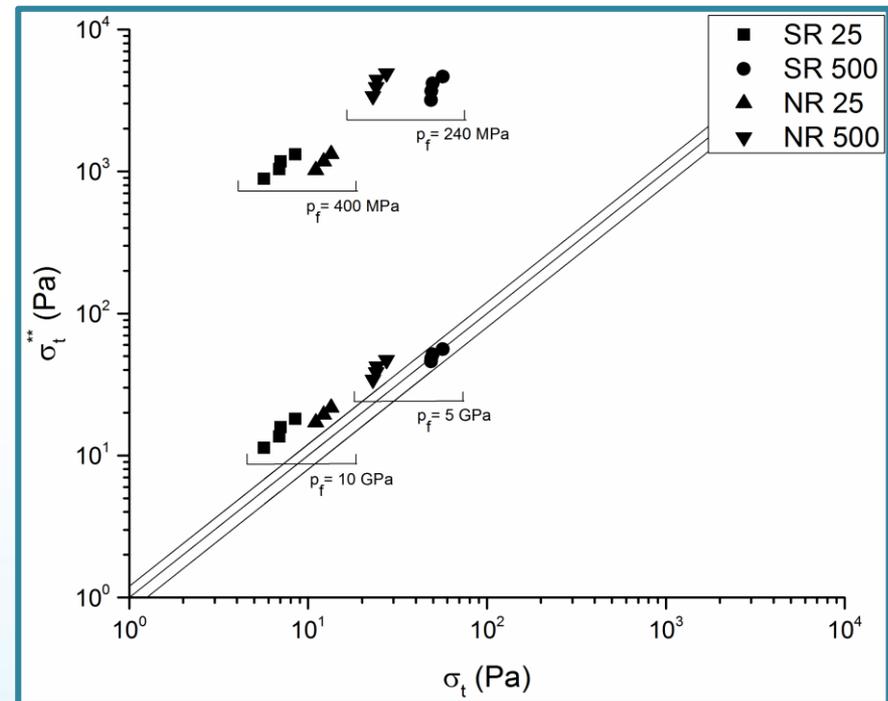


with UCL

Two Titania powders 150 μm at 25 and 500 $^{\circ}\text{C}$

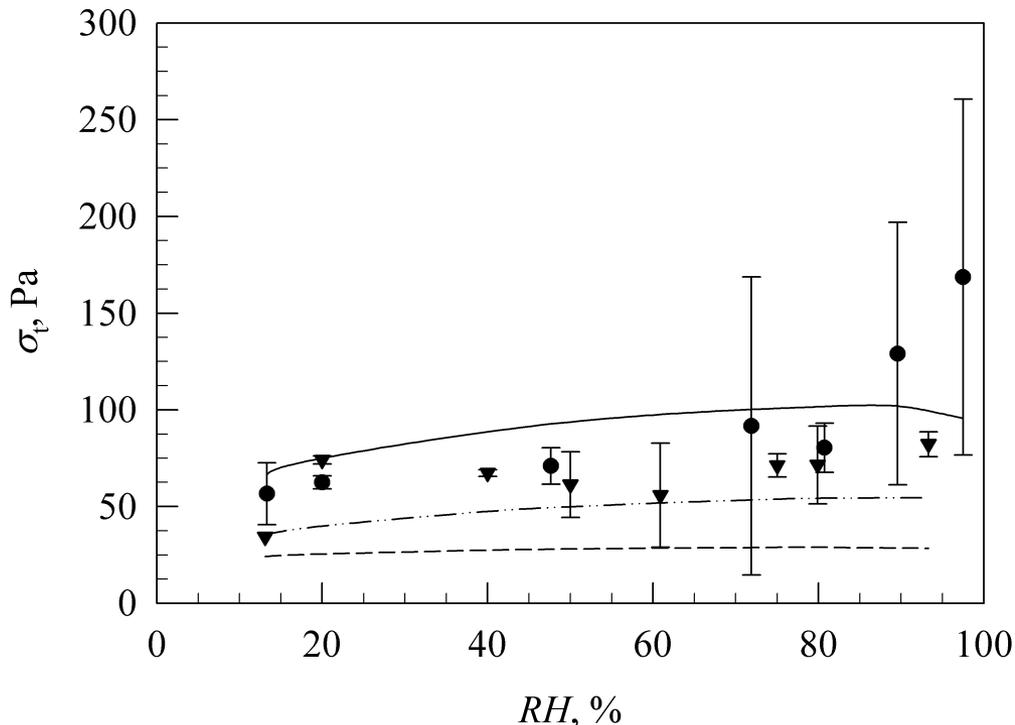
- Tensile strength predicted with Rumpf model
- van der Waals interparticle forces predicted with the Tomas model for elastic plastic deformation of contact
- equivalent radius at the contact derived from the mean Sauter diameter
- 2 different physical hypotheses for the plastic deformation strength of the contact

with UCL



Glass beads conditioned with humid powders

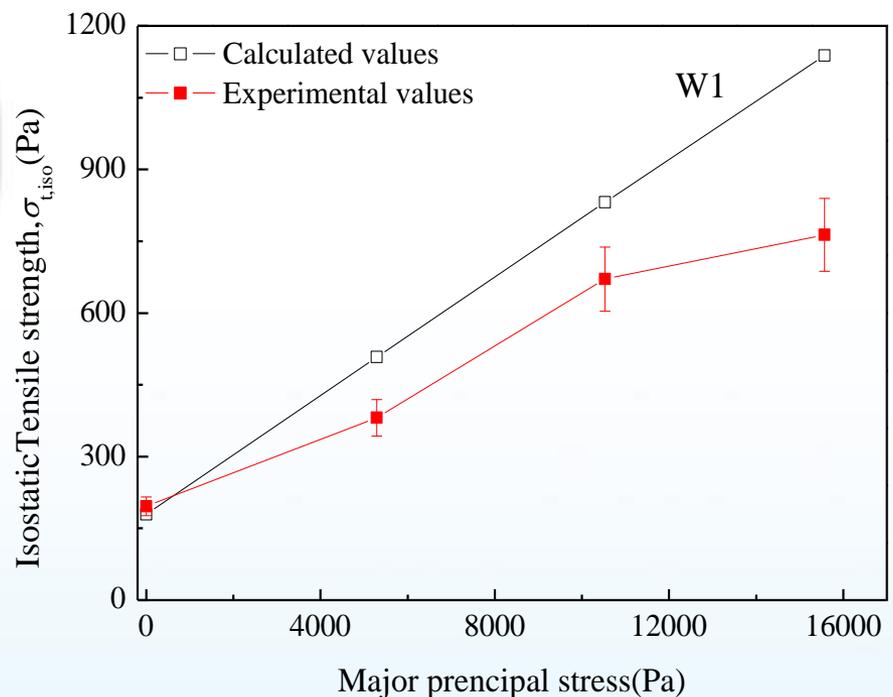
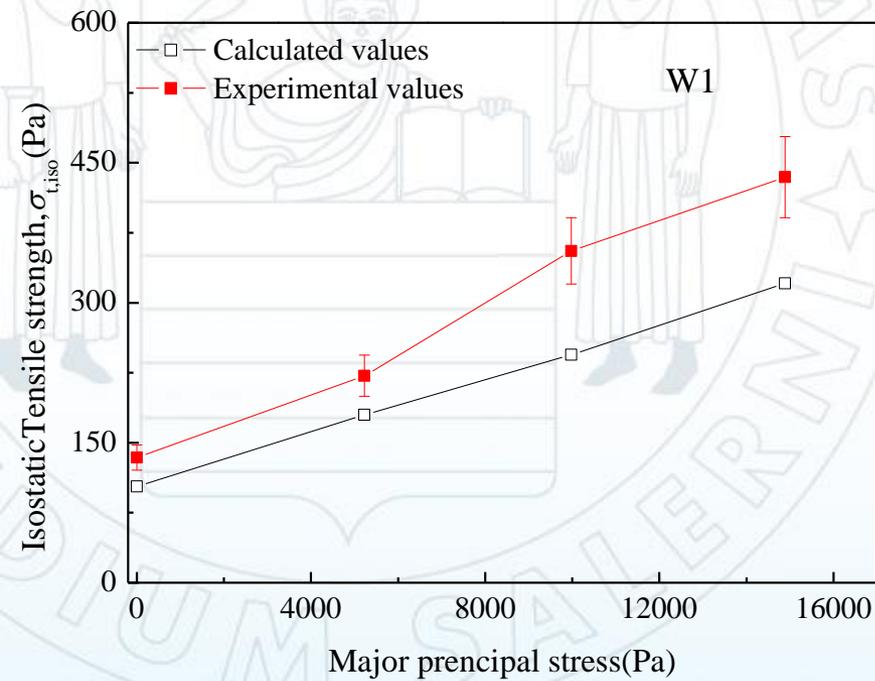
- Tensile strength predicted with Rumpf model
- Capillary bridge volume and forces estimated with the Rabinovich et al. (2002) equations and the Kelvin equation from air humidity
- Assumed asperity radius and interparticle distance in the bridge



Coal powders with large PSD

with East China University of Science and Technology

- Tensile strength predicted with modified Rumpf model accounting for large PSD
- Interparticle forces predicted with Tomas model with the Tomas model for elastic plastic deformation of contact with size dependence fitted on narrow sized samples



Three scientific questions

1) How to measure relevant powder flow properties at low consolidation?

New powder preparation procedures, in place of preshearing, should be tested. May be specific for the different kinds of application.

2) Can powder rheometry be related to powder characterization for design?

Different set up of powder rheometers can be used in order to find geometries and procedures to lead to the measurement of physically well-defined powder properties to be applied in powder flow regimes not covered by conventional shear testers.

3) Are interparticle forces estimated from bulk properties significant?

Powders of increasing complexity can be experimentally characterized at the particle and at the bulk level to verify the ability of analytical or numerical calculations to relate particle properties to powder properties.

Acknowledgements

- Prof Paola Lettieri at University College of London
- Dr Haifeng Lu and Prof Xin Gong at East China University of Science and Technology
- Dr Diego Barletta at the University of Salerno