



IFPRI Project Abstract

Flowability Assessment of Weakly Consolidated Powders

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Project Objective:

Measurement of unconfined yield strength of powders can be made with a variety of commercially available shear testing devices. Traditional flowability measurement devices have a number of shortcomings, e.g. reproducibility of unconfined yield strength is greatly reduced at low stresses, sometimes measurement is inconsistent with observed behaviour, or materials found to be cohesionless may still have practical differences. Generally the onset of flow is measured, which may not be a complete flow description. IFPRI seek to develop a theoretical understanding of flow of weakly consolidated and weakly cohesive powders and develop a practical means of making the measurement.

Approach:

We adopt the ball indentation method for determining powder flowability by measuring the resistance of a powder bed when penetrated by a sphere, which is quasi-statically introduced. It is necessary to determine the constraint factor of a powder in order to infer the yield stress from the indentation measurement. Indentation measurements are carried out on vertically consolidated beds at the same stress as uniaxial compression measurements, in order to compare flowability measurements and determine constraint factor. The influence of single particle properties and flow properties on constraint factor is explored in order to be able to predict its value so that indentation alone can be used to infer the yield stress. The shear cell method is also utilized as a comparative test.

Recent Results:

Ball indentation measurements were carried out on beds of titania prepared by sieve-filling prior to vertical consolidation, using the Freeman FT4 Powder Rheometer, to determine the influence of indenter size and position on the hardness measurement. Indents were carried out in the 50 mm diameter cell, with the centre of the radial indents (five indents for the 4 mm diameter indenter, four for the 6 mm indenter) at a radial distance of 14 mm. As shown in Figure 1, for both indenter sizes the hardness measured

by the single indent in the centre is greater than the average of the radial indents¹. This may indicate a greater packing fraction in the centre of the bed.

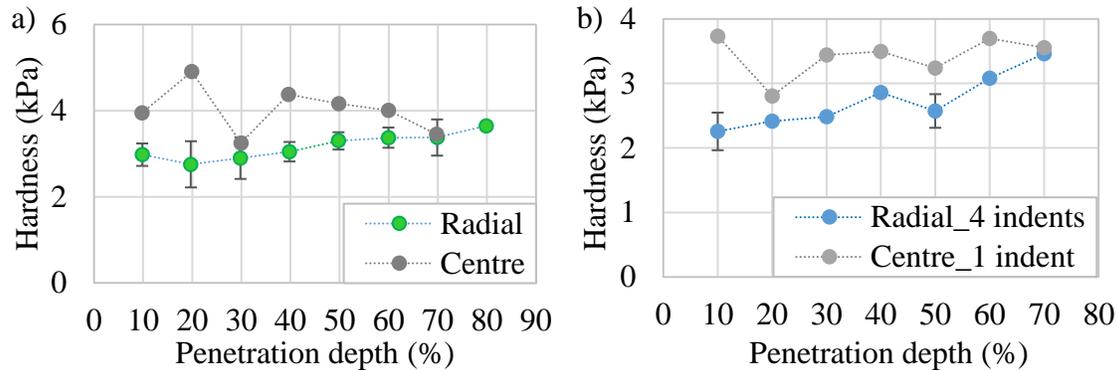


Figure 1. Hardness against dimensionless penetration depth at central and radial indentation positions (a) 4 mm indenter (b) 6 mm indenter

Indents were carried out in the central position of sieved, vertically consolidated beds using 4, 6 and 10 mm diameter indenters, with the hardness measurements shown in Figure 2. For the 10 mm indenter the hardness is relatively constant at penetration depths of 20 – 50% of the indenter radius, then increases beyond this. For the 4 and 6 mm indenter there is greater fluctuation in the hardness measurement with depth, particularly for the 4 mm indenter. Table 1 shows the maximum force measured for each indenter at all tested penetration depths. The force measurement increases as penetration depth and indenter size increase. The FT4 force sensor has a resolution of 0.1 mN and an accuracy better than the greater value of 1 % of the reading or 125 mN (0.25% of full-scale measurement). The results of Figure 2 and Table 1 suggest that as indenter size and penetration depth are reduced the hardness is overestimated due to the reduced accuracy of the force measurement.

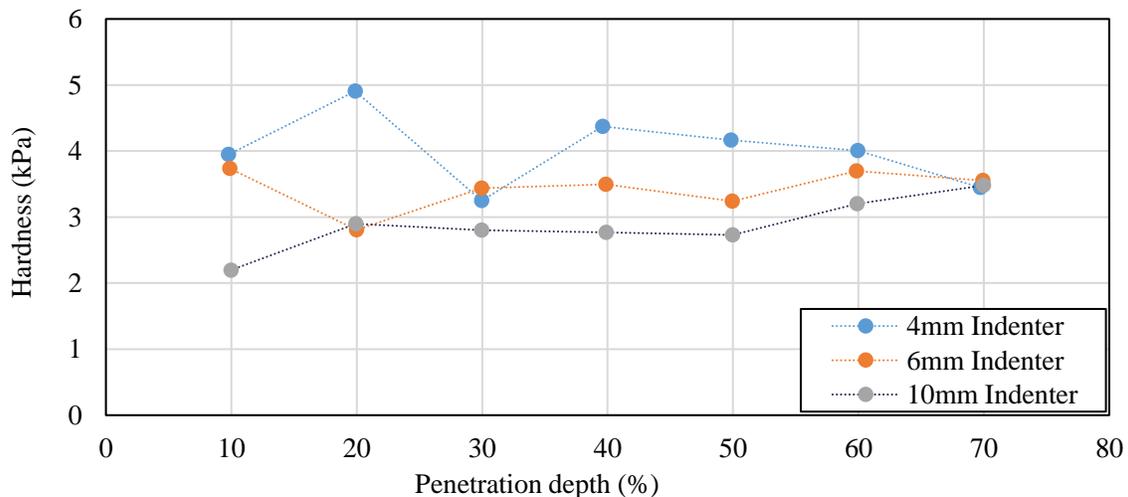


Figure 2. Hardness for various indenter sizes

¹ Note that due to lab closure in response to Covid-19, only 1 measurement has been carried out at each penetration depth for all centrally applied indents, as well as on only 1 bed for the 6 mm radial indents.

Table 1. Maximum indentation force (mN) for indenter sizes and penetration depths

Depth (%)	10	20	30	40	50	60	70
d_{Ind} (mm)							
4	9.23	22.1	20.8	34.9	39.2	42.3	39.4
6	19.9	28.5	50	63	68.7	87.7	91.4
10	32.7	81.7	112.1	139	160	211	248.6

In the first 3-year IFPRI funded period the influences of individual particle properties on constraint factor were explored experimentally using silanised glass beads (size, size distribution) and by DEM simulations (surface energy, sliding and rolling friction coefficients). Individual relationships were found, though no relationship was determined for non-glass bead samples, the results have since been reanalysed based on flow properties, i.e. the flow function coefficient, ff_c (Figure 3). Since the indentation depth has been shown to influence the hardness measurement (Figure 2) and therefore the constraint factor, only materials indented to the same depth of 50% of the indenter radius are compared in Figure 3. The constraint factor increases approximately linearly with flow function for very cohesive materials ($1 \leq ff_c < 2$), then remains relatively stable around a value of 4 for cohesive ($2 \leq ff_c < 4$) materials. It should be noted that pea protein exhibited slip-stick behaviour, compromising the reliability of the constraint factor data for this material.

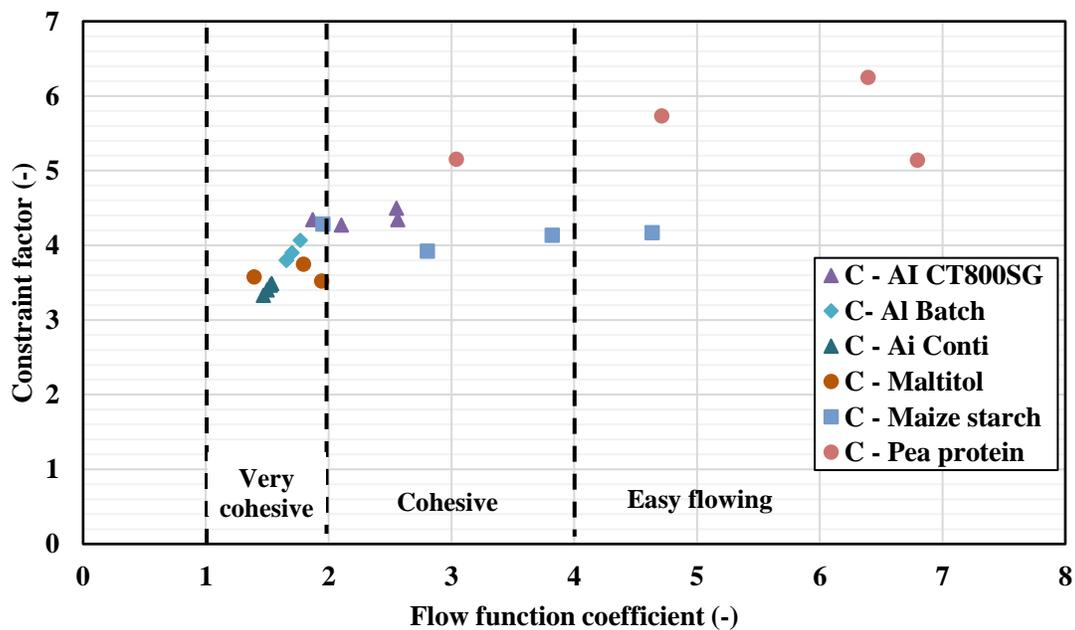


Figure 3. Relationship between constrain factor and flow function coefficient

It has previously been shown for titania that ball indentation onto sieve-filled, vertically consolidated beds and shear cell analysis using the Schulze RST XS.s with low stress cell

can achieve unconfined yield stress measurements with coefficients of variation $< 2\%$ at an applied stress of 0.5 kPa, however the unconfined yield stress measurements do not agree between the techniques. In order to assess the accuracy of these two techniques, conical hoppers will be designed for mass flow based on each approach and the resulting flow behaviour will be assessed. The necessary measurements for design have been completed, resulting in a hopper angle of $\sim 10^\circ$ and outlet diameters of 10 and 25 mm for flow functions determined by ball indentation and RST X.S.s measurements, respectively.

Next Steps:

Reproducible measurements of unconfined yield stress are achievable with suitable bed preparation methods, i.e. by sieve-filling prior to ball indentation or by pre-shearing. An open question remains on the accuracy of these measurements and their consistency with observed flow behaviour. Furthermore, the homogeneity of the bed packing state in these two systems is unknown.

In the remainder of the project the flowability of various powders will be assessed using indentation, uniaxial compression and the shear cell method. The constraint factor will be determined for all materials, allowing the unconfined yield stress at low stresses to be determined from ball indentation measurements and compared to those from the shear cell method. The operability range and reproducibility of these techniques, in relation to particle and flow properties, will be assessed. Hopper flow measurements will be carried out to assess the accuracy of these two techniques. Additionally, the packing fraction distribution will be assessed by X-Ray tomography (Leeds. UK) for vertically consolidated beds to determine the flow field around the ball indenter.
