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Characterization of Woody Biomass Flowability

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In this paper a simple method for characterizing the flowability of consolidated samples of woody biomass is presented. The apparatus used consists in a cylindrical bin provided with a circular orifice at the centre of its flat bottom. Biomass samples were consolidated in the bin by applying loads on the material bed surface while the bin orifice was closed by a plug. After the consolidation phase the loads were removed and the orifice was opened to assess if an arch or a rathole had formed. Critical values of consolidation loads for the formation of a stable arch were determined for different orifice sizes. These results obtained with two different samples of sawdust were compared in terms of material strength with those of flow functions obtained with a conventional Schulze shear tester.

1. Introduction

Chipped and particulate solid biomass alone or mixed with coal may cause problems related to storage, transfer and feeding to power plants (Dai *et al.*, 2008). Irregular flow of solids and blockage from storage units may occur by formation of stable arches due to cohesion or interparticle mechanical interference. Despite the occurrence of these problems, there is a poor knowledge of the flow properties of biomass materials, which may significantly differ from those of conventional granular solids used in the process industry. The few studies available in the literature report the use of shear testers to measure biomass flow properties (Zulfiqar *et al.*, 2006; Miccio *et al.*, 2009; Chevanan *et al.*, 2009) or of simple devices to directly verify the tendency to form arches (Mattsson and Kofman, 2002). In the latter case, however, the effect of the consolidation of the solids was not assessed.

In this paper two different techniques were used to evaluate the flowability of biomass. One of these techniques is a standard shear testing technique, based on the use of a Schulze Ring Shear Tester (Schulze, 1994), and a new technique originally developed in the attempt to reproduce at the laboratory scale the material behaviour close to a container orifice. The purpose is to verify if the new technique is able to classify powder flowability in the same order of the standard tester and to verify if biomass materials show peculiar behaviour in condition closer to the silo discharge.

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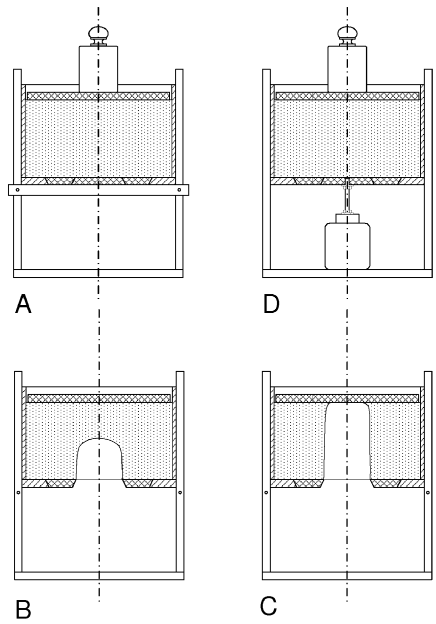

Figure 1: Apparatus and procedure: A) consolidation; B) discharge with arching; C) discharge with piping; D) measurement of transmitted load.

2. Experimental

The original apparatus consists of a cylindrical vessel, where the sample is charged and consolidated. Figure 1 shows schematically the main principles of the tester. The equipment is completely made in stainless steel AISI 304 and perspex. It consists of a pedestal and a cylindrical vessel 190 mm ID and 100 mm high, having a volume of 2.83 L, that contains the powder sample. The bottom face of the vessel can be replaced, so that different circular diaphragms can be arranged in order to test different orifice sizes. Diaphragms are available with orifices with diameters between 50 and 130 mm ID with 10 mm increments. With each of these diaphragms, a plug sustained from below with a removable beam is used to keep the bottom orifice closed during the consolidation phase (Figure 1A). A perspex cover 188 mm OD is used to apply vertical consolidation loads. The orifice can be opened from below during the test by removing the holding beam (Figure 1B-C). The transparent lid allows to discriminate between conditions in which an arch (Figure 1B) or a pipe (Figure 1C) is formed.

Two different woody biomass materials made of sawdust sieved below 4 mm and 2mm respectively and a gypsum powder with a Sauter diameter of 6.7 μm were tested (Table 1). Moisture weight fractions, X_W, were measured with an Ohaus gravimetric tester. Bulk density, ρ_b, the effective angle of the internal friction, δ, are average values from those measured in the Ring Shear Tester used to evaluate the powder flow functions (Figure 2) with a standard procedure (Schulze, 1994)

Table 1: Material properties and parameters

Material	X_W %	ρ_b kg m^{-3}	δ deg	K -	h_a mm
Gypsum	5.8	1013	60	6.4	2.0
Dry sawdust	16.0	133	53	4.2	2.0
Fresh sawdust	49.5	204	58	5.4	2.0

The procedure followed for the experiments on the arching tester is here summarized: 1) for each tested diaphragm, the cell with the closed orifice is filled with a fixed amount of powder and the surface is levelled; 2) the Perspex lid is placed on the sample; 3) a load is applied on the lid and hold for 5 min (Figure 1A); 4) the load is removed; 5) the orifice plug is smoothly removed and the fallen material is collected, and it is observed the formation of an arch (Figure 1B) or of a pipe (Figure 1C). The procedure is repeated in order to find out the critical load which determines the transition between the pipe and the arch formation. This value is registered and a new test is made with the same amount of material, by applying the found critical load and with the orifice plug supported by the load cell 500 N and precision of 0.1% (Figure 1D). This new test allows to measure the load transmitted at the cell bottom.

3. Results and discussion

Bed masses, M_b, and corresponding heights, H_b, are reported in Table 2 together with the orifice diameters, D_o, and the corresponding critical loads, F_c. Apart from some deviations, results show an increasing consolidation load with the increase of the orifice diameter to obtain a critical transition between piping and arching. This is expected since the abutment stress on the arch increases with the arch size and, therefore higher consolidation stresses are necessary to provide the material with the required strength. In Table 2 also the stress deriving from the load on the sample top, σ_{1t}, and the stresses measured at the orifice level, σ_{1b}, are reported. A common feature of these results is the fact that almost always $\sigma_{1b}>\sigma_{1t}$. This is due to the additional load at the bottom due to the weight of the bed that is not compensated by the holding effect of the container walls. The application of the Jenike criterion (Jenike, 1961) for the arch at the critical conditions stability allows an estimate of the powder unconfined yield strength with the following equation:

$$f_{cJ} = D_o \, \rho_b \, g \, / \, 2 \qquad (1)$$

where ρ_b is the powder bulk density and g is the acceleration due to gravity. Since the largest powder consolidation is obtained at the bed bottom, this consolidation condition is assumed as that which is able to determine the powder consolidation at the critical conditions between piping and arching in the powder tested. Figure 2 show a comparison between the powder flow function (f_c vs. σ_1) obtained with the Schulze shear tester and the powder flow function as it is obtained by plotting f_{cJ} values obtained

Table 2: Experimental results obtained with the arching tester

Material	D_o mm	M_b kg	H_b mm	F_c N	σ_{1t} Pa	σ_{1b} Pa
Gypsum	60	2.0	70	3.4	121	783
Gypsum	70	2.0	70	9.5	335	1006
Gypsum	80	2.0	70	11.4	404	1076
Gypsum	90	2.0	70	25.4	897	1582
Gypsum	100	2.0	70	33.3	1174	1865
Dry sawdust	50	0.22	40	0	0	40
Dry sawdust	60	0.22	50	2.0	69	53
Dry sawdust	70	0.22	50	3.9	138	100
Dry sawdust	90	0.22	70	10.4	368	379
Dry sawdust	100	0.22	70	16.3	576	628
Fresh sawdust	50	0.12	30	2.5	86	94
Fresh sawdust	70	0.22	50	2.0	69	58
Fresh sawdust	90	0.29	70	2.9	104	386
Fresh sawdust	100	0.29	70	8.0	282	477
Fresh sawdust	110	0.29	70	9.5	334	455
Fresh sawdust	120	0.29	70	20.7	732	656
Fresh sawdust	130	0.29	70	22.2	784	993

by eq (1) as a function of the corresponding σ_{1b} values. The two flow functions compare rather poorly for all the materials tested. It is difficult to explain this discrepancy with non conventional features of the new apparatus such as anisotropy, which is the different orientation of the major principal stresses during consolidation and failure (Schwedes, 2002). Even the use of a consolidation procedure which does not assure the critical state cannot justify the increasing ratio between f_{cJ} and f_c with the consolidation load. A possibility, instead, is that in the tester eq (1) may not apply. It is provided by Jenike as a safe limit for no arch formation and it is derived assuming the worst possible condition at which an arch should break, that is under its own weight only. In the experiments performed in this work, instead, the consolidation stress decreases with height; this means that in a forming cylindrical pipe the material above the arch is not self sustained but is partially held by the material at lower heights. An estimate of the maximum vertical stress, σ_v, acting on the arch can be obtained from the maximum stress obtainable with the application of the Janssen approach to the forming pipe:

$$\sigma_v = \frac{\rho_b g D_o}{4K\tan(\delta)} \tag{2}$$

where K and δ are the horizontal to vertical stress ratio and the angle of internal friction of the material, respectively. The abutment stress, σ_a, can therefore be related to this load by assuming the equilibrium of forces on the arch:

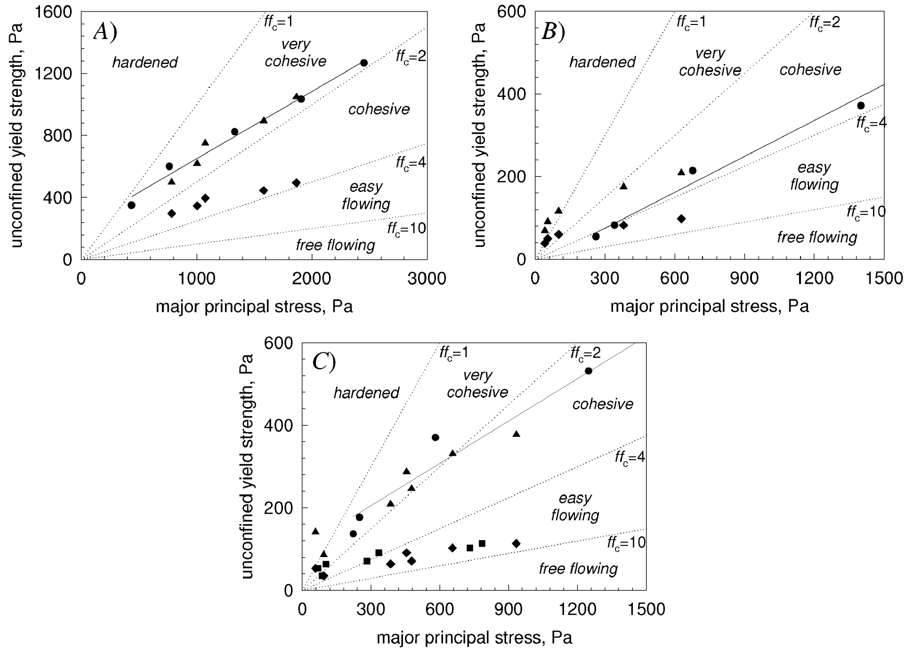

Figure 2: Flow functions for gypsum powder: ●, Schulze RST ; ◆, arching tester: f_{cJ} vs. σ_{1b}; ▲, arching tester: f_{cP} vs. σ_v. A) gypsum, B) dry sawdust, C) fresh sawdust.

$$\frac{\pi D_o^2}{4}\left(\sigma_v + \rho_b g h_a\right) = \frac{\sigma_a \pi D_o h_a}{2} \tag{3}$$

where h_a is the thickness of the supporting arch. At critical condition we have $\sigma_a = f_c$. By combining eqs (2) and (3), it is possible to find a new estimate of the unconfined yield strength:

$$f_{cP} = \frac{\rho_b g D_o}{2}\left(1 + \frac{D_o}{4K\tan(\delta)}\frac{1}{h_a}\right) \tag{4}$$

In order to carry out these estimates, however, a value for h_a has to be assumed, and in this paper it was considered as a fitting parameter. As suggested by Schulze (2008), estimates of K were calculated from the effective angle of internal friction. The passive state was assumed:

$$K = 1/1.2\left[1 - \sin(\delta)\right] \tag{5}$$

Values of K for the material are reported in Table 1 together with the fitting values found for h_a. For all the three tested material we had h_a=$2\cdot10^{-3}$. The estimates of f_{cP} are plotted vs the consolidation stress σ_{1b} in Figure 2. The correlation between the values of f_c obtained with the Schulze tester and those obtained from equation (4) is fairly good. However, this cannot be considered a real proof of the physical interpretation behind the proposed analysis. Other approaches can provide similar results. Probably the only definite conclusion that can be drawn is the fact that a linear relationship between the unconfined yield strength and the orifice diameter as reported in eq (1) cannot explain the experimental results with the newly proposed apparatus and procedure. It is likely instead that a quadratic relationship as shown by eq (4) is more suitable.

4. Conclusions

A new procedure to evaluate powder flow function from the critical orifice diameter was developed. The procedure had a fitting parameter and quantitative evaluations might be possible in terms of variation with respect to a reference condition with the same material. No significant difference occurs between the biomass materials and the gypsum powder tested suggesting that within the procedure tested woody biomass materials do not show any peculiar behaviour. Further work is required to be able to evaluate h_a independently for each material, or to change the geometry of the tester in order to make the proposed procedure an industrially acceptable testing method.

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