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Wheat flour flowability as affected by water activity, storage time and consolidation**

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A b s t r a c t. The influence of water activity, storage time and consolidation on the flowability of wheat flour were evaluated. Powder flowability was measured using a Jenike shear tester according to the Jenike procedure at four levels of normal consolidating stress within the range of 4.9-17.5 kPa. Flour was placed in a humidity chamber to obtain samples of flour at 0.33 and 0.8 water activity. Instantaneous shear tests were performed at temperature of 20°C on each sample, from which the instantaneous flow functions were obtained. Time consolidation tests on the flour at 0.33 and 0.8 water activity were carried out using a Jenike shear cell and consolidating bench for the consolidation time of 1 and 7 days. Temporal flow functions of the flour were determined to quantify the combined effect of moisture content, time and compression stress.

K e y w o r d s: flow function, powder, shear test, wheat flour

INTRODUCTION

Powder properties measurement is important because these properties intrinsically affect powder behaviour during storage, handling and processing. Powder flow properties are important in handling and processing operations, such as flow from hoppers and silos, transportation, mixing, compression and packaging. Powder flow characteristics are commonly investigated by various measurements, such as handling angles, tap testing, shear cell measurements, *etc*. All these approaches allow the calculation of indices characterizing powder flowability (Peleg, 1978; Schwedes, 1996; Tchoreloff *et al*., 1999). Flow properties of powder must be studied in terms of quality control of raw materials in order to maintain product uniformity, but also to avoid situations in which process breakdown may occur, with respect to imposed conditions.

Changes in particle properties (moisture content, particle size) and storage conditions may influence the flowability of powders, sometimes even small changes can have significant effects. Storage conditions include storage temperature, exposure to humidity of air, storage time, and consolidation (Fitzpatrick *et al*., 2004b; Horabik, 2001; Teunou and Fitzpatrick, 1999). Moisture content usually has a significant impact on powder flowability. Increasing moisture content leads to reduced flowability due to the increase in liquid bridges and capillary forces acting between the powder particles. Even a free flowing powder can develop flow problems after an extended period of storage. This effect is due to time-consolidation, where a powder consolidates under its own weight over time (Teunou and Fitzpatrick, 2000).

It is obvious that flow characteristics of powders are highly dependent on their compaction. Powders can be more or less expanded or contracted when stressed, thus leading to a large variety of inter-particle forces. Factors associated with the nature of the particles are size, shape, surface morphology (Molerus and Nywlt, 1984; Teunou *et al*., 1999). Packing ability should be considered when studying powder flow properties, but particle forces associated with these factors should also be taken into consideration. Then, a powder must be considered as a whole medium that sums up all these interactions at the particle contacts. Powder flow properties are influenced by any factor that can have an effect on these interactions (Deleuil *et al*., 1994).

Powder flow characteristics are commonly investigated under loading conditions of gravity, using measurements such as the angle of repose and other handling angles, standardized flow rate, apparent and 'tapped' densities, and derived indices such as defined by Abdullah and Geldart

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(1999), Carr (1965) or Hausner (1967). Such measurements have demonstrated the dependence of powders flow on particle shape and size distribution, on temperature and relative humidity, but they have been proved difficult to relate to features at particulate level.

Thus, a more fundamental and physical measurement should be easily achievable using shear cells (Horabik and Grochowicz, 2002; Jenike, 1964; Kamath *et al.*, 1993; Schulze, 1996). These cells are designed to condition powders under a known load and to measure forces needed to shear powder beds (Fitzpatrick *et al*., 2004a; Knowlton *et al.*, 1994). This measurement is able to provide useful indications of powder flow threshold, while the powder bed is being loaded. Then, if the forces applied on a powder are approximately known during a given process, intrinsic information regarding the frictional and cohesive nature of granular material can be gathered. This information could then be relevant during a real process. It is important to note that this methodology is time and product consuming and that correct and reproducible preparation of samples is quite difficult to achieve, and results can be very operator and know-how dependent. Once frictional properties of a given powder have been identified by shear testing, tap testing can be profitably used for routine checks or to establish conformity of different batches because empirical connections have been found between tap density values and shear cell determined flow functions (Tchoreloff *et al*., 1999).

As the characterization of flowability, wide acknowledgment was gained by the flow function *FF* introduced by Jenike (1964), being the dependence of the unconfined yield strength, σ_c on the major consolidating stress, σ_1. The flow function *FF* characterizes the susceptibility of a material to disturbances of free outflow from container under the force of gravity, and applies it for design engineering of silo hoppers. Besides, results of shear cell tests make possible the qualitative comparison of different bulk materials, on the basis of a parameter proposed by Jenike and Carson (1985) and Schubert (1987). This parameter is the flow index, ff_c, calculated as the relation σ_1 / σ_c. Bulk materials can be classified in accordance to their flowability using values of the flow index, ff_c into the following manner: very cohesive ($ff_c < 2$); cohesive ($2 < ff_c < 4$); easy flowing ($4 < ff_c < 10$); free flowing ($10 < ff_c$).

The aim of this work was to evaluate the influence of moisture content, storage time and consolidation on wheat flour flowability.

MATERIAL AND METHODS

Wheat flour type 500 with different degrees of moistening was used as a material for investigation. The flour was examined at the water activity, a_w: 0.33 and 0.8; the water content, u: 11 and 16.1% w w^{-1} respectively, *ei* the commercial and moistened flour. A pneumatic moistening cell (laboratory made model) was used to obtain the required level of water activity.

Physical properties measurement

- Particle size distribution determination was performed with a Kamika model AWK – V 97 particle size analyzer in air with powder feeder unit.
- Moisture content (wet basis) was measured gravimetrically by weighing 3 g of a sample before and after drying at 105°C for 6 h. Each test was carried out in triplicate.
- Bulk density was measured using an Engelsmann model A-G mechanical tapping device, where the volume of a given mass of powder after 500 taps was measured to calculate the tapped bulk density.
- Water activity was measured using a Rotronic model Hygroskop DT 1 device.

Shear cell measurements

All measurements were performed with a Jenike shear cell (laboratory made model, diameter of 9.5 cm). Under a uniaxial normal stress, σ, a powder bed may develop irreversible packing, resulting in consolidation and leading to a tangential force needed to shear the bed. The shear cell was then placed in a chamber, with a temperature of 20°C, where the shear tests for measuring the instantaneous flow function were conducted. The procedure used to measure the instantaneous flow function, using the Jenike shear cell. For any flow function, four yield loci and four points for each yield locus were obtained. To construct a yield locus, the powder was critically consolidated under a known normal consolidating stress, σ_1, and the shear stress, τ, required to cause the powder to fail under four normal stress, σ, less than the consolidating stress and at the consolidating stress were measured. A yield locus is a plot of failure shear stress versus normal stress for a given consolidating stress. This is repeated for four different consolidating stresses to obtain four yield loci. Every point of the yield locus was repeated four times. A yield locus is presented in Fig. 1. The results of shear stress measurements are classically interpreted as yield loci in the Mohr space (Schubert, 1987; Schwedes, 1996). The intercept of the yield loci with τ axis gives the cohesion parameter τ and the slope gives rise to kinematic angles, φ, of internal friction. From each yield locus, the following two quantities were estimated by two specific Mohr circles tangent to the yield loci give rise to the major consolidating stress, σ_1, and to the unconfined yield strength, σ_c. It gives the stress needed to make an arch collapse and make the material flow. A plot of σ_c versus major consolidating stress, σ_1 can be obtained and represents the flow function *FF* (Schwedes, 2002). Time-consolidation tests were carried out using a Jenike shear cell and a consolidating bench. Time-consolidation test is performed in a similar way to an instantaneous flowability test. The four normal consolidating stress, σ_E, was 4.9, 9.1, 13.3 and 17.5 kPa and 1 and 7 days consolidation times were chosen.

RESULTS AND DISCUSSION

Unconsolidated wheat flour type 500 with the standard water activity of 0.33 showed good flowing properties. Materials characterized by Hausner ratio, I_H, smaller than 1.25 are qualified as powders with good flowability (Abdullah and Geldart, 1999; Hausner, 1967). The moistening of the flour to the water activity of 0.8 (moisture content of about 16%) causes the decreasing of loose and tapped bulk density, ρ_L, ρ_T – respectively (Table 1). According to the Jenike criterion, the moistening of flour to the water activity of 0.8 of the tested flour does not cause changes in the flowability. The instantaneous flow functions of the flour with the water activity of 0.33 and 0.8 are found in one section of the flowing criterion (the flow index $4 < ff_c < 10$) and present them as weakly cohesive, easy flowing materials (Table 1, Fig. 2). Moisture content affected flow parameters, however the impact was not strong (Domian and Poszytek, 2004).

The storage time of the consolidated flour with the consolidating stress $\sigma_E = 17.5$ kPa causes a worsening of the flowability, especially conditioned to the higher moisture content. Flow function *FF* of the dry flour (a_w =0.33) stored for 0, 1 or 7 days was included in the range ($4 < ff_c < 10$) (Fig. 2a). Instead, the flow function of the moist flour (a_w = 0.8) consolidated respectively for 0, 1 and 7 days was found in the range ($4 < ff_c < 10$) and ($2 < ff_c < 4$) (Fig. 2b). The position of the flow function *FF* curve gives a basis to the classification of stored flour according to the Jenike criterion as follows: dry flour – a powder weakly cohesive and easy flowing, moist flour – a cohesive material with quite difficult flow. The storage time of moist flour can result in considerable difficulties in the gravitational discharge – in a partial set-back (the creation of tunnels) or complete stoppage (the creation of vaults over the spout) of the flow of material and damage of the behindhand flour basin.

Detailed analysis of the parameters of plastic flow showed a statistically significant influence of the consolidation time and water activity on bulk density, cohesion and strength of stored consolidated flour.

Bulk density for consolidated (stored) flour, ρ, increases with storage time aside from of the consolidation stress σ_E and water activity, a_w. The kinetic angle of internal friction, φ, of stored flour is characteristic for the given water activity, a_w, and is related to the storage time (Table 2). The value of the angle φ fluctuates within 19-31° for the flour with a_w = 0.33 and within 27-30° for the flour with a_w =0.8. Values of the effective angle of internal friction, δ, change with consolidation time for the flour with a_w = 0.33 in the range 25-36°. The average effective angle of internal friction, δ, for the consolidated flour about a_w = 0.8 in the range 30-38°.

Cohesion, *C*, of stored flour increases together with the value of the consolidating stress, σ_E, from 4.89 to 17.5 kPa, with the extension of the storage time from 0 to 7 days and with the moisture content from 11 to 16% (Table 2). Differences in cohesion between dry flour (a_w = 0.33) and moist flour (a_w = 0.8) decrease along with increasing storage time. The dry flour, characterized with the lower level of cohesion, *C*, after 0 and 1 day of storage, after 7 days of storage attains the level of cohesion of the moist flour. The cohesion *C* of the flour with the water activity a_w = 0.33 and 0.8 increases with increasing consolidation time.

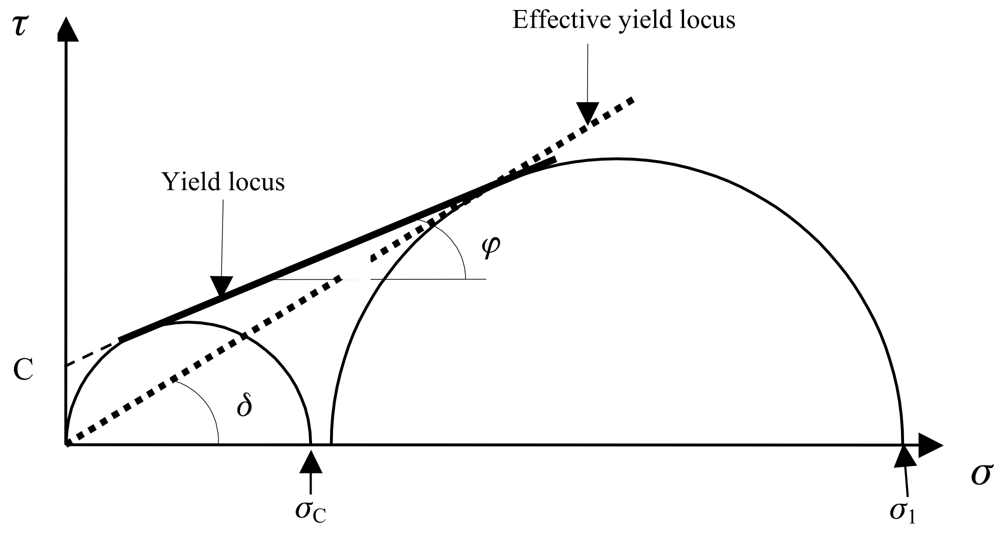

Fig. 1. Illustration of a powder yield locus. φ – kinetic angle of internal friction (°), τ – shear stress (Pa), δ – effective angle of internal friction (°), σ – normal stress (Pa), σ_1 – major consolidating stress (Pa), σ_c – unconfined yield strength (Pa).

T a b l e 1. Physical properties of tested wheat flour

d_{50}* (μm)	u (% w w^{-1})	a_w (-)	ρ_L (kg m^{-3})	ρ_T (kg m^{-3})	I_H (-)
103	11.0	0.33	600	744	1.24
	16.4	0.80	593	725	1.22

*d_{50} – mean particle size.

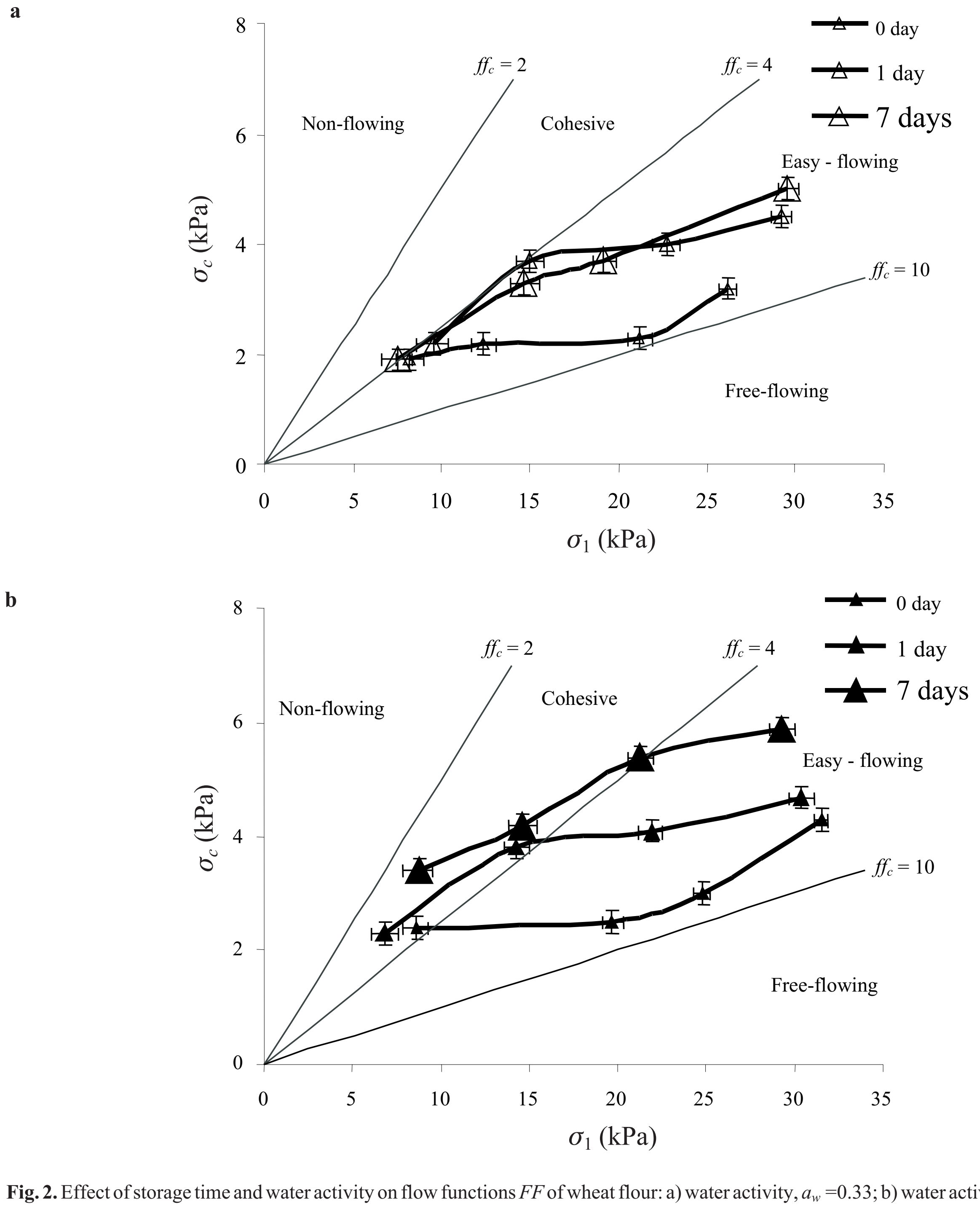

Fig. 2. Effect of storage time and water activity on flow functions *FF* of wheat flour: a) water activity, a_w =0.33; b) water activity, a_w=0.8.

T a b l e 2. Effect of storage time, water activity and consolidation stress on the flow parameters of wheat flour

Storage time (days)	a_w (-)	σ_E (kPa)	ρ (kg m^{-3})	φ (°)	δ (°)	C (kPa)	σ_c (kPa)	σ_1 (kPa)	ff_c (-)
0	0.33	4.89	792	27	33	0.60	1.9	8.2	4.3
		9.09	805	26	29	0.74	2.2	12.4	5.6
		13.30	820	28	30	0.74	2.3	21.2	9.2
		17.50	825	28	33	0.97	3.2	26.2	8.2
0	0.80	4.89	772	31	38	0.92	2.4	8.6	3.6
		9.09	789	30	33	1.02	2.5	19.7	7.9
		13.30	795	32	34	1.19	3.0	24.8	8.3
		17.50	805	26	32	1.79	4.3	31.5	7.3
1	0.33	4.89	813	25	33	0.61	2.2	9.5	4.3
		9.09	827	33	39	0.83	3.7	15.0	4.1
		13.30	837	33	36	0.95	4.0	22.7	5.7
		17.50	842	34	35	1.01	4.5	29.2	6.5
1	0.80	4.89	781	21	30	1.17	2.3	6.8	3.0
		9.09	805	30	36	1.52	3.8	14.3	3.8
		13.30	813	32	35	1.63	4.1	21.9	5.3
		17.50	832	30	33	1.94	4.7	30.4	6.5
7	0.33	4.89	827	17	24	0.77	1.9	7.5	3.9
		9.09	840	19	25	1.38	3.3	14.7	4.5
		13.30	844	20	25	1.51	3.7	19.2	5.2
		17.50	847	21	26	1.90	5.0	29.6	5.9
7	0.80	4.89	789	28	38	1.07	3.4	8.7	2.6
		9.09	818	24	32	1.49	4.2	14.6	3.5
		13.30	827	30	36	1.69	5.4	21.3	3.9
		17.50	837	25	30	2.02	5.9	29.3	5.0

a_w – water activity, σ_E – consolidating stress, ρ – bulk density of consolidated material, φ – kinetic angle of internal friction, δ – effective angle of internal friction, C – cohesion, σ_c – unconfined yield strength, σ_1 – major consolidating stress, ff_c – flow index.

The unconfined yield strength, σ_c, increases with the storage time and the consolidating stress, σ_E. The moist flour (a_w = 0.8) is characterized by a higher strength, σ_c, in comparison with the dry flour (a_w = 0.33). Differences in the strength increase along with the extension of the storage time (Table 2). After 7 days of storage, the moist flour (a_w =0.8) was characterized by a higher unconfined yield strength, by 34% in relation to the same flour with water activity of 0.33. Aside from of the water activity of the flour and the storage time, an increase in the value of unconfined yield strength, σ_c, together with the level of the consolidating stress, σ_E, was observed.

CONCLUSIONS

1. Temporal flow functions were used to assess the effect of moisture content, storage time and consolidation on the flowability of flour.
2. The tested flour demonstrated time-consolidation effect. Flowability was reduced with increasing consolidation time, especially conditioned to the higher moisture content.
3. The bulk density and cohesion of the flour increased during the consolidation time resulting in a more compact and cohesive powder with reduced flowability.
4. The wet flour with water activity of 0.8 (water content of 16.1%) was more cohesive than the flour with water activity of 0.33 (water content of 11%) and showed greater sensitivity to time-consolidation.
5. The storage of the moist flour could cause a lot of difficulties at the gravitational outflow from the reservoir.

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