# Direct shear testing of flowability of food powders

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**ABSTRACT**: The flow properties were determined for two groups of food powders used in industry: cereal powders and non-starch powders. Materials were different in mean sizes of particles *d** ranging from 0.033 mm for potato flour to 4.449 mm for oatmeal. Experiments were performed in 60 mm in diameter direct shear tester (Jenike shear tester) for four values of consolidating stress $\sigma_r$: 30, 60, 80 and 100 kPa. The highest values of flow function (*FF*) and the widest range of its variability (ranging from 0.5 kPa to 35 kPa) were found in the case of pearl barley groats. For the non-starch powders values of *FF* were more stable and did not exceed a limit characteristic for easy flowing materials. The highest values of *FF* in the group of the non-starch materials were obtained for icing sugar (from 19 kPa to 24 kPa) while the lowest found were values of *FF* for salt (from 3 kPa to 7 kPa). Powdered milk and potato flour showed the widest variability of *FF* values within the non-starch materials.

**Keywords**: powders; flow function; consolidation pressure; flow properties; milk powder; cereal powder

With an increasing quantity and variety of powders being produced in industry, there is growing need for information about material characteristics important for handling and processing. Knowledge of mechanical properties of food powders is essential for design of industrial equipment, efficient and reliable material processing as well as for estimation of quality of raw material (MOLENDA, STASIAK 2002). The knowledge of physical properties of food powders is also important for quality assessment of final product on-line as well as during later storage, handling and transport. Flow properties of powders influence handling and processing operations, such as flow from silos and hoppers, transportation, mixing, compaction and packaging (KNOWLTON et al. 1994).

Two basic patterns of the flow in silos can be distinguished: mass flow and funnel flow (KNOWLTON et al. 1994; FITZPATRICK et al. 2003; JENIKE 1964; SCHWEDES 1996). During mass flow all the powder is in motion and moving downward towards the discharge opening while for funnel flow powder discharge through a flow channel formed within the grain bulk and no sliding along the wall is present. Serious industrial problem that occur during technological operations on food powders is case of stop of flow. This is usually a result of an arch forming across the discharge opening, which has strength sufficient to be self-supporting. One of the applications of flowability characteristics is its use in design of hoppers for mass flow. The design consist of predicting hopper dimensions required to produce mass flow, the maximum angle of the hopper and the minimum outlet dimension for mass flow (JENIKE 1964; SCHWEDES 1996, 2002; TEUNOU et al. 1999; KNOWLTON et al. 1994).

Currently a number of methods and testers is available to determine the strength and flow properties of bulk solids. Choosing the right method for the specific application requires knowledge and some experience in handling of bulk materials as outlined by SCHWEDES (2002). The flow properties of bulk solids can be determined by performing shear test. Testing to determine the strength properties of granular material consists of two stages: consolidation and shear force measurements. The replications of the test give similar results only if the consolidation was identical (SCHWEDES 2002; FEISE 1998).

JENIKE (1964) proposed the theory of flow of granular material and methods of determination of material parameters including the shear cell technique for measuring powder flow properties. As a result of two-dimensional stress analysis this author recommended the method of estimation of the minimum hopper opening dimension for mass flow from conical and wedge shaped hoppers. The design requires determination of following material characteristics: the flow function *FF*, the effective angle of internal friction $\delta$ and the angle of wall friction $\varphi_w$. The flow function is a plot of unconfined yield strength $\sigma_c$ of the powder against major consolidating stress $\sigma_1$, and represents the strength of the consolidated powder that must be surpassed to initiate flow of the powder (see Fig. 1). Regarding values of flow function powders may be characterized as free flowing, easy flowing, cohesive and strong cohesive as illustrated in Fig. 2 (JENIKE 1964; TEUNOU, VASSEUR 1996). Based on linearized flow function the flow index *i* is defined as the slope of the flow function.

Typical application of flow function as a material characteristic in industry is quality assessment of powders (SCHWEDES 1996; KNOWLTON et al. 1994; BELL et al. 1994). It was suggested by many researchers that physical properties have strong influence on flow properties of powders (JOHANSON 2000). FITZPATRICK et al. (2003) determined flow properties of 13 food

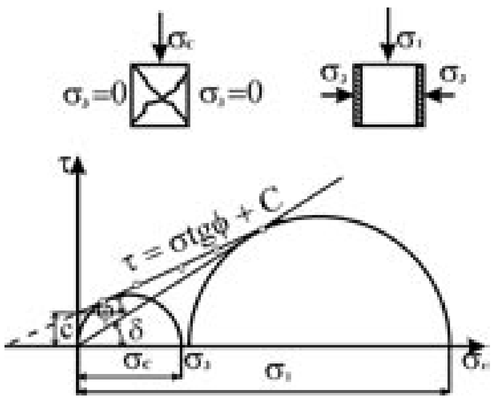


Fig. 1. Unconfined yield strength $\sigma_c$; determination $\sigma_c$ and $\sigma_1$ from linear yield locus

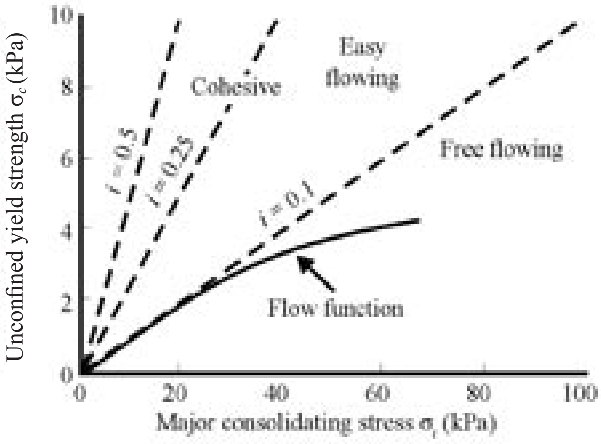


Fig. 2. Flow function

powders of various particle sizes, moisture contents, bulk densities and particle densities using annular shear cell. Based on results obtained materials were classified in groups from easy flowing to very cohesive. The authors concluded that particle size and moisture content influenced flowability, but no strong enough relationship was found to relate the flowability of the food powders based solely on these physical properties. They also stated that surface forces between particles influence flowability in a considerable degree.

TEUNOU et al. (1999) reported results of flowability determination in annular shear tester for 4 food powders and discussed possible relations between flowability and physical properties and relative humidity of surrounding atmosphere. Authors presented an evaluation of the effect of storage time and consolidation on the flowability of the food powders. All tested food powders demonstrated time-consolidation effect such that their flowability was reduced with increasing consolidation time.

HORABIK and GROCHOWITZ (2002) examined the strength characteristics of powdered milk, agglomerated milk and potato flour using Jenike shear tester in a range of applied consolidation stress from 30 to 240 kPa. Their experiments revealed a significant effect caused by shear stress vibration resulting from dilatation and hardening of the material during the slow shearing phase of tests.

The objective of this work was to examine the influence of particle sizes and moisture contents of two groups of food powders used in industry on their angles of internal friction and flowability characteristics (flow function *FF* and flow index *i*).

## MATERIALS AND METHODS

Two groups of materials were investigated: cereal powders (pearl barley groats, coarse flour, manna, oat meal, semolina) and non-starch powders (sugar, icing sugar, powdered milk, potato flour, salt). Materials were different in mean sizes of particles *d**, in ranging from

Table 1. Physical properties of food powders and their mean particle sizes

| Powder | Moisture content (%) | Mean particle sizes $d^*$ (mm) | Poured density $\rho_2$ (kg/m$^3$) | Tapped density $\rho_3$ (kg/m$^3$) | Porosity $p$ (%) |
|---|---|---|---|---|---|
| Cereal | | | | | |
| Coarse flour | 13.4 | 0.147 | 647 ± 1 | 790 ± 7 | 61.7 |
| Semolina | 12.7 | 0.176 | 652 ± 2 | 785 ± 7 | 57.7 |
| Wheat groats | 13.6 | 0.683 | 738 ± 2 | 866 ± 10 | 51.0 |
| Pearl barley groats | 13.2 | 2.849 | 702 ± 2 | 874 ± 9 | 52.7 |
| Oat meal | 11.0 | 4.499 | 444 ± 1 | 557 ± 4 | 71.5 |
| Non-starch | | | | | |
| Icing sugar | 0.4 | 0.061 | 726 ± 2 | 957 ± 9 | 64.5 |
| Table sugar | 0.4 | 1.070 | 858 ± 2 | 1,070 ± 7 | 49.2 |
| Potato flour | 18.2 | 0.033 | 685 ± 1 | 762 ± 7 | 66.0 |
| Powdered milk | 4.4 | 1.252 | 577 ± 2 | 701 ± 4 | 67.9 |
| Table salt | 0.2 | 0.553 | 1,087 ± 3 | 1,531 ± 11 | 41.7 |

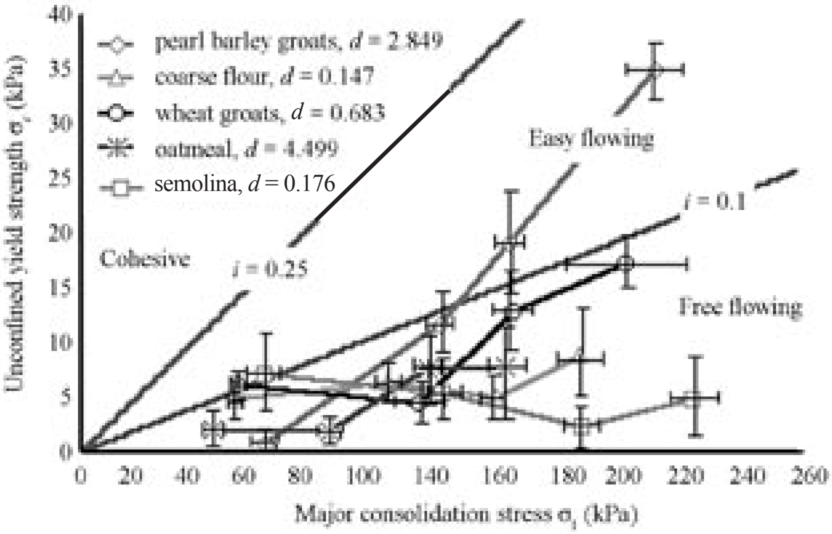


Fig. 3. Cereal powders flow functions

0.033 mm for potato flour to 4.449 mm for oat meal, and in moisture contents. Properties of the powders are shown in Table 1. Parameter $\rho_2$ is the density measured for material poured into measurement vessel without vibration or other compacting action whereas tapped density $\rho_3$ was determined after densifying material by vibration as described by DOBRZAŃSKI et al. (1994).

Experiments were performed in 60 mm in diameter direct shear tester (Jenike shear tester) for four values of consolidating stress $\sigma_r$: 30, 60, 80 and 100 kPa. During testing a displacement velocity of 0.03 mm/s was used. Linear yield locus in the form of Mohr Coulomb yield criterion was assumed and determined as recommended by Eurocode 1 (2003) and Polish Standard (2002) using values of maximum shear stress under two values of consolidating stress $\sigma_r$ and 1/2 $\sigma_r$.

From determined yield locus the following material characteristics were estimated: angle of internal friction φ, effective angle of internal friction δ, cohesion *c* and with two particular Mohr circles: unconfined strength $\sigma_c$ and major consolidating stress $\sigma_1$ (Fig. 1). Tests were performed in 3 replications.

## RESULTS

Figs. 3 and 4 show flow functions obtained for cereal food powders and non-starch food powders tested. The flow index *i* of each powder, that is given as the slope of the *FF*, took values characteristic for free flowing and easy flowing materials for the range of applied consolidating stresses. The highest values and the widest range of variability (from 0.5 kPa to 35 kPa) of *FF* were obtained for pearl barley groats. For the other powders values of *FF* were more stable and did not exceed a range of values of flow function characteristic for easy flowing materials ($i$ = 0.1). A comparison of results for table sugar and icing sugar shows that decrease in particle size tends to reduce flowability, probably because the particle surface area per unit mass increases providing larger surface area for cohesive forces to act that in turn causes more cohesive behavior.

In the case of the non-starch materials the highest were values of *FF* found for icing sugar (from 19 kPa to 24 kPa) while the lowest were those of salt (from 3 kPa

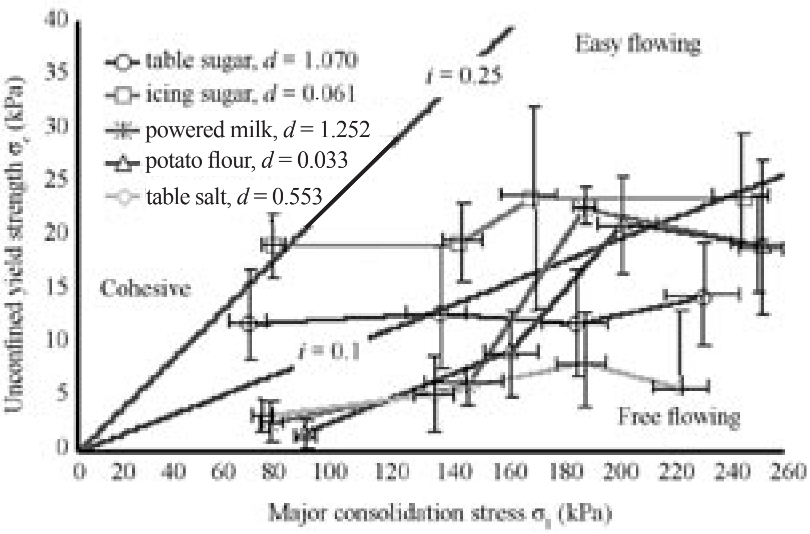


Fig. 4. Non-starch powders flow functions

Table 2. Characteristics of direct shear test

| Powder<br>Moisture content (%) | Consolidation stress $\sigma_z$ (kPa) | Effective angle of internal friction δ (deg) | Angle of internal friction φ (deg) | Cohesion $c$ (kPa) | Flow index $i$ |
|---|---|---|---|---|---|
| **Cereal** | | | | | |
| Coarse flour<br>13.4 | 30 | 28.3 ± 2.4 | 25.9 ± 0.9 | 1.5 ± 0.4 | 0.09 |
| | 60 | 27.6 ± 1.8 | 26.1 ± 0.7 | 2.0 ± 0.6 | 0.06 |
| | 80 | 27.9 ± 1.5 | 27.1 ± 0.6 | 1.5 ± 0.6 | 0.03 |
| | 100 | 26.8 ± 2.1 | 25.5 ± 0.8 | 2.8 ± 1.2 | 0.05 |
| Semolina<br>12.7 | 30 | 34.1 ± 4.4 | 31.3 ± 1.1 | 2.0 ± 1.1 | 0.10 |
| | 60 | 33.0 ± 3.0 | 32.0 ± 0.7 | 1.5 ± 0.9 | 0.04 |
| | 80 | 33.9 ± 1.7 | 33.7 ± 0.1 | 0.6 ± 0.7 | 0.01 |
| | 100 | 33.3 ± 3.5 | 32.8 ± 0.8 | 1.3 ± 1.7 | 0.02 |
| Wheat groats<br>13.6 | 30 | 28.9 ± 2.1 | 25.8 ± 0.6 | 1.9 ± 0.3 | 0.11 |
| | 60 | 30.9 ± 3.2 | 29.9 ± 1.1 | 1.3 ± 0.4 | 0.04 |
| | 80 | 29.8 ± 2.6 | 27.6 ± 0.8 | 3.9 ± 1.1 | 0.08 |
| | 100 | 30.2 ± 0.7 | 27.8 ± 0.2 | 5.2 ± 0.4 | 0.08 |
| Pearl barley groats<br>13.2 | 30 | 33.3 ± 3.8 | 33.0 ± 1.3 | 0.2 ± 0.5 | 0.01 |
| | 60 | 33.4 ± 2.2 | 31.0 ± 0.7 | 3.3 ± 0.6 | 0.09 |
| | 80 | 29.7 ± 3.1 | 26.6 ± 1.1 | 5.9 ± 1.4 | 0.11 |
| | 100 | 31.5 ± 3.3 | 29.0 ± 1.7 | 10.5 ± 0.5 | 0.10 |
| Oat meal<br>11.0 | 30 | 22.0 ± 3.5 | 20.8 ± 1.0 | 0.7 ± 0.6 | 0.04 |
| | 60 | 19.4 ± 2.2 | 18.8 ± 1.2 | 0.7 ± 0.3 | 0.02 |
| | 80 | 21.5 ± 2.3 | 19.8 ± 0.9 | 2.7 ± 1.1 | 0.06 |
| | 100 | 21.4 ± 2.5 | 19.2 ± 0.9 | 2.8 ± 1.5 | 0.05 |
| **Non-starch** | | | | | |
| Icing sugar<br>0.4 | 30 | 34.2 ± 3.6 | 31.0 ± 0.7 | 5.4 ± 0.5 | 0.12 |
| | 60 | 34.1 ± 3.2 | 32.5 ± 0.8 | 5.3 ± 0.9 | 0.06 |
| | 80 | 32.5 ± 3.9 | 28.7 ± 2.6 | 7.0 ± 3.2 | 0.14 |
| | 100 | 36.9 ± 2.5 | 34.6 ± 0.6 | 6.2 ± 1.6 | 0.09 |
| Table sugar<br>0.4 | 30 | 33.1 ± 7.5 | 27.8 ± 2.1 | 3.6 ± 1.1 | 0.09 |
| | 60 | 34.0 ± 7.9 | 31.5 ± 1.9 | 3.6 ± 2.3 | 0.09 |
| | 80 | 34.6 ± 6.9 | 33.1 ± 1.9 | 3.2 ± 1.4 | 0.06 |
| | 100 | 34.7 ± 3.7 | 33.2 ± 6.0 | 3.9 ± 1.2 | 0.06 |
| Potato flour<br>18.2 | 30 | 39.8 ± 2 | 39.3 ± 0.7 | 0.4 ± 0.3 | 0.02 |
| | 60 | 39.4 ± 4 | 37.5 ± 1.5 | 2.3 ± 1.2 | 0.07 |
| | 80 | 37.5 ± 3 | 35.2 ± 1.0 | 5.5 ± 1.1 | 0.10 |
| | 100 | 35.0 ± 2 | 35.8 ± 0.8 | 4.9 ± 1.1 | 0.08 |
| Powdered milk<br>4.4 | 30 | 35.5 ± 3 | 34.2 ± 1.1 | 0.7 ± 0.5 | 0.05 |
| | 60 | 35.8 ± 6 | 34.6 ± 3.4 | 1.6 ± 0.3 | 0.06 |
| | 80 | 35.8 ± 1 | 32.6 ± 0.2 | 6.2 ± 0.3 | 0.12 |
| | 100 | 35.8 ± 1 | 35.7 ± 1.4 | 4.9 ± 1.9 | 0.11 |
| Table salt<br>0.2 | 30 | 34.4 ± 7.1 | 33.0 ± 1.7 | 0.9 ± 0.3 | 0.05 |
| | 60 | 32.9 ± 3.5 | 31.9 ± 0.9 | 1.5 ± 1.0 | 0.04 |
| | 80 | 35.0 ± 3.5 | 33.9 ± 0.9 | 2.2 ± 1.4 | 0.04 |
| | 100 | 33.3 ± 3.2 | 32.6 ± 0.8 | 1.6 ± 1.5 | 0.03 |

to 7 kPa). Powdered milk and potato flour showed the widest range of variability of the *FF*.

Similarly to results of FITZPATRICK et al. (2003) no meaningful relationship between the powder physical properties and its flowability was found.

Values of angle of internal friction φ were found stable in a range of applied consolidation stress for each of food powders tested and varied from approximately 21° for oatmeal to approximately 38° for potato flour. The highest values of cohesion *c* were obtained for pearl barley groats that was consolidated under 100 kPa of vertical stress (Table 2).

## CONCLUSIONS

There is no clear relationship between the powder physical properties and the powder flowability.The flow functions (*FF*) of all tested materials take values characteristic for free flowing and easy flowing materials in a range of applied consolidating stresses.

The tendency reported for the mineral powders that material with larger individual particles flow easier is confirm for non-starch materials (icing sugar, sugar) and is not valid for cereal powders.

Powders of more regular shape of particles flow easier (table salt).

Values of angle of internal friction for each powder were found stable in a range of applied consolidation stress.

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## Přímý smykový test tokové funkce potravinářských prášků


**ABSTRAKT**: Byly určeny tokové vlastnosti dvou druhů potravinářských prášků používaných v průmyslu: mouky a neškrobové prášky. Tyto materiály se vyznačovaly různým rozměrem částic *d** v rozmezí od 0,033 mm pro bramborovou mouku do 4,449 mm pro ovesný šrot. Experimenty byly prováděny ve smykovém testovacím zařízení o průměru 60 mm (Jenikův tester) pro čtyři hodnoty konsolidačních tlaků $\sigma_r$: 30, 60, 80 a 100 kPa. Nejvyšší hodnoty tokové funkce (*FF*) a nejvyšší obsah její variability (v rozsahu od 0,5 kPa do 35 kPa) byly nalezeny v případě ječné krupice. Pro neškrobové prášky byla *FF* mnohem stabilnější a nepřesahovala limitní charakteristiky snadno tekoucích materiálů. Nejvyšší hodnoty *FF* ve skupině neškrobových materiálů byly získány pro cukr do cukrářské polevy (od 19 kPa do 24 kPa) a nejnižší hodnoty *FF* byly nalezeny pro sůl (od 3 kPa do 7 kPa). Práškové mléko a bramborová mouka vykazovaly nejvyšší variabilitu z neškrobových materiálů.



**Klíčová slova**: prášky; toková funkce; konsolidační tlak; toková vlastnost; sušené mléko; mouka



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