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DIRECT SHEAR TESTING OF FOOD POWDERS FLOWABILITY – INFLUENCE OF DEFORMATION SPEED AND APPARATUS STIFFNESS*

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A b s t r a c t. The objective of the project was the determination of conditions producing stick-slip effect during shear test of food powders and the examination of the influence of speed and stiffness of apparatus on their flowability. Experiments were performed in a shear tester of 60 mm in diameter for four different food powders: corn flour, wheat starch, potato starch and fine potato starch. For all of the materials examined, oscillations of shear stress vs. displacement experimental curves were observed, for all speeds and stiffness values, except for potato starch at 2 mm min^{-1} and lower stiffness. Changing the speed of deformation in the case of wheat flour, fine potato starch and potato starch did not cause changes in the values of flow functions. In the case of corn flour, an increase in speed resulted in flow functions of values characteristic for cohesive materials.

K e y w o r d s : shear test, flowability, food powders, powder properties

INTRODUCTION

With increasing quantity and number of types of powders being produced in industry, there is a growing need for information about their material characteristics important for handling and processing. Knowledge of mechanical properties of food powders is essential for the design of industrial equipment, efficient and reliable material processing, as well as for estimation of the quality of raw material [11]. The knowledge of physical properties of food powders is also important for quality assessment of final product on-line as well as during subsequent storage, handling and transport. Flow properties of powders influence the handling and processing operations, such as flow from silos and hoppers, transportation, mixing, compaction and packaging [10].

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Two basic patterns of the flow in silos can be distinguished: mass flow and funnel flow [6,8,10,12]. During mass flow, all the powder is in motion and moving downward towards the discharge opening, while for funnel flow powder discharges through a flow channel formed within the grain bulk and no sliding along the walls is present. Cessation of flow is a serious industrial problem that occurs during technological operations on food powders. 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 the design of hoppers for mass flow. The design consists in predicting hopper dimensions required to produce mass flow, the maximum angle of the hopper, and the minimum outlet dimension for mass flow [8,10,12,13,15].

Currently a number of methods and testers are 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 bulk materials, as outlined by Schwedes [13]. The flow properties of bulk solids can be determined by performing the shear test. Testing to determine the strength properties of granular material consists of two stages: consolidation and shear force measurement. The replications of the test give similar results only if the consolidation was identical [5,13].

Jenike [8] 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 the determination of the following material characteristics: the flow function *FF*, the effective angle of internal friction δ and the angle of wall friction φ_w. The flow function is a plot of unconfined yield strength σ_c of the powder against major consolidating stress σ_1, and represents the strength of the consolidated powder that must be surpassed to initiate flow of the powder. Regarding the values of flow function, powders may be characterized as free flowing, easy flowing, cohesive and strongly cohesive [8,14]. Based on linearlized flow function, the flow index *i* is defined as the slope of the flow function.

A typical application of flow function as a material characteristic in industry is the quality assessment of powders [3,10,12]. It was suggested by many researchers that physical properties have a strong influence on the flow properties of powders [9]. Fitzpatrick and others [6] determined the flow properties of 13 food powders of various particle sizes, moisture contents, bulk densities and particle densities using the annular shear cell. Based on the results obtained, the 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 to a considerable degree. Teunou and others [14] 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. The 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. Numerous papers were published that considered the influence of physical and mechanical properties of investigated materials on their flow properties measured in shear tester but there is still lack of information about the influence of speed of shearing and stiffness of apparatus on flowability.

The objective of the reported project was the determination of conditions producing stick-slip effect in food powders and the examination of the influence of speed and stiffness of apparatus on flowability described by flow function *FF*.

MATERIALS AND METHOD

The experiments were performed in a shear tester of 60 mm in diameter, for four different food powders: corn flour, wheat starch, potato starch and fine potato starch. Tests were performed following the Eurocode 1 procedure in a range of consolidation stress from σ_r = 4 kPa to σ_r = 10 kPa, for two speeds of shearing – V = 2 and V = 4 mm min^{-1} and for three levels of stiffness of washer supporting test box: G0 $E = 2{\cdot}10^5$ MPa, G1 E = 6.5 MPa and G2 E = 4.8 MPa. The washer was placed between the upper part of the test box and the strain gauge. The yield locus was determined according to the recommendations of Eurocode 1 [1] and Polish Standard [2] using values of maximum shear stress under two values of consolidating stress σ_r and ½ σ_r in three replications.

With the yield loci determined, Mohr circles were drawn and unconfined yield strength σ_c and the major consolidating stress σ_1 were determined. The relationship between the two parameters represents the flow function *FF* of the material.

RESULTS

Relationships between shear stress τ and relative displacement $\Delta l/d$ were measured in the experiments. Oscillations of shear stress were observed for all of the examined materials, speeds and stiffness values, with the exception of potato starch for 2 mm min^{-1} and stiffness G0 for all consolidation pressures (Fig. 1).

Differences were observed between the experimental relationships in the first part of the experiments performed. Decreased stiffness resulted in longer increasing part of the shear stress-displacement curve and in a higher value of stress taken for determination of yield locus. To determine the yield locus, the higher values of shear stress during oscillations were used (Fig. 1).

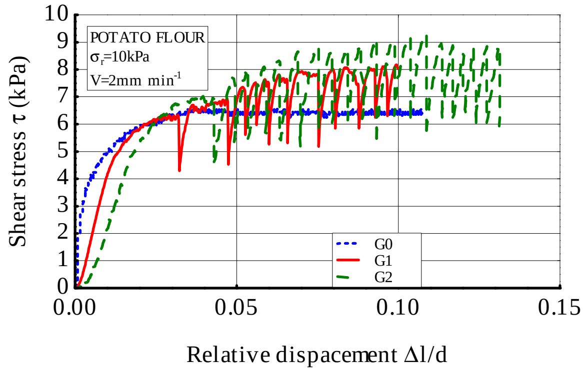

Fig. 1. Experimental curves obtained for potato flour for three stiffnesses of washer supporting stress

The amplitude of oscillations for each material increased with an increase in consolidation stress. The change in velocity from 2 mm min^{-1} to 4 mm min^{-1} resulted in an increase in the amplitude of oscillations that depended to an extent on the material and consolidation pressure. Oscillations in stress-displacement characteristics occurred when shear stress values were close to the limit condition. Typical relationships between amplitude and speed of deformation determined for corn flour are shown in Figure 2. Probably the main reason for the observed oscillations was cycling dilatation and compaction of the material in the area of the shear plane. Compaction of the material caused a gradual increase of strength of material that resulted in an increase of support shear stress, but when the maximum strength was surpassed dilatation of material occurred with a ramp down of the stress.

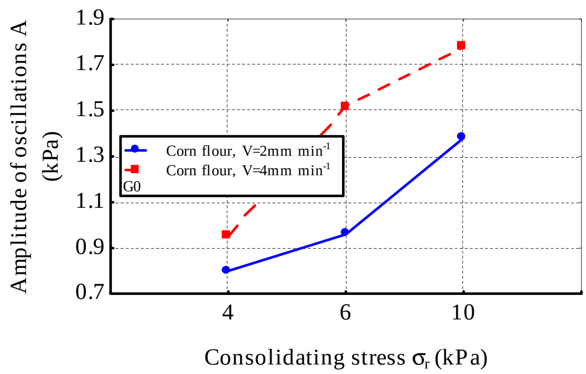

Fig. 2. Relationship between amplitude of oscillations *A* and consolidating stress σ_1 for corn flour for two speeds of deformation and support stiffness G0

The highest values of the amplitude of oscillations of approximately 2.6 kPa were obtained for corn flour at the displacement speed of 4 mm min^{-1}, stiffness G2 and consolidation stress of 10 kPa. The lowest was the amplitude for fine potato starch at V = 4 mm min^{-1}, G0 and consolidation stress of 4 kPa.

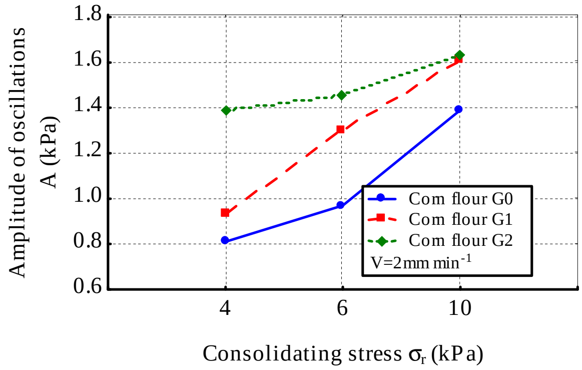

Fig. 3. Amplitude of oscillations A as a function of consolidating stress σ_1 for corn flour at three levels of support stiffness, and V of 2 mm min^{-1}

The amplitude of oscillations increased with a decrease in stiffness (Fig. 3). Oscillations occurred only for potato flour at three stiffness levels for deformation speed of 2 mm min^{-1}. No oscillations in the case of potato flour occurred at G0, but they appeared for the two remaining levels of stiffness (see Fig. 4).

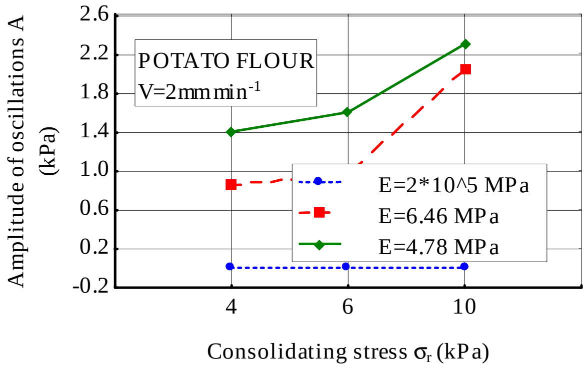

Fig. 4. Amplitude of oscillations A as a function of consolidating stress σ_1 for potato flour

Flow functions of wheat starch, fine potato starch and potato starch at 2 mm min^{-1} speed of deformation and for three levels of stiffness of the washer took values characteristic for easy flowing materials.

Flow functions took values characteristic for cohesive materials in the case of corn flour and G1 for all tested consolidation stresses as well as for σ_r = 4 kPa and

σ_r = 6 kPa for both G0 and G1 (Fig. 5 and Fig. 6). The experiments performed showed that to obtain comparable values of *FF*, apparatuses of identical stiffness and the same speed of deformation have to be used.

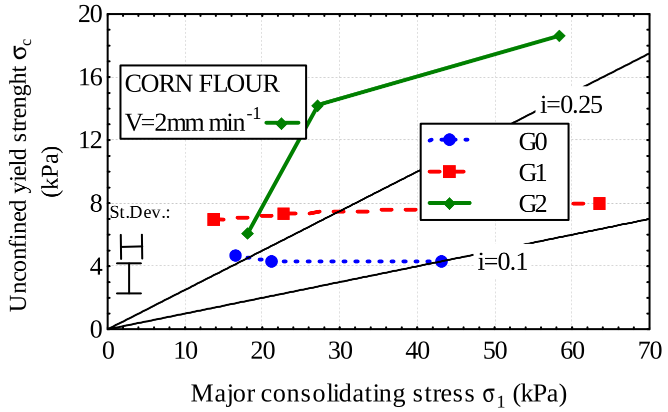

Fig. 5. Mean values of flow functions of corn flour for 2 mm min^{-1} speed of deformation

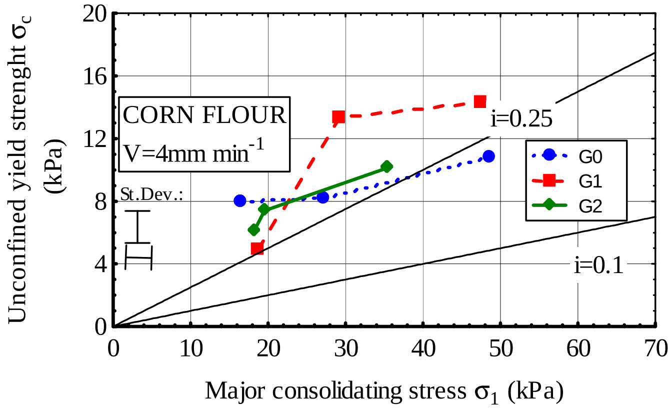

Fig. 6. Mean values of flow functions of corn flour for 4 mm min^{-1} speed of deformation

CONCLUSIONS

1. Speed of deformation and stiffness of the apparatus strongly influenced flow parameters obtained with Jenike shear tester.
2. Testing of materials for comparison of flowability should be carried out with the same equipment.
3. Oscillations were observed for all tested materials, in all experimental conditions except for the case of potato flour.

4. Increase in both consolidation stress and speed of displacement resulted in an increase in the amplitude of oscillations. Increase in stiffness of the apparatus resulted in a decrease of the oscillation amplitude.

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WYZNACZANIE PARAMETRÓW SYPKOŚCI PROSZKÓW – WPŁYW PRĘDKOŚCI DEFORMACJI I SZTYWNOŚCI APARATURY

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S t r e s z c z e n i e. Celem pracy była identyfikacja warunków powstawania efektu stick-slip w złożach proszków spożywczych oraz identyfikacja wpływu sztywności aparatu i prędkości deformacji na sypkość. Eksperymenty przeprowadzono w aparacie bezpośredniego ścinania o średnicy 60 mm dla czterech materiałów: maki kukurydzianej, skrobi pszennej, skrobi ziemniaczanej i drobnej frakcji skrobi ziemniaczanej. Oscylacje przebiegów eksperymentalnych pojawiły się w przypadku wszystkich eksperymentów z wyjątkiem skrobi ziemniaczanej przy prędkości deformacji 2 mm min^{-1} i największej sztywności podparcia w całym zakresie naporu konsolidującego. Dla skrobi pszennej i dwu typów skrobi ziemniaczanych wartości *FF* nie zmieniały się ze zmianą prędkości deformacji, podczas gdy dla mąki kukurydzianej wzrost prędkości skutkował wzrostem wartości *FF*.

S ł o w a k l u c z o w e: bezpośrednie ścinanie, sypkość, proszki spożywcze