Mechanical Properties of Native Maize, Wheat, and Potato Starches

Mateusz STASIAK[1], *Marek MOLENDA*[1], *Ireneusz OPALIŃSKI*[2] and *Wioletta BŁASZCZAK*[3]

[1]*Institute of Agrophysics, Polish Academy of Sciences, Lublin, Poland;* [2]*Department of Chemical and Process Engineering, Rzeszów University of Technology, Rzeszów, Poland;* [3]*Institute of Animal Reproduction and Food Research, Polish Academy of Sciences, Olsztyn, Poland*

Abstract

Stasiak M., Molenda M., Opaliński I., Błaszczak W. (2013): **Mechanical properties of native maize, wheat, and potato starches.** Czech J. Food Sci., **31**: 347–354**.**

The interrelations between moisture content and mechanical properties of dry and wet native starches of wheat, maize, and potato were investigated. Strength parameters of powders were tested using direct shear and ring shear tester. Carr indices and associated parameters were determined using a Hosokawa Powder Tester. Particle size distribution of powder was analysed using an Infrared Particle Sizer. Uniaxial compression test was conducted to determine the reaction of powder in a cylindrical probe to vertical load. Mechanical behaviour of the material was found to be changing with increasing moisture content. Mechanical behaviour of potato starch was found to be different from that of cereal starches, which may require different utilisation in some processes.

Keywords: moisture content; food powders; flowability; slip-stick

Starch is one of the major components in our diet and plays an important role in the formulation of food products. Morphological, rheological, thermal, and textural properties of powders are of major interest in food technology, but for storage, handling and transport mechanical phenomena such as friction or flowability are important as well. Flowability is even more complex and depends on shear strength, compressibility, air content, the rate of flow and other factors such as sticky or hygroscopic substances. Freeman (2007) tested the flow properties of six powders and observed that flowability determination is still a very long way from being exact, but the need for the industry to be able to predict flow performance is more important than ever. One of the popular and standardised methods of flowability determination is a direct shear test originally proposed by Jenike (1961). For some materials and under certain experimental conditions, fluctuations of shear force occurred, which made interpretations of testing difficult. Such fluctuations, termed slip-stick, were observed while testing feed powders such as ground maize (Molenda *et al.* 2002) or food powders such as potato starch (Molenda *et al.* 2006).

Singh *et al.* (2003) reported differences in physico-chemical properties of potato starch as compared to cereal starches (wheat, maize, and rice). Native starch is semi-crystalline in nature with a varying level of crystallinity that is associated with the amylopectin component, while the amorphous regions represent amylase. The packing of amylase and amylopectin has been reported to vary among the starches from different species. Granules of maize and wheat starches may swell up to 30 times of their volume and potato starch

Supported by the State Committee for Scientific Research, Poland, Grant No. N 313 141938.

up to 100 times of their original volume, without disintegration. Baldwin *et al*. (1998), based on AFM images, have shown that the surfaces of wheat and potato starch granules possess substantially different topographies. Potato starch granules have a rougher surface than that of wheat starch granules, consisting of large raised blockets (50–300 nm in diameter) above the flatter surface containing structures of diameters from approximately 10–50 nm. Wheat starch (cv. Riband) had a flatter surface made up of regularly spaced structures with diameters in the range from 10 nm to 50 nm.

The main objectives of the reported project were (a) to provide a set of mechanical characteristics of three widely used starches measured using common methods, and (b) to find possible interrelations between moisture content and mechanical characteristics of tested materials.

MATERIAL AND METHODS

Material. Three types of starches were tested: commercial potato starch, 16% moisture content, produced by Melvit (Ostrołęka, Poland); wheat starch, 20% moisture content, and maize starch, 12% moisture content, both produced by Cargill (Warsaw, Poland). The values of moisture content were determined for the materials as they were delivered to our laboratory and tested, thus as present in the market. Moisture content (wet basis) was measured gravimetrically by weighing 10 g of the sample before and after drying at 105°C for 24 hours. The characteristics of the starches were quantified at the levels of moisture content occurring in practical technological processes. Dried materials were obtained by 24 h drying in a laboratory drier with forced circulation at a constant temperature of 30°C and moisture content of 6% was obtained for maize and wheat starch and 4% in the case of potato starch.

Methods. Particle size distribution was analysed using the IPS UA Infrared Particle Sizer (Kamika, Warsaw, Poland). The method consists in measurements, in continuous and gradual manner, of changes in the laser radiation stream scattered by moving particles in the air. The parameters are defined as follows: D_n (in μm) is the mean diameter for a given amount of particles; D_{geo} (in μm) is the mean geometric diameter; D_{med} is the size in μm at which 50% of the sample is smaller and 50% is larger; *WK* is the shape coefficient which is the ratio of two dimensions (height/width) of a single particle (for the sphere $WK = 1$) (Kamika Operator's Guide).

Carr indexes (aerated density, packed density, compressibility, angle of repose, angle of fall, angle of difference) were determined using a PT-S Powder Characteristics Tester, Hosokawa Micron, Cheshire, UK (Carr 1965).

Direct shear testing was performed in a shear tester with the box of 60 mm in diameter. The tests were performed following the Eurocode 1 (2006) procedure for consolidation reference stresses σ_r of 4, 6, and 10 kPa and speed of shearing *V* of 2 mm/min. Yield locus was determined based on values of maximum shear stresses at two levels of consolidation stress σ_r and ½ σ_r. With the yield locus determined, Mohr circles were drawn that gave values of unconfined yield strength σ_c and major consolidation stress σ_1. The relationship σ_c/σ_1 describes the ability of a powder to flow and is termed the flow function, *FF*, of the material (Molenda *et al*. 2006).

Ring shear testing was conducted using a Schulze annular shear cell of 120 mm outer diameter and 60 mm inner diameter. Tests were performed for 4 kPa pre-shear stress and under four levels of normal stress of 3.2, 2.4, 1.6, and 0.8 kPa. The Standard Ring Shearing procedure was performed and a set of parameters was determined, including major consolidation stress at steady-state flow σ_1 and unconfined yield strength σ_c (Schwedes & Schulze 1990; Schulze 2008). Flow factor ff_c, which is the ratio of σ_1 to σ_c (inverse of flow function *FF*), is used to compare flow properties of different powders; a powder with higher ff_c under the same σ_1 flows easier (Kamath *et al*. 1994). Shear stress τ, density ρ, effective angle of internal friction ϕ_{fe}, slope angle of the linearised yield locus ϕ_{lin}, and angle of internal friction at steady-state flow ϕ_{st} were also determined.

Uniaxial compression tests were performed following Eurocode 1 (2006), using a test chamber 54 mm in diameter with 50 mm high sample. During the test, the top cover of the apparatus was moving down at a constant speed of 5 mm/min until the vertical reference stress *σ* of 12 kPa was reached. After reaching the prescribed level of σ, the movement of the top cover was stopped and unloading was realised at the same speed until the stress level of 0 kPa was achieved.

All experiments were performed in three replications, and mean value and standard deviation were used for analyses.

Table 1. Particle size parameters and shape factor of tested starches by Infrared Particle Sizer

	Wheat starch		Maize starch		Potato starch	
	20%	6%	12%	6%	16%	4%
D_n (μm)	7.50 ± 0.01	7.60 ± 0.14	5.85 ± 0.07	5.80 ± 0.01	12.35 ± 0.07	13.00 ± 0.14
D_{geo} (μm)	6.50 ± 0.01	6.65 ± 0.07	5.10 ± 0.01	5.05 ± 0.07	10.05 ± 0.07	10.80 ± 0.14
D_{med} (μm)	12.30 ± 0.01	13.30 ± 1.27	11.95 ± 1.34	11.15 ± 0.21	24.70 ± 0.14	23.90 ± 1.56
WK	1.57 ± 0.02	1.59 ± 0.01	1.12 ± 0.01	1.10 ± 0.01	2.92 ± 0.012	3.14 ± 0.03

D_n – mean diameter for a given amount of particles; D_{geo} – mean geometric diameter; D_{med} – size at which 50% of the sample is smaller and 50% is larger; *WK* – shape coefficient which is the ratio of two dimensions (height/width) of a single particle

RESULTS AND DISCUSSION

Particle size distributions measured with Infrared Particle Sizer are presented in Table 1. Values of diameters for wheat and maize starch were found close, with no distinct difference between dry and wet particles. D_n of dry wheat starch and maize starch particles were of 7.7 and 5.8 μm, respectively. Values of D_n of potato starch were higher, 12.9 and 12.4 μm for dry and wet particles, respectively. The shape coefficient of potato starch was also the highest, approximately 3 for dry and wet starch, while in the case of wheat and maize starches it was approximately 1.6 and 1.1, respectively. These results corroborate results of earlier investigations that potato starch granules are oval and irregular or cuboid-shaped while maize and wheat starch granules are angular, spherical and lenticular-shaped (Singh *et al.* 2003). Potato starch granules are the largest in size (< 110 μm), followed by wheat (< 30 μm) and maize (< 25 μm). According to these authors maize, rice and wheat starch granules are less smooth-surfaced than potato starch granules.

Table 2 shows the Carr indices of tested materials determined with Hosokawa Powder Tester. In the case of dry starches the highest aerated density ρ = 763 kg/m^3 was found for potato, while the lowest, 510 kg/m^3, was that of maize starch. The same tendency was observed in the case of wet materials, where the densities were distinctly lower. Change in density expressed as compressibility of cereal starches, found in a range from 34% to 54%, was higher than that of potato starch amounting to 22% and 30% for dry and wet material, respectively. An increase in moisture content resulted in an increase in compressibility of all materials with the highest difference in potato starch. Probably, particles of wet starch are softer than dry particles.

The angles of repose and angles of fall were higher for materials with higher moisture content. In the case of maize starch the angle of repose increased from 52° to 56°, for wheat starch from 42° to 56°, and from 38° to 58° for potato starch.

Relationships between shear stress τ and relative displacement $\Delta l/D$ obtained in direct shear testing showed fluctuations for all tested materials at lower moisture content, while the curves of wetter materials followed smooth paths. Such fluctuations of experimental relationships observed in mechanical systems with frictional damping are termed the slip-stick effect and are attributed to a difference between static and dynamic friction (e.g. Abdo *et al.* 2010). Typical stress versus relative displacement curves obtained for potato starch are presented in Figure 1. Experimental curves

Table 2. Carr indices determined with Hosokawa Powder Tester

Bulk solid	Density (kg/m^3)		Compressibility (%)	Angle (deg)		
	aerated (ρ)	packed (ρ_p)		repose (ϕ_r)	fall (ϕ_f)	difference (ϕ_d)
Maize starch 6%	510	847	40	52.2	25.2	23.0
Wheat starch 6%	558	849	34	42.2	35.6	6.6
Potato starch 4%	763	986	22	38.1	26.7	11.4
Maize starch 12%	444	725	41	56.0	36.3	19.7
Wheat starch 20%	283	621	54	56.5	37.6	18.9
Potato starch 16%	593	850	30	58.4	41.0	17.4

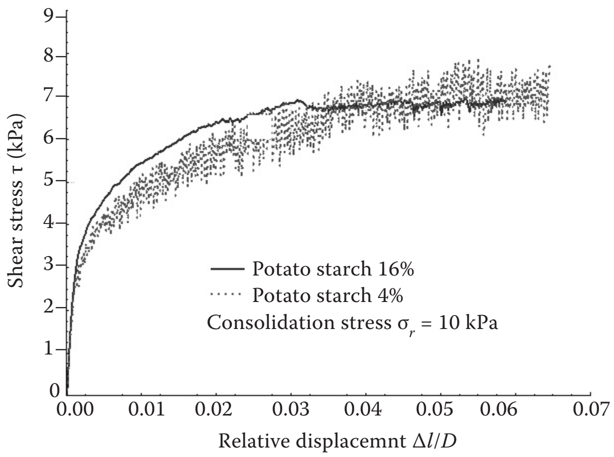

Figure 1. Shear stress τ – relative displacement $\Delta l/D$ relationship of dry and wet potato starch for consolidation stress σ_r of 10 kPa

for starches at higher moisture content stabilised earlier than those for dry materials. In experiments showing the slip-stick effect higher values of shear stress were obtained that resulted in higher values of calculated parameters. Values of the angle of internal friction ϕ were found higher for materials of lower moisture content. In the case of wheat starches 6% in moisture content the values of ϕ varied from 37° to 39° while at moisture content of 20% ϕ varied from 28° to 34°. For wet potato starch ϕ ranged from 27° to 32° while values from 34° to 38° were obtained for dry material. The highest values of the angle of friction ϕ, in a range from 35° to 42°, were obtained for maize starch at 6% of moisture content. Based on linearised yield locus the values of cohesion were also determined that were found to be under a strong influence of moisture content of the material. An increase in moisture content resulted even in a 3- to 4-fold increase of cohesion. Cohesion of dry materials varied from 0.04 kPa for maize starch at 10 kPa of consolidation stress to 0.26 kPa for potato starch at 10 kPa of consolidation stress. In the case of wet starches, cohesion varied from approximately 0.65 kPa for potato starch to approximately 0.8 kPa for wheat starch. Cohesion of agricultural materials was widely analysed by Moya *et al.* (2002, 2006). The authors determined values of apparent cohesion by the direct shear test using square and circular shear cells. The values obtained were much higher (about 10 times) than in this project but this is probably the reason of the normal stress range from 100 kPa to 300 kPa and differences in the single granule size of the material.

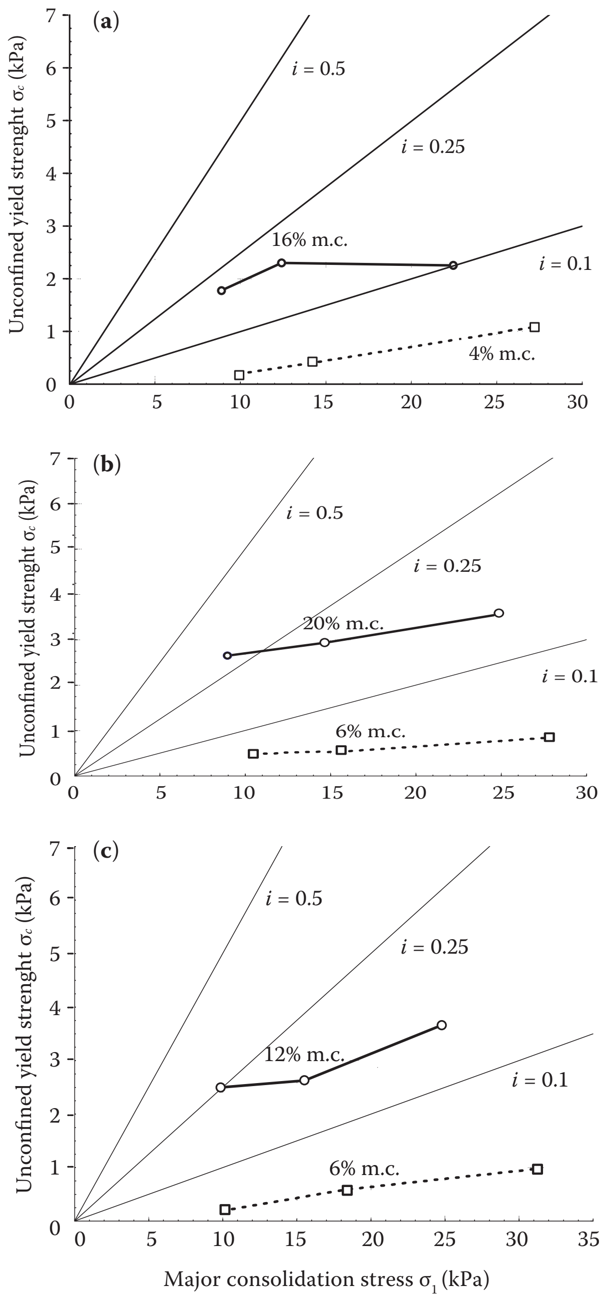

Figure 2. Flow functions of experimental materials (**a**) potato starch, (**b**) wheat starch, and (**c**) corn starch

Flow functions, i.e. relationships between major consolidation stress σ_1 and unconfined yield strength σ_c obtained in Jenike shear tester, are shown in Figure 2. Moisture content strongly affected flow functions. Dry starches had nearly equal values of unconfined yield strength σ_c, characteristic of free flowing materials, in a range from approximately 0.3–1 kPa. The values of flow functions of wet materials were characteristic of easy flowing materials. Moist wheat and maize starches had approximately equal values of flow functions *ff*

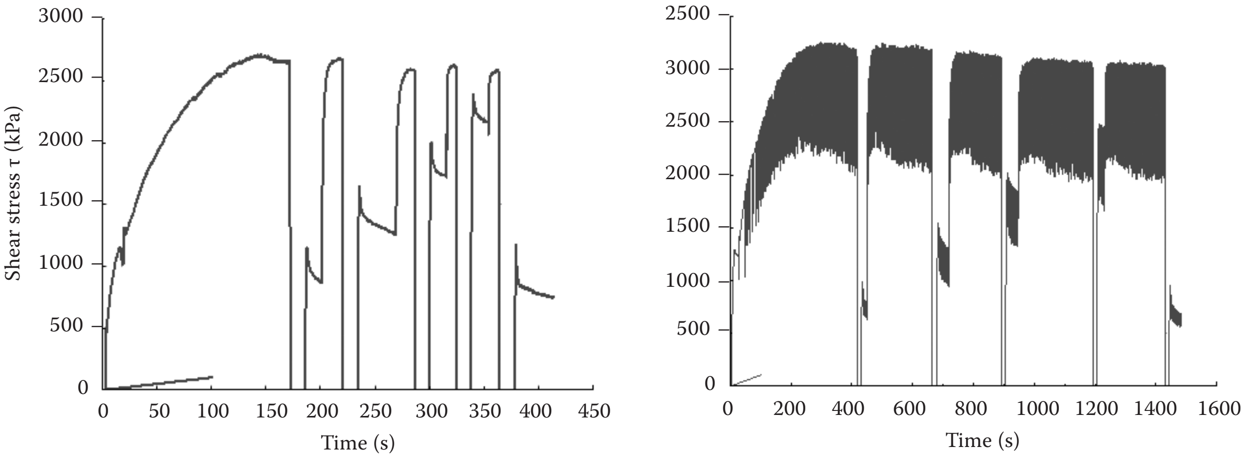

Figure 3. Ring shear tester experimental curves obtained for dry and moist maize starch

in a range from 2.5 kPa to 3.5 kPa. Values of *ff* of potato starch were 30% lower and ranged from approximately 1.8–2.2 kPa. This effect was probably caused by a difference in single particle diameter D_n of potato starch that was approximately two times of those of wheat and maize starches. The value of compressibility was increasing with an increase in moisture content as the reason of more deformable and sticky particles. The highest increase from 34% to 54% was noted for wheat starch. For potato starch compressibility changed from 22% to 30% with the change in moisture content. This parameter obtained in potato starch at 16% of moisture content was the lowest of all materials with higher moisture content. No change in compressibility was obtained for maize starch.

Typical experimental curves obtained in the ring shear tester for maize starch at two levels of moisture content are presented in Figure 3. Strong slip-stick effects were observed in dry starches, similar to those found in direct shear testing. In the case of wet starches, the highest value of shear stress at preconsolidation τ_{pre} of 2850 Pa was obtained for wheat starch, the lowest τ_{pre} of 2300 Pa was that of potato starch, while for maize starch it was of 2700 Pa. Similar tendencies were obtained in shear box testing. In the case of wet powders the stable value of preconsolidation stress for potato starch was obtained earlier than for wheat and maize starches where stabilisation required twice longer displacement. An opposite tendency was observed in dry materials where experimental curves for potato starch stabilised after 1.5 times longer shear path than for wheat and maize starch. Maximum values of shear stresses of all starches were approximately equal, having the value of 3250 Pa.

Based on experimental data, yield loci were drawn by connecting neighbouring τ(σ) data points. Yield loci with flow parameters estimated for wet and dry tested materials are presented in Figures 4 and 5. Linearised yield loci of dry materials run very close, while those of wet materials differed. Yield loci of wheat starch were located the highest,

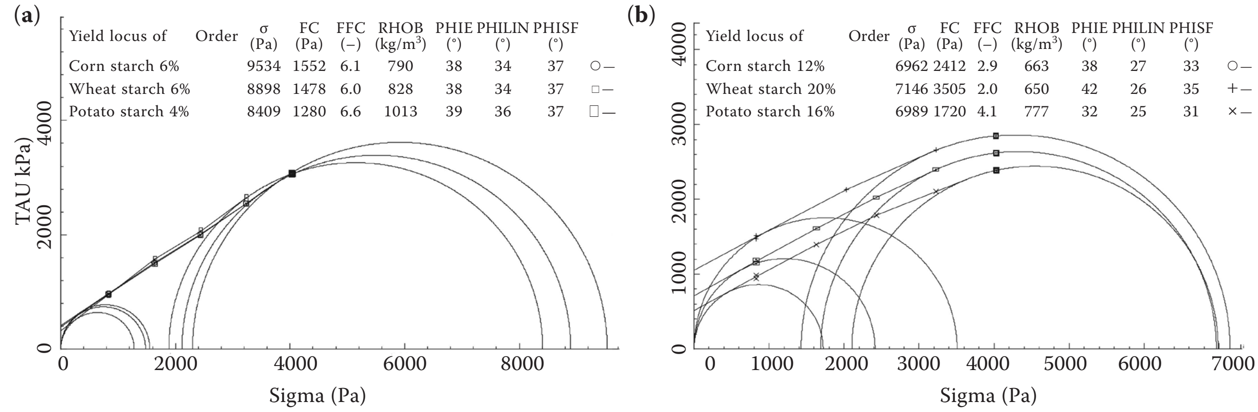

Figure 4. Linearised yield loci for (**a**) dry and (**b**) wet starches

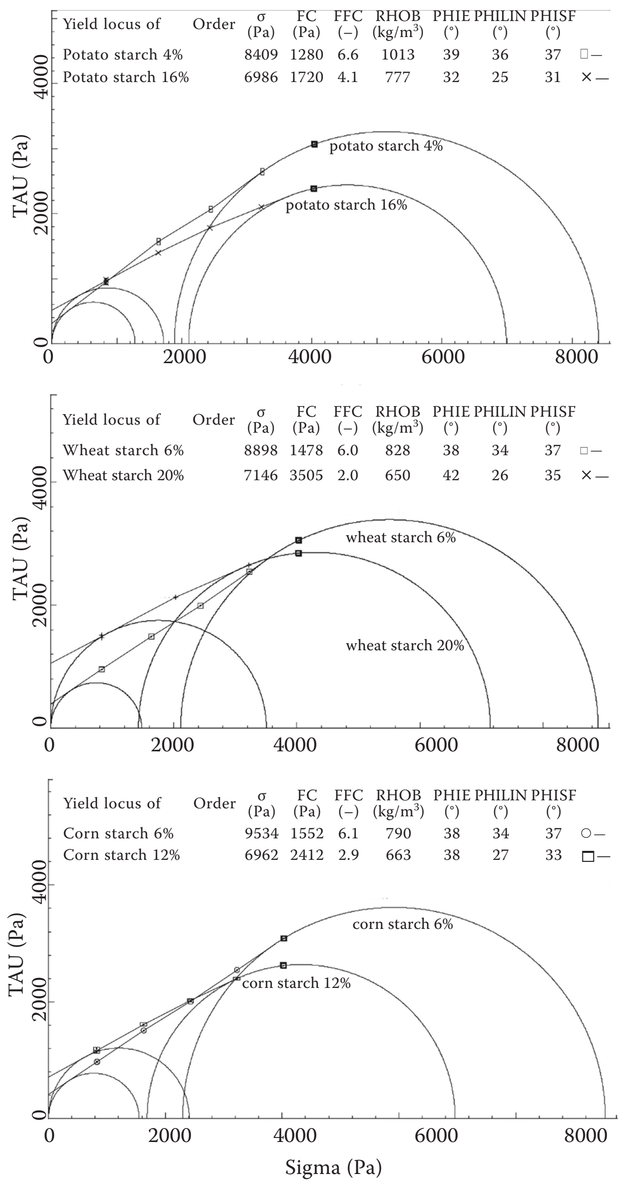

Figure 5. Moisture content influence on yield loci for experimental starches

those of potato starch the lowest. The effective angle of internal friction ϕf_c was approximately equal for all tested starches, with values from 38° for maize and wheat starch to 39° for potato starch. The angle of internal friction at steady-state flow was found to be 37° for all tested starches. Flow characteristics termed flowability ff_c by Schulze for dry starches were found to be higher than those of wet materials, indicating that flow in dry materials is easier. The lowest value of ff_c was that of wheat starch at 2.0; the highest, equal to 4.1, was ff_c of potato starch. The ff_c is an inverse of flow index i as shown in Figure 2. Flowabilities obtained in Schulze tester expressed as $i = 1/ff_c$ (see Table 3) were found in fairly good agreement with the results of determinations in Jenike tester, provided that values for the lowest normal stress σ_1 of approximately 10 kPa were considered.

In the case of wet materials the highest values of the angle of friction and effective angle of friction were obtained for material with the worst flowability. This effect corroborates the opinion of numerous researchers that the angle of internal friction is a rough measure of flowability at low normal stress (e.g. Teunou *et al*. 1995).

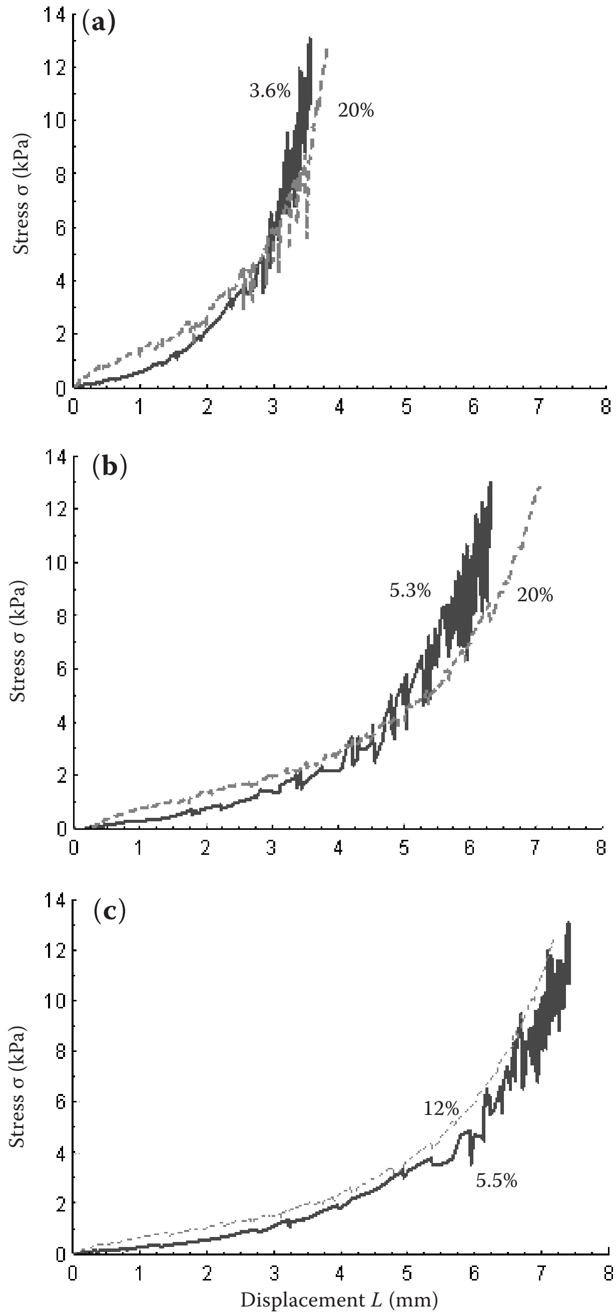

Figure 6. Uniaxial compression results for dry and wet starches (**a**) potato starch, (**b**) wheat starch, and (**c**) corn starch
Deformation speed 5 mm/min, H = 54 mm, D = 54 mm

Uniaxial compression tests revealed distinct differences in the values of displacement reached at maximum consolidation stress of 12 kPa (Figure 6). Deformation of the sample of potato starch of 3.5 mm was lower than that obtained for cereal starches, while maximum deformation of 7.2 mm was that of maize starch. Differences in maximum deformation results come from the shape and dimensions of individual particles of powders. Granules of maize starch, in which the highest values of relative displacement were observed, were the smallest (D_n of 5.8 µm compared to 7.7 µm for wheat and 12.4 µm for potato, Table 1) and of more regular shape (WK of 1.11 compared to 1.57 of wheat and 2.92 of potato, Table 1). Similar results were obtained by Wiącek *et al.* (2012) in uniaxial compression testing of pea and bean seeds as well as in numerical simulation of these tests. A change in the particle shape from spherical to oblong resulted in a decrease in porosity and increase in stiffness of the specimen.

In uniaxial compression of all dry starches a strong slip-stick effect occurred. The highest amplitude of frictional vibrations of approximately 4 kPa was observed in wheat starch, while fluctuations of shear stress for potato and maize starches did not exceed 2 kPa.

CONCLUSIONS

Cereal and potato starches were found to differ markedly in morphology as well as in mechanical properties. Granules of potato starch tested were nearly twofold larger in linear dimensions and were more oblong with the coefficient of shape *WK* approximately twice larger. Aerated and packed density of potato starch was higher than that of cereal starches, as well as the angle of repose. Compressibility of potato starch was the highest of the three tested materials. The *ff* of potato starch was higher than that of cereal starches, particularly at higher moisture content examined. This was associated with larger mean diameter of granules, larger shape ratio, larger density, larger angle of repose and weaker compressibility.

Due to these differences potato starch may require different utilisation in some processes than cereal starches.

Flowability of powder depends to a large extent on operation conditions, the main factors being: level of compression pressure, time of exposure to load, stability of moisture content and temperature. A large, and still growing, number of experimental methods is offered in the market and the proper one should be chosen considering the factors listed.

No clear influence of moisture content on morphological characteristics of starch granules was observed in conditions of testing. Moisture content was proved to be a factor strongly influencing mechanical properties of examined starches. Densities ρ_a and ρ_p of wet starches were found to be from 0.5 to 0.9 of those of dry starches. Compressibility of wet wheat and potato starches was approximately 1.5 times higher than that of dry ones, while no difference was observed in the case of maize starch. An increase in moisture content resulted in an increase in flowability, decrease in the angle of internal friction, increase in compressibility (the largest in potato starch). With an increase in moisture content the angle of difference decreased more than twofold in cereal starches while remained essentially unchanged in the case of potato starch.

An increase in moisture content resulted in the cessation of slip-stick effects in all tested starches in shear testing as well as in uniaxial compression.

References

Abdo J., Tahat M., Abouelsoud A., Danish M. (2010): The effect of frequency of vibration and humidity on the stick-slip amplitude. International Journal of Mechanics and Materials in Design, **6**: 45–651.

Baldwin P.M., Adler J., Davies M.C, Melia C.D. (1998): High resolution imaging of starch granule surfaces by atomic force microscopy. Journal of Cereal Science, **27**: 255–265.

Carr R.L. (1965): Evaluating flow properties of solids. Chemical Engineering, **72**: 163–168.

Eurocode 1, Part 4 (2006): Basis of design and actions on structures. Actions in silos and tanks. EN 1991-4.

Freeman R. (2007): Measuring the flow properties of consolidated, conditioned and aerated powders – A comparative study using a powder rheometer and rotational shear cell. Powder Technology, **174**: 25–33.

Jenike A.W. (1961): Gravity flow of bulk solids. Bulletin No. 108 of the University of Utah, 52(29).

Kamath S., Puri V.M., Manbeck H.B. (1994): Flow property measurement using the Jenike cell for wheat flour at various moisture contents and consolidation times. Powder Technology, **81**: 293–297.

Molenda M., Stasiak M., Horabik J., Fornal J., Błaszczak W., Ornowski A. (2006): Microstructure and mechanical parameters of five types of starch. Polish Journal of Food and Nutrition Sciences, **15/56**: 50–57.

Molenda M., Montross M.D., Horabik J., Ross. I.J. (2002): Mechanical properties of corn and soybean meal. Transactions of the ASAE, **45**: 1929–1936.

Moya M., Guaita M., Aguado P., Ayuga F. (2006): Mechanical properties of granular agricultural materials, Part 2. Transactions of the ASABE, **49**: 479–489.

Moya M., Ayuga F., Guaita M., Aguado P. (2002): Mechanical properties of granular agricultural materials. Transactions of the ASABE, **45**: 1569–1577.

Singh N., Singh J., Kaur R., Sodhi N.S., Gill B.S. (2003): Morphological, thermal and rheological properties of starches from different botanical sources. Food Chemistry, **81**: 219–231.

Schulze D. (2008): Powders and Bulk Solids: Behaviour, Characterization, Storage and Flow. Springer, Berlin-Heidelberg-New York-Tokyo.

Schwedes J., Schulze D. (1990): Measurement of flow properties of bulk solids. Powder Technology, **61**: 59–68.

Teunou E., Vasseur J., Krawczyk M. (1995): Measurement and interpretation of bulk solids angle of repose for industrial process design. Powder Handling and Processing, **7**: 219–227.

Wiacek J., Molenda M, Horabik J, Ooi J.O. (2012): Influence of grain shape and intergranular friction on material behavior in uniaxial compression: Experimental and DEM modeling. Powder Technology, **217**: 435–442.

Received for publication September 3, 2012
Accepted after corrections November 23, 2012

Corresponding author:

Dr Mateusz Stasiak, Institute of Agrophysics, Polish Academy of Sciences, ul. Doświadczalna 4, 20-290 Lublin 27, Poland; E-mail: mstasiak@ipan.lublin.pl