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Characterizing moist food-powder flowability using a Jenike shear-tester

I. Opaliński [a,*], M. Chutkowski [a], M. Stasiak [b]

[a] Department of Chemical and Process Engineering, Rzeszow University of Technology, al. Powstancow Warszawy 6, 35-959 Rzeszow, Poland
[b] Institute of Agrophysics, Polish Academy of Sciences, Doswiadczalna 4, 20-290 Lublin, Poland

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ABSTRACT

A range of commercially-available crop seeds and food powders were tested using a Jenike shear-tester. At low normal loads, all the materials are found to change their strength characteristics regularly, with increasing moisture content resulting in higher values for shear stresses. However, under high normal loads, an opposite trend was observed for some materials, for which there is the potential of a lubricating effect to develop, resulting in unpredictable bed behavior in a silo. Low moisture contents reduced shear-stress oscillations occurring in the bed of dry material considerably. At higher moisture contents, an unacceptably long horizontal shear displacement was needed to establish steady-state shearing conditions. This may render the Jenike shear-tester inappropriate in the examination of powders of higher moisture content, especially those composed of easily deformable particles. NMR analysis proved that chemical composition of water surrounding the moistened seeds was changing during the time and that may affect the granular bed flow characteristics.

1. Introduction

The storage, transportation and processing of granular materials are common operations in various process industries, notably those centered on food, chemicals and pharmaceuticals. Powder flow properties are critical where the design and operation of industrial equipment is concerned, as well as the avoidance of such problems as developing arching in silos, segregation in solids and other problems often resulting in process stoppage or a poor-quality product. Proper equipment design and appropriate process production efficiency thus require the acquisition of extensive data on powder flowability, affected by different factors such as operational parameters, equipment characteristics and material properties.

While moisture can exert a marked effect on powder flow, the behavior of moist powders may be unpredictable where moisture content in a powder bed is changing. Increasing moisture content contributes to strengthened interactions between particles, usually by way of the formation of stable liquid bridges that bond particles together and worsen bulk-flow properties (Zou and Brusewitz, 2002; Harnby et al., 1996). The flowability and cohesion properties of food powders are also dependent on biochemistry. Protein and pentosans, for example, are responsible for the formation of non-covalent hydrogen bonds and chemical links. Landillon et al. (2008) found that starch and soluble pentosans may increase the viscosity of liquid bridges, thereby increasing their strength. Soluble components of grains or seeds may likewise lead to a plasticizing of powder, with the result that contact area and surface stickiness are increased (Rennie et al., 1999). Fitzpatrick et al. (2007) further show that food powders with a greater amount of amorphous lactose are more sensitive to the absorption of moisture giving rise to lumping and caking problems.

Flowability and physical properties were measured for a variety of food powders of different moisture contents by Teunou et al. (1999) and Fitzpatrick et al. (2004). They found that, while powder flowability varied from easy flow to very cohesive, the effect of moisture content was complex and not clear. The effect of water content on food powder mechanical properties was also investigated in detail by Baumler et al. (2006) and Coskuner and Karababa (2007) for coriander and safflower seeds, respectively. They showed that seed volume and weight, equivalent diameter, bed porosity and sphericity increased with moisture content. The static coefficient of friction, angle of repose and true seed density also assumed higher values at higher moisture contents. The only seed properties for which values decreased with moisture were seed length and bulk density. Not all of these trends later gained support in the paper by Kashaninejad et al. (2008) in relation to soybeans.

The flowability of milk powders of different milk-fat content and other dairy powders was compared by Fitzpatrick et al. (2007, 2004) and Rennie et al. (1999). An interesting finding following from their investigations was that lactose, fat and moisture all contribute to cohesion, such that the effect of moisture on powder cohesion may be different or even contradictory when some or all parameters are changed. Some diversity to the flow properties of food granular materials has also been reported as regards the effect of moisture on such physical properties as force required for

* Corresponding author.
E-mail address: ichio@prz.edu.pl (I. Opaliński).

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initiating seed rupture (Saiedirad et al., 2008), granulation properties during mixing (Landillon et al., 2008) and milling properties (Dijkink and Langelan, 2002). Ganesan et al. (2008a,b)found for DDGS, that flow-function values decreased with increasing moisture content (10–20%), but increased for 25% and 30% moisture content. This indicates that, above a certain moisture content, moisture can act as a lubricant and ease flow.

The test methods and apparatus that have been used in powder classification can be divided into three classes of powder flowability indicators: those used for uncompacted powders (e.g. angle of repose) of powders that are tapped (Hausner ratio and Carr index) or consolidated (shear tests). While the first two simple methods are of problematic accuracy, the industrial standard has become the Jenike shear-tester, as a reliable tool in industrial silo design (Schulze, 1996a,b). The Jenike shear-tester is a widely-accepted method for predicting the flow of powder in a compacted state, but it is common opinion that this requires a high level of training and skill, is time-consuming and is sensitive to the way powder is conditioned before testing (Schwedes, 2003; Krantz et al., 2009).

In this research undertaking we have used two experimental measuring techniques to investigate how moisture content, particle size and material nature affect powder flowability. The results obtained for various materials of markedly different solid properties will be useful in assessing which powders and process conditions the Jenike shear-tester is appropriate for, as a method of predicting powder flowability and apparatus design and for which dynamic testing is needed. The prospective objective of our experimental program concerning powders was to measure the effect of moisture on the flow properties of food powders and to compare the results obtained with those for some typical industrial powders. Such a comparison allows for an indication of those research areas more or less important for a given group of powder materials, with a view to research methods and equipment suitable for given materials and operations being codified, and research possibilities widened by reference to the experience of various groups of researchers.

The objective of this paper is to investigate the effect of water content on flow properties of a variety of food materials of different particle sizes and to assess critically Jenike's powder flowability methodology, particularly with reference to materials of higher moisture content.

2. Materials and methods

2.1. Measurement of physical properties

The materials tested were commercially available oil-crop seeds (mustard seeds, amaranth and rapeseed), as well as the food powders (semolina, millet groats, coarse wheat-flour, common wheat-flour, corn flour, potato starch and whole milk powder). Particle-size distributions (PSD) for the food powders were obtained using a Malvern Mastersizer 2000E laser diffraction analyzer. The powders in the form of particle suspensions in isopropyl alcohol were used to allow for PSD measurement.

The average particle sizes of oil-crop seeds and some coarse food powders were determined using the simple, common method of sieving through an EKO-LAB sieve set (PN-ISO 3310-1: 2000), the main, usually narrow cut fraction being chosen for further experiments.

Hydration of materials was accomplished by direct addition of water to samples, plus mixing until a homogeneous consistency was obtained. In the case of highly dispersed food powders, e.g. potato starch, wheat-flour and others, the moisturizing method entailed passing a stream of air of controlled humidity through the materials being mixed in the V-type drum mixer. This was a protracted process. To obtain higher moisture contents of the materials under investigation, it was necessary to keep mixing for many hours or even days, as for example, it was found for common wheat-flour of the required final saturation level of 20%.

Moisture content was determined by weighing about a 5–7 g sample before and after drying at 70 °C. The drying and weighing procedure was repeated several times until constant mass of the sample was obtained. The procedure to be accomplished usually required a period of time ranging from a few hours for crop seeds to a few days for common wheat-flour.

2.2. Flowability measurement with the Jenike shear-tester

The strength of materials, as an indication of their potential flow properties, was determined using a Jenike-type shear-tester fabricated and used in accordance with the EUROCODE 1 procedure. A schematic representation of the Jenike tester is offered in Fig. 1. The main part of the tester was a 60 mm diameter stainless steel cell with a bottom part moving at a constant velocity of 0.047 mm s^{-1}. The shear force resulting from material resistance during shearing was measured with a Hottinger Baldwin Messtechnik (HBM) C9B force transducer with a range of 200 N and an accuracy class of 0.5. The measured force signals were transmitted and amplified by an HBM 4-channel electronic unit SPIDER8, with a signal transfer rate of 50 Hz. Integrated with the force transducer and SPIDER8 amplifier was the HBM Catman®Easy computer program – an intuitive software for the acquisition and visualization of measured data.

A reference normal consolidating stress σ_n = 23 or 81 kPa was applied in a regular experimental protocol. In order to obtain more (usually 4 or 5) experimental points on the yield locus diagram, the

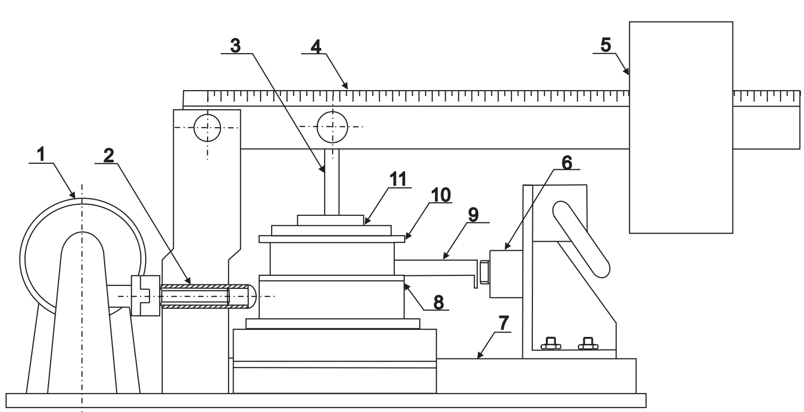

Fig. 1. Schematic representation of the Jenike-type shear tester. 1 – Drive engine, 2 – drive pin; 3 – lever bar; 4 – lever; 5 – normal load; 6 – shear stress transducer; 7 – base; 8 – movable shear cell; 9 – arm of immovable shear cell; 10 – immovable shear cell; 11 – twisting cover.