*Int. Agrophysics, 2002, 16, 183–189*

INTERNATIONAL
**Agrophysics**
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# Strength characteristics and dilatation of food powders**

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*Received March 4, 2002; accepted May 6, 2002*

Abstract. The strength characteristics of fine milk, agglomerated milk and potato starch were examined. Experiments were performed using the Jenike shear tester according to Eurocode 1 recommendations. The tester was 60 mm in diameter and the displacement velocity was 0.03 mm $s^{-1}$. A reference normal stress ranging from 30 to 240 kPa was applied. Experiments revealed a significant effect caused by shear stress vibration resulting from dilatation and hardening of the material during the slow shearing phase of these tests. The frequency of these vibrations were found to decrease with an increase in normal stress. Two components of the total strength were suggested: the physical friction strength and the extra component of strength caused by dilatation.

Keywords: food powders, Jenike tester, flowability, dilatation

## INTRODUCTION

Many raw food materials like cereal grains, flour, milk, salts, sugar etc. are stored, transported, handled and processed in the form of bulk materials. Specific properties of food powders impose strong requirements on structures. An important part of powder production and processing is maintaining the consistency of the product so that in-plant powder flow problems, which could effect packaging or the use of the die-filling machine, do not occur. Cohesive particulate solids in storage and transportation containers, conveyors or processing apparatuses can develop flow problems which can lead to bridging, channelling, oscillating mass flow rates, feeding and dosing problems, time consolidation or caking. Finally it may result in chemical conversion and food deterioration. The mechanism of caking is most often attributed to the formation of salt bridges and capillary adhesion (Kalman *et al.*, 2000). To ensure the reliable operation of processing lines designers must be equipped with properly measured strength parameters of powders (Lubert *et al.*, 2000). The principles of powder consolidation and flow behaviour are essential for the better design of those type of processes.

Figure 1 shows a typical $\tau - \sigma$ diagram for particulate solids. The solid line tangent to the circles is called the yield locus and represents the maximum shear stress $\tau$ the sample can support under a certain normal stress $\sigma$. Yield locus is significantly effected by the bulk density of the product being tested. With higher preconsolidation loads the product bulk density increases and the yield loci move upwards. Each yield locus terminates at point E which represents steady state flow, i.e., the conditions at which flow will occur with no change in the stresses and bulk density. The major principal stresses of the two Mohr stress circles are characteristics of a yield locus; $\sigma_1$ is called the major consolidation stress and is the major principal stress at steady state flow, and $\sigma_c$ is called the unconfined yield strength of the sample. To explain the meaning of these stresses the theoretical experiment shown in Fig. 1 can be used. A bulk solid is fed into a cylinder and is compressed by a vertical stress $\sigma_1$ without friction at the wall. After consolidation the cylinder is removed and the sample is stressed once again by a vertical stress $\sigma_1$ up to the point of failure $\sigma_c$ (i.e., the unconfined yield strength of the bulk material being consolidated by the stress $\sigma_1$). Plotting $\sigma_c$ versus $\sigma_1$ leads to the Flow Function of a bulk material which is the most popular doming – no doming criterion (Schwedes, 2000).

Jenike (1964) published his best known work on determining the strength and flowability characteristics using shear strength testing, this technique was soon accepted by researchers and knowledgeable practitioners as a definitive means of flowability characterisation. Eurocode 1

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**This work was supported by the State Committee for Scientific Research, Poland under the Grant No. 5 P06F 021 17.

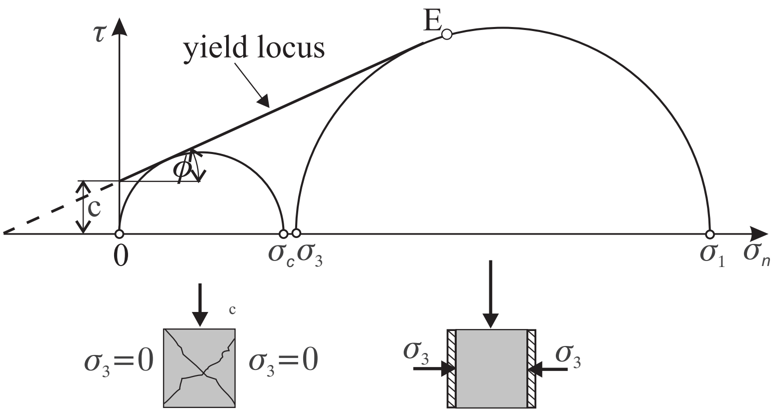

**Fig. 1.** Yield locus and unconfined yield strength of particulate solids.

(1996) recommends using the Jenike shear tester to determine the strength of granular materials. As part of this code a recommended test procedure and sample preparation is included. The Jenike method is frequently applied as the reference method for calibration of other simplified methods of determination of the relative flowability of powders (Ploof and Carson, 1994; Teunou *et al.,* 1995).

Tomas (2000) explained the principles of particulate solids consolidation and flow behaviour using a reasonable combination of particle and continuum mechanics. This behaviour depends on the nature of the acting binding mechanisms at the contact areas among particles (Molerus, 1975; Tomas, 2000). Some powder materials exhibit the tendency to change volume during shear, known as dilatation. Strength and resistance to slow deformation can be profoundly affected by dilatation and this property is important during the bulk handling of materials in the process industries (Dunstan *et al.*, 1988; Gebhard, 1982). The saw blades model of dilatation indicates the contribution of the energy dissipation mechanism from local collapsing columns to the effective strength in the slow steady state flow (Bolton, 1986).

The objective of this study was to determine strength characteristics of food powders which reveal the dilatation during shearing.

## MATERIALS AND METHOD

The flow characteristics of fine milk, agglomerated milk and potato starch were determined according to the Eurocode 1 (1996) recommendations using the Jenike (1964) shear tester. The tester was 60 mm in diameter. During testing a displacement velocity of 0.03 mm $s^{-1}$ was used. To begin each test a sample was poured into the test box, without vibration or other compacting forces, and the reference stress applied. The top plate was rotated backwards and forwards three times through an angle of 10 degrees to consolidate the sample. A reference normal stress of 30, 57, 85 and 240 kPa was applied to consolidate the sample. Two shear tests were carried out for each variant of experiments. One sample was sheared when loaded at the reference stress, the other was sheared at half the reference stress after pre-loading to the reference stress (Fig. 2). Each variant of experiments was repeated three times. Shear forces were measured using a load cell with a range of 500 N

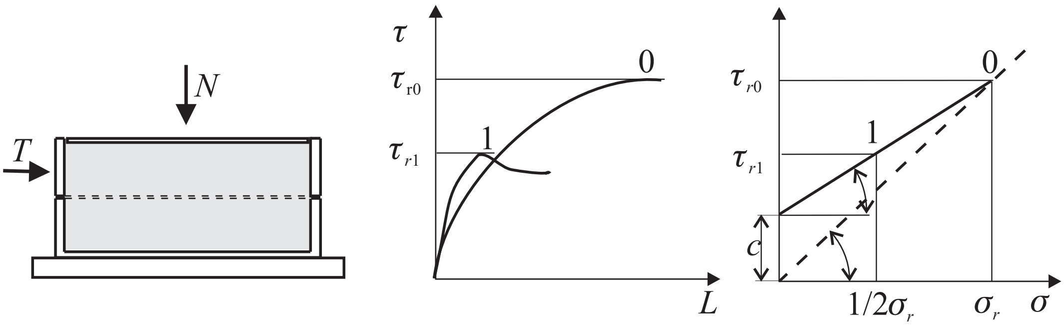

**Fig. 2.** Jenike shear tester and procedure of the strength testing (Eurocode 1, 1996).

and an accuracy of 0.5 N. The data was recorded using a data acquisition system.

Eurocode 1 (1996) recommends that a horizontal displacement be used equal to 0.05 of the tester diameter to determine the maximum shear stress for particulate materials. However, for the materials tested in this study the horizontal displacement was increased to 0.1 of the tested diameter because in some cases the maximum shear stress was found to develop after the recommended value of horizontal displacement was attained (Łukaszuk *et al.*, 2001).

## RESULTS

In Figure 3 the tangent stress – shear displacement relationships for different materials: a smooth curve for wheat flour and groats, small irregular vibrations for NaCl salt (Horabik and Grochowicz, 2000), and a saw blade curve for fine milk can be seen. For the three materials tested in this study: fine milk, agglomerated milk and potato starch very regular oscillations occurred in the shear stress while approaching the maximum strength of the material. This saw-tooth pattern resulted in a large variation in the shear strength of the material for very small displacements. Sequences of compaction-dilation events were thought to be the most probable source of these oscillations. Compaction of the particulate material resulted in an increase in material strength, and the ability to withstand higher shear loads. When the maximum strength of the particulate material is exceeded, dilation in the shear zone occurs resulting in a sharp decrease in the shear load. This leads to limiting mechanisms of slow dilatant plastic shear deformation.

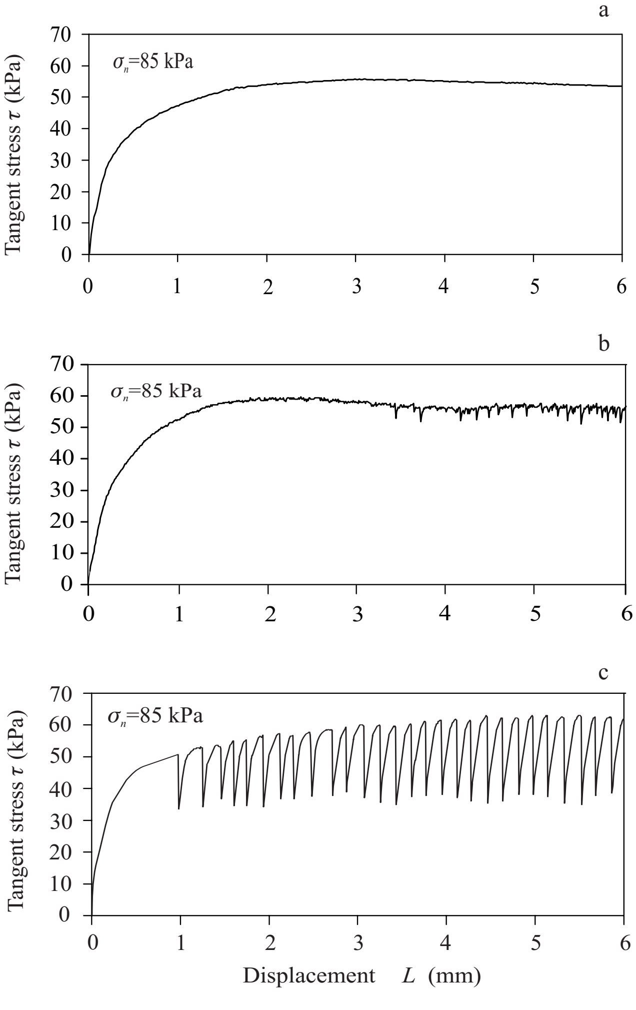

**Fig. 3.** Comparison of the tangent stress-displacement relationships for: a) smooth curve for wheat flour and groats (Horabik and Grochowicz, 2000), b) irregular vibration for NaCl salt, and c) saw blade curve for fine milk.

Based on the saw blades model of dilatation (Bolton, 1986) the two following strength components were determined from the tangent stress – shear displacement relationships (Fig. 4): the physical friction strength and the extra component of strength caused by dilatation. The extra angle of shearing of dense powders can be related to the rate of dilation and hence to the relative density and mean effective stress.

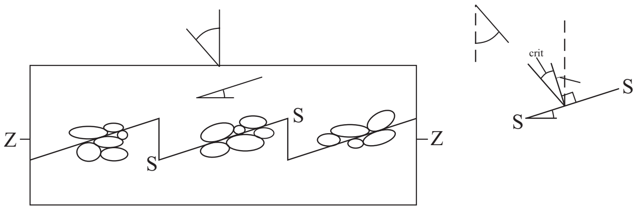

**Fig. 4.** The saw blades model of dilatation: the angle of internal friction, $\phi$, as the sum of the critical angle of friction, $\phi_{crit}$, and the angle of dilatation, $\Psi$ (Bolton, 1986).

Using plots of the tangent stress – shear displacement curves the yield loci for the maximum shearing strength, MS, (maximum value of the tangent stress during oscillation); and the critical strength, CS, (minimum value of tangent stress during oscillation) were determined (Fig. 5). It was assumed that the minimum value of tangent stress during oscillation corresponds to a critical state of the sample with zero dilation. The angle of internal friction $\phi$ corresponding to the maximum shear strength was found to decrease for a corresponding increase in the consolidation stress. Values of the friction coefficient $\mu$=tan$\phi$ and the cohesion *c* are presented in Fig. 5.

The flow index *i* indicates that over the range of consolidation stress, from 30 to 240 kPa, the three materials tested in this study can be classified as free or easy flowing powders (Fig. 6). The largest flow index value was obtained for the agglomerated milk while the fine milk and the potato starch were found to have nearly the same flowability.

The effective angle of internal friction $\delta$ of agglomerated milk and potato starch was determined to decrease with a corresponding increase in the normal stress, although the differences were not statistically significant (Fig. 7). In the case of fine milk the effective angle of internal friction $\delta$ was independent on the value of normal stress.

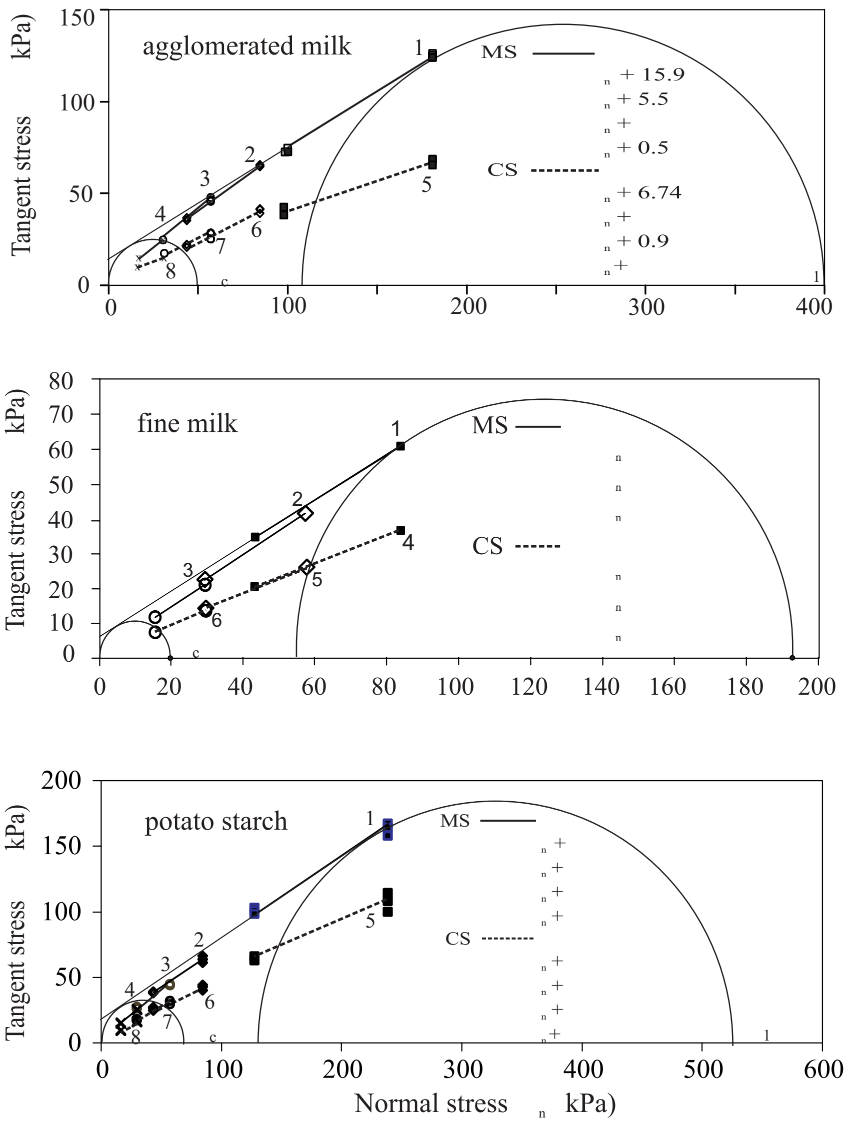

**Fig. 5.** Yield locus for the maximum shear strength (MS) and for the critical strength (CS) of the three tested materials.

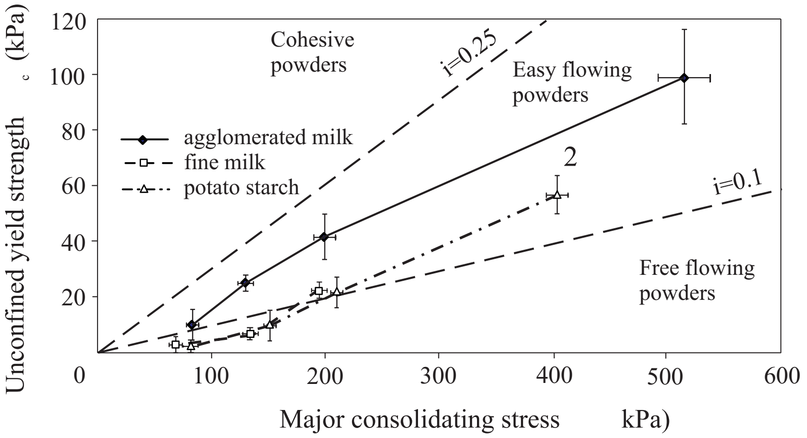

**Fig. 6.** Flow functions of tested materials (Mean ±St. Dev.).

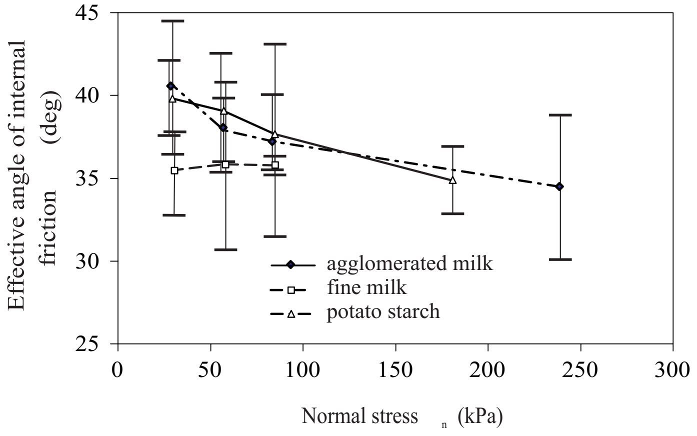

**Fig. 7.** Effective angle of internal friction (Mean ±St. Dev.).

Characteristics of the shear stress oscillation are shown in Figs 8 and 9. The amplitude of oscillation was found to be proportional to the normal stress (Fig. 8). The contribution of the stress oscillation to the total strength was approximately 30% for the agglomerated milk, 35% for the fine milk and 45% for the potato starch. The pitch of oscillation was determined to increase for an increase in normal stress (Fig. 9). This means that the frequency of collapse decreased for an increase in normal stress. The pitch of oscillation was the highest for the agglomerated milk (about 0.5 mm) and the lowest for the potato starch (about 0.1 mm).

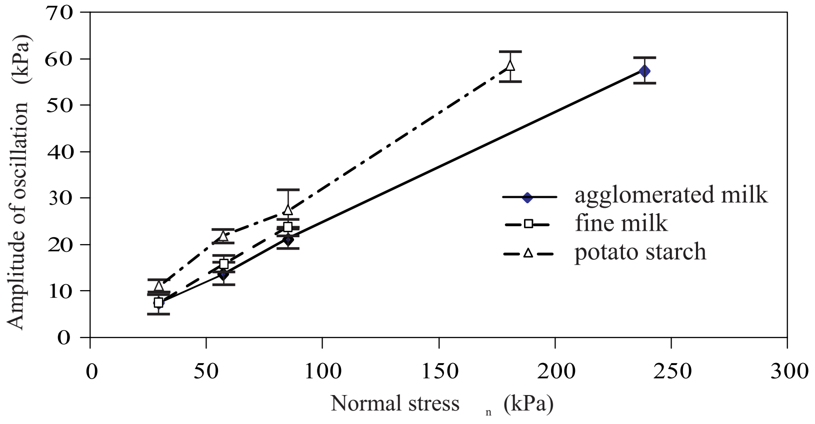

**Fig. 8.** Amplitude of the tangent stress oscillation (Mean ±St. Dev.).

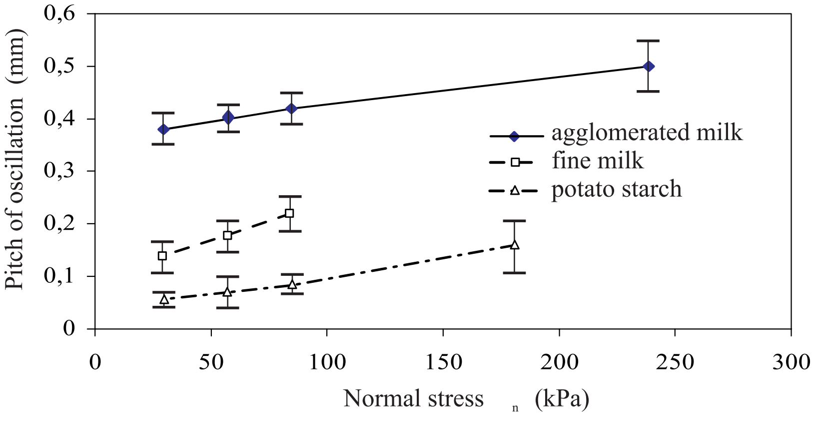

**Fig. 9.** Pitch of the tangent stress oscillation (Mean ±St. Dev.).

## DISCUSSION

A large number of powders show the tendency to change volume during shear, this volumetric change is known as dilatation. The volume changing results in an oscillation in the shear stress during slow shearing. Stress oscillation can lead to strong vibrations on silo walls and should be avoided for many reasons (Molenda *et al.,* 1997; Tejchman and Gudehus, 1999). For a better understanding of the mechanism of the stress oscillation during shearing the packing behaviour of powders should be considered. Molenda *et al.* (2001) indicated that a probable reason for the stress oscillation during shearing was the high compressibility of the material. Oscillation can be considered as part of a sequence of compaction-dilation events occurring around the area of shear zones developing in the material. Compaction results in an increase in material strength, and the ability to withstand higher shear loads. Exceeding the maximum strength is associated with dilation in the shear zone, reorientation of stresses and a sharp decrease in the shear load. This jump is immediately followed by a period of slower increase in strength that resulted from material compaction in a new shear zone. In densely packed granular materials shearing concentrates in a narrow shearing band of 12–16 grains thick (Horabik *et al.*, 2000; Nedderman and Laohakul, 1980). Maksimovic (1996) indicates four components related to the angle of maximum shearing strength: the angle of physical friction, the angle of degradation, the angle of reorientation, and the angle of dilatation. All four components are of different significance for different types of granular solids. The angle of physical friction depends on the material. This value is recorded only as combined with the values of angles of degradation and reorientation. The interlocking resistance of the particles inside this band is overcome by grain breakage and dilation. All of these components depend on the stress level. The effects of dilatation are more significant at lower stresses. At very high stresses the behaviour of most powders is governed by friction and particle breakage only. The ability of granular materials to achieve the dilatant plastic deformation is influenced by the relation between the compressibility of powders, particle breakage strength and particle adhesion forces. All of these parameters depend on the chemical composition of powders and particle size grading.

## CONCLUSION

The shear experiments performed on three tested food powders revealed a considerable effect of shear stress vibration resulting from dilatation and hardening of the material during slow deformation. The frequency of these vibrations were found to decrease as normal stress increased. Two components of the total strength were suggested: the physical friction strength and the extra component of strength caused by dilatation. The amplitude of the stress oscillation was found to be proportional to the normal stress. The pitch of the oscillation was determined to increase linearly with an increase in normal stress. Over the range of consolidation stress, from 30 to 240 kPa, the materials tested were determined to have flow functions which would classify them as free or easy flowing powders.

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