Biosystems Engineering

Research Paper: PH—Postharvest Technology

Flowability and handling characteristics of bulk solids and powders – a review with implications for DDGS☆

V. Ganesan[a], K.A. Rosentrater[b,*], K. Muthukumarappan[a]

[a]Department of Agricultural and Biosystems Engineering, South Dakota State University, Brookings, SD 57007, USA
[b]USDA, ARS, North Central Agricultural Research Laboratory, Brookings, SD 57006, USA

Much research regarding handling and storage characteristics of bulk solids has been conducted over the years. Physical properties of granular solids play a significant role in their resulting storage and flow behaviour, and are therefore essential to design appropriate, efficient, and economic bulk solids handling and storage equipment and structures. Distillers Dried Grains with Solubles (DDGS) is a bulk material that has been widely used as a protein source for ruminants and non-ruminants for more than two decades. Distillers grains are energy and nutrient dense, and are often used as a replacement for corn in animal diets. With the exponential growth of the fuel ethanol industry in the last few years, large quantities of distiller's grains are now being produced. To effectively utilize these feeds in domestic and international markets, however, these co-product streams are increasingly being transported greater distances, and must be stored until final use. DDGS flow is problematic as it often becomes restricted by caking and bridging which occurs during transportation and storage. This issue probably results from a number of factors, including storage moisture, temperature, relative humidity, particle size, time, or temperature variations, to name a few. The objective of this study was to review the primary factors affecting flowability, handling, and storage of granular solids and powders, as well as appropriate testing methodologies for these materials. Considering these will be helpful when examining granular flowability and storage challenges for byproduct feeds, including those surrounding the use of DDGS.

Published by Elsevier Ltd on behalf of IAgrE.

1. Introduction

Maize is the U.S.A.'s number one field crop; maize production measures more than two times that of any other crop. In 2006, U.S. maize production was 10.5 billion bushels (NCGA, 2007). The two most important manufactured maize products are corn sweeteners (i.e., high fructose corn syrup) and fuel ethanol. As fossil fuel reserves diminish and increase in price, there is growing interest in utilizing biomass and other renewable energy sources, including fuel ethanol. Ethanol from maize is a major fuel additive, and many ethanol plants have been constructed in the last decade in the Midwestern parts of United States. The production of ethanol from maize results in three main co-product streams: Distillers Wet

---

☆ Mention of trade name, propriety product or specific equipment does not constitute a guarantee or warranty by the United States Department of Agriculture and does not imply approval of a product to the exclusion of others that may be suitable.
* Corresponding author.
E-mail address: kurt.rosentrater@ars.usda.gov (K.A. Rosentrater).

Grains (DWG), Condensed Distillers Solubles (CDS) which is also known as ''syrup'', and the combined product Distillers Dried Grains with Solubles (DDGS) (which is the most common). These are produced from the non-fermentable maize residues which remain after the starch has been converted to ethanol. DDGS has been widely used as a protein source for ruminants and non-ruminants for several years. DDGS usually contains about 86–93% (db) dry matter, 26–34% (db) crude protein, and 3–13% (db) fat (Tjardes and Wright, 2002; Rosentrater and Muthukumarappan, 2006). As the U.S. ethanol industry has grown exponentially over the past several years, the supply of DDGS has also significantly increased. As a consequence, it is important to continue to increase the use of distillers grains in the marketplace. To achieve this, however, they will have to be hauled greater distances, and will have to be stored in bins and silos until use; sometimes this may be a relatively long time, depending on the animal production setting. DDGS storage and transportation can often be problematic, as it can harden inside storage structures, trucks and railcars. This can lead to damage when the cars are unloaded.

Furthermore, marketing of distillers grain products can be hampered by inconsistencies in physical and nutritional properties, both within a single plant over time, as well as between plants. Physical and chemical properties are important, because DDGS storage and flow behaviour will depend in large part on these parameters, as well as environmental variables. At times, small differences in variables such as moisture content, particle size, storage time, temperature, and relative humidity can cause caking/bridging of granular materials. This results in a great disparity in the flowability of DDGS. In light of the growth of the industry, the flowability of DDGS and their flow behaviour under various conditions are important vis-à-vis handling operations (storage in silos or bins) and transportation.

As there is currently little information available regarding the handling and flow behaviour of DDGS, there is a critical need for this data. This review discusses various factors affecting the flowability and handling of granular solids and powders, as well as appropriate test methods. Hence, it will be helpful for examining DDGS, as well as other co-product feed materials, and should be a useful resource base from which to address and remediate DDGS flowability problems.

2. Factors influencing the flowability of granular solids and powders

Flowability is the ability of granular solids and powders to flow. Flow behaviour is multidimensional in nature, and it depends on many physical characteristics. Flowability, in fact, is a consequence of the combination of a material's physical properties that influence material flow, environmental conditions, and the equipment used for handling, storing, and processing these materials (Prescott and Barnum, 2000). Because of this, no single test can fully quantify a product's flowability. Some of the factors that affect flowability of bulk solids and powders include moisture content, humidity, temperature, pressure, fat, particle size, and flow agents.

2.1. Moisture content

Amid all factors affecting a product's storage, moisture is a key factor, as it strongly influences microbial growth. Moreover, most organic granular materials are hygroscopic in nature, and they gain or lose moisture when they are exposed to various humidity conditions. Moisture sorption is often coupled with increased cohesiveness, chiefly because of inter-particle liquid bridge formation. Moisture content thus affects the cohesive strength and arching ability of bulk materials (Johanson, 1978). As the moisture content of a powder increases, the adhesion (Craik and Miller, 1958) and cohesion (Moreyra and Peleg, 1981) tend to increase. Even a small change in moisture content can substantially affect the frictional properties (e.g., wall friction angle, internal angle of friction) of material (Marinelli and Carson, 1992).

Physical properties of a material are also highly dependent on the material's moisture content, and each material will behave differently. For example, the angle of internal friction of zinc ore was found to be 32° and 56° at 18 and 23% moisture contents, respectively. This material adhered strongly to the steel bin during experimentation, and would have caused a severe flowability problem (Johanson, 1978). Duffy and Puri (1994) studied the flowability of confectionary sugar and detergent at two moisture contents. As the moisture content increased, the internal angle of friction of both the sugar and detergent decreased. Also the unconfined yield strength of sugar increased sevenfold as the moisture was increased by only 3%. It has also been found that with an increase in moisture, bulk density of granular solids generally decreases and the compressibility increases (Moreyra and Peleg, 1981; Yan and Barbosa-Canovas, 1997). Additionally, moisture at high levels can possibly alter the surface properties of particles to such an extent that the adherence pattern may be modified (Hollenbach et al., 1983).

Ganesan et al. (2008c) conducted one of the first studies to characterize the flow properties of DDGS, and found that DDGS flowability decreased with increase in moisture content. For example, at 10% soluble solids, angle of repose increased from 43.47° (at 10% moisture content) to 44.13° (at 30% moisture content); at 20% soluble solids, however, angle of repose increased from 42.57° (at 10% moisture content) to 44.77° (at 30% moisture content). At 10% soluble solids, the compressibility of the DDGS increased from 2.30 to 5.77%, while at 20% soluble solids it increased from 1.90 to 6.63%, at moisture contents of 10 and 30%, respectively.

2.2. Humidity

Relative humidity of the air (interstitial as well as head space) in a storage container, such as a bin or silo, also affects bulk materials' properties. Many bulk materials are hygroscopic and thus the exposure to humid conditions results in increased moisture content of the bulk. This can lead to an increase in bulk strength (Marinelli and Carson, 1992), and also to an increase in angle of repose. Flowability of any material reduces with an increase in the angle of repose of that material. Many researchers have observed that higher humidities had significant effects on the flowability and cohesiveness of granular powders (Craik and Miller, 1958;

Irani et al., 1959; Peleg and Mannheim, 1973; Johanson, 1978; Stanford and Corte, 2002; Fitzpatrick et al., 2004b).

Controlled humidity chambers are employed in many laboratories for studying the physical properties and stability of foods and feeds. Sulphuric acid, glycerol, or saturated salt solutions are often used to control the humidity (Rockland, 1960). Saturated salt solutions are most useful, as the three phase systems (vapour–liquid–solid) are independent of changes in their total moisture content. A number of salt solutions suitable for sustaining a wide range of specific relative humidity conditions at various temperatures are available (Spencer, 1926; Hodgman, 1954/55). ASTM standard method E-104 also provides information regarding maintaining constant relative humidity by means of aqueous solutions (ASTM, 2002b).

2.3. Temperature

Temperature also has a substantial effect on bulk solid flowability. The most drastic temperature effect is the freezing of the moisture contained within the granular materials and on particle surfaces. The resulting ice bonds weaken the flow (Irani et al., 1959; Johanson, 1978; Fitzpatrick et al., 2004b). Varying the storage temperature from above freezing to 30 or 40 °C does not usually have a great impact on powder flowability, if there is no melting of components or no component exceeds its glass transition temperature (Teunou and Fitzpatrick, 1999). But severe caking can occur whenever a granular material undergoes a change in crystallinity or other properties due to temperature variations (Johanson, 1978). Temperatures of both the wall material and the bulk material may affect the wall friction angle (Marinelli and Carson, 1992). For example, Fitzpatrick et al. (2004b) investigated the effect of temperature on the flow properties of skim milk powder (SMP), whole milk powder (WMP), and high fat milk powder (HFP); the authors observed that HFP showed highest wall friction at lowest temperatures, whereas SMP and WMP had higher wall friction at higher temperatures.

Ganesan et al. (2007a, 2008a) studied both the dynamic and equilibrium water adsorption characteristics of DDGS at four temperature (10, 20, 30, and 40 °C) and four relative humidity (60, 70, 80, and 90%) levels, and used common mathematical models to fit the adsorption and equilibrium data. The authors observed that DDGS showed characteristics similar to a type III isotherm, which often occurs in high sugar foods; this may be an indication of one of the reasons for DDGS flow problems. The authors did not, however, examine the effect of moisture sorption on resulting flow properties of the DDGS.

2.4. Pressure

Compacting pressure is also an important factor that affects the flow properties of bulk solids (like DDGS). The bulk may be subjected to compaction due to vibration (e.g., during transportation), impact from a falling stream of solids (e.g., during silo filling), or external loading. The effect of increased pressure on flowability of powders is twofold: (1) it leads to a larger number of contact points between particles, thus causing more inter-particle adhesion (Irani et al., 1959); and (2) the increased compaction produces a significant increase in

critical arching dimensions. Overpressure effects are not linear and they vary significantly with the sample. The crushing of particles due to overpressure can be predicted from the shape of the bulk density versus compacting pressure graph (Johanson, 1978).

2.5. Fat content

Free surface fat is expected to play a key role in granular flowability as well, but has not been extensively researched to date. For example, high fat content (20%) spray dried soymilk led to worse flow of the resulting soymilk powders (Perez and Flores, 1997). Further, free fat content, varying from 13 to 74%, had no major impact on the cohesion of a 26% fat milk powder at 20 °C (Fitzpatrick et al., 2004b). There are many reports available on the chemical composition of DDGS, but there is no study on the surface fat content of DDGS and its effect on DDGS flow properties. Granular material and powder flowability depend on the surface composition as surface free fat plays a key role in determining the flowability and stickiness of a powder.

2.6. Particle size

Particle size, and particle size distribution, both play significant roles in flowability and other properties, such as bulk density, angle of repose, and compressibility of bulk solids. Even a small change in particle size can cause significant alterations in the resulting flowability. Reduction in particle size often tends to decrease the flowability of a given granular material due to the increased surface area per unit mass (Fitzpatrick et al., 2004a, b). For example, Farely and Valentin (1967/68) investigated the influence of particle size distribution on bulk powder properties; they found that particle size was the most important factor governing the 'structure' of the powder compact, and at the same time, the interparticulate force governs the strength of the 'structure'.

Particle size also plays an important role in the compressibility of powders. An increase in particle size generally leads to an increase in compressibility (and thus volume reduction) (Yan and Barbosa-Canovas, 1997). In a mass flow scenario, if the particles are less than 1/4 inch in size, then cohesive arching will occur during discharge (Marinelli and Carson, 1992). The finer the particle size and greater the range of particle sizes, the greater the cohesive strength, and lower the flow rate (Marinelli and Carson, 1992). Reduction in size increases the contact area between the particles, thereby increasing the cohesive forces.

2.7. Flow conditioners and anticaking agents

Caking and stickiness are common problems that almost every industry dealing with granular solids and powders encounters. Caking is defined as when two or more macroparticles, each capable of independent translational movement, contact and interact to form a congregate in which the particles are incapable of independent translations (Barbosa-Canovas and Yan, 2003). Flow conditioners and anticaking agents are commonly used as additives that can assist a powder in maintaining a steady flow and/or increase its flow

rate. Flow conditioners are usually made from chemically inert substances and are often effective at concentrations up to 2%. Most are insoluble in water, but many of them can adsorb significant quantities of moisture as a result of their very large surface areas.

Many research studies have examined the effect of flow conditioners on flow properties of granular solids and powders in the past few decades (Craik, 1958; Craik and Miller, 1958; Irani and Callis, 1960; Sjollema, 1963; Peleg and Mannheim, 1973; Johanson, 1978; Chen and Chou, 1993; Onwulata et al., 1996; Perez and Flores, 1997; Jaya and Das, 2004). To be effective, a flow agent must be finer than the material to be conditioned. The finer the particle size of the conditioner, the less severe the caking of the original material should be (Irani et al., 1959). Additionally, the conditioner's particles must stick to the host powder particles, thereby producing a smoother and less frictional surface by filling the void spaces (Peleg and Hollenbach, 1984). Flow properties of conditioned powders are strongly influenced by the kind of surface interaction between the host powder and the conditioner particles (Hollenbach et al., 1983). If there is no attraction between the particles, then the conditioner particles themselves could segregate and fill the inter-particle voids instead of reducing the cohesiveness (Peleg, 1983). Above a certain inclusion rate, however, the conditioner can actually retard the overall flow of the material (Irani et al., 1959; Nash et al., 1965; Danish and Parrott, 1971; Hollenbach et al., 1982). If the surface affinity between the host powder and conditioner is strong, then large effects will be present in the bulk density and compressibility at inclusion concentrations between 0.1 and 0.5%. When there is little affinity, the effects become noticeable only at higher concentrations, such as 1–2% (Hollenbach et al., 1983).

There is limited information available on using different flow agents with DDGS. Ganesan et al., 2008b examined the use of calcium carbonate at inclusion levels of 0, 1, and 2%, and determined the effects on Carr properties. They found that without any flow agent, at 10% soluble solids, angle of repose increased from 44.77° (at 10% moisture content) to 45.17° (at 30% moisture content); at 20% soluble solids, however, angle of repose increased from 43.13° (at 10% moisture content) to 44.87° (at 30% moisture content). At 10% soluble solids, the compressibility of the DDGS increased from 1.70 to 4.27%, while at 20% soluble solids it increased from 1.33 to 4.50% at moisture contents of 10 and 30%, respectively. Thus, these results were similar to those of Ganesan et al. (2008c). They also found that the effect of adding calcium carbonate, even at 2%, did not significantly improve the DDGS flow properties. Furthermore, there is currently no literature available on improving the flow of DDGS at commercial settings (i.e., ethanol plants or livestock feeding operations). Thus further research is warranted.

3.　Flowability-related properties

The handling, storage, and flow of particulate materials are important in industries associated with agricultural, food, chemical, ceramic, pharmaceutical, metallurgical, and other bulk solids and powder processing. Flow is defined as the relative movement of a bulk of particles among neighbouring particles, or along the wall surface of a container (Peleg, 1977). Flow characteristics are of vital significance in bulk material handling and processing, since they impact conveying, blending, and storage options. DDGS often clumps together and forms cakes when it is stored for a long time. These clumps are sometimes very hard to break and often lead to damage to storage structures and economic losses (due to the use of sledgehammers and labour – time and salaries). To ensure steady and reliable flow, it is crucial to accurately characterize the flow behaviour of these granular materials (Kamath et al., 1994).

Barbosa-Canovas and Yan (2003) allowed a granular material to flow through a laboratory bin/conical funnel and evaluated its flowability based on the mass flow rate. The mass flow rate V_m is denoted as

$$V_m = \alpha \rho_b (D - \varphi d) \tag{1}$$

where ρ_b is bulk density (g cm^{-3}); D is orifice diameter (cm); d is mean diameter of the constituent particles (cm); α and φ are empirical coefficients (–). This approach should work for a variety of materials. Material flowability can also be quantified via several additional parameters, including angle of repose, bulk density, angle of internal friction, cohesion, adhesion, and compressibility.

3.1.　Angle of repose

Angle of repose is defined as the angle between the horizontal and the slope of a heap of granular material dropped from some designated elevation. Angle of repose corresponds qualitatively to the flow properties of that material, and is a direct indication of potential flowability. Angle of repose of a bulk solid can be described using the following equation (Fowler and Wyatt, 1960; Mohsenin, 1986; Rao, 1992):

$$\tan\Phi_r = an^2 + b\frac{M}{D_{av}} + cs_g + d \tag{2}$$

where Φ_r is angle of repose (degrees); n is shape factor based on specific surface (–); M is moisture content (db %); D_{av} is average particle diameter (cm); s_g is specific gravity (–); a, b, c, and d are empirical constants.

Most often, however, angle of repose is determined experimentally by allowing a sample to flow onto a flat surface, and then measuring the angle with respect to horizontal. There is much literature available on the angle of repose of granular materials (like food, grains, industrial powders, pharmaceutical powders, etc.) but not on DDGS. Typically, the lower the angle of repose of a dry material, the more flowable the material is, and vice versa (Carr, 1965a). Higher angles (i.e., 50–60°) indicate material with difficult flow, while a lower angle, such as 30–40°, represents a material with relatively easy flow. Angle of repose gives a reproducible numerical value, so it has been adopted as a common method to assess flow properties (Craik and Miller, 1958). Generally the magnitude of angle of repose increases with increase in moisture content.

3.2.　Bulk density

Bulk density of granular solids and powders is important when determining the volume of transport vehicles and

storage vessels. It mostly depends on particle size, moisture, and chemical composition, but also on handling and processing operations. It dictates the stability of flow and loads on bin walls (Johanson, 1971/72). Bulk density is defined as the mass of particles that occupies a unit volume of a container.

Increases in bulk density have been observed when conditioners are added (Peleg and Mannheim, 1973; Hollenbach et al., 1983), which results in modification of density via lowering the inter-particle interactions. Bulk density of food powders has also been observed to decrease with an increase in the particle size as well as with an increase in equilibrium relative humidity (Yan and Barbosa-Canovas, 1997).

The bulk density values of DDGS have been shown to range from 389 to 501 kg m^{-3} (Rosentrater, 2006). As of now, however, there is very little known about the influence of DDGS bulk density on its flow, or the effect of storage conditions on the resultant bulk density.

The ratio between tapped (a defined number of taps) and loose bulk density is known as the Hausner ratio, and it is often used as an internal friction index in cohesive powders (Guo et al., 1985; Malave et al., 1985).

Porosity, which is related to bulk density, can be expressed as the percentage of voids in a bulk solid:

$$P = \left[(V - V_p)/V\right] \times 100 \,(\%) \tag{3}$$

where P is porosity (%); V is bulk volume of the bulk (cm^3); and V_p is particle volume of the bulk (cm^3). P is affected by the flow of the granular material. As porosity decreases, bulk density increases (Sjollema, 1963).

3.3. Frictional forces

The angle of internal friction is a measure of the force required to cause particles to move or slide on each other. Stable slopes and hang-ups in bins are highly dependent on angle of internal friction (Johanson, 1971/72). Internal friction is influenced by many parameters, including particle surface friction, shape, hardness, size, and size distribution. Angle of internal friction data is needed for calculating the lateral pressure on walls of storage bins and for the design of gravity flow bins and hoppers (Mohsenin, 1986; Rao, 1992). Shear testing is used to measure the angle of internal friction (Peleg and Mannheim, 1973; Teunou et al., 1999; Fitzpatrick et al., 2004b).

Wall friction is a key parameter in the design and operation of hoppers, silos, and storage and discharge chutes. It is defined as the frictional resistance to bulk flow that exists between particles and wall material (Iqbal and Fitzpatrick, 2006). Wall friction is a complex phenomenon influenced by many factors, such as wall surface characteristics, bulk solids properties, and handling conditions (Prescott et al., 1999). Moreover, the wall surface is affected by the surface material, surface roughness, surface wear (Bradley et al., 2000), and surface corrosion. Savage (1967) carried out an analysis of gravity flow of cohesionless bulk solids in a vertical converging channel and observed that the wall friction was more influential than the angle of internal friction in reducing the flow rate for small values of cone wall half angle.

Cohesion is the property of particles adhering together in a bulk. Cohesive forces can occur from a variety of sources, namely liquid bridges, Van der Waals' forces, electrostatic

forces, and magnetic forces. The most prevalent inter-particle forces in systems composed of particles are the liquid bridging force and the Van der Waals force (Weber et al., 2004). Cohesion generally increases with a decrease in particle size and with an increase in moisture (Fitzpatrick et al., 2004a), depending on the material. A yield locus plot of failure shear stress versus normal stress for a given consolidating stress is often fitted using the Warren Spring equation (Farely and Valentin, 1967/68; Harwood, 1971; Peleg and Mannheim, 1973; Rooda, 1975; Peleg, 1977; Moreyra and Peleg, 1981; Barbosa-Canovas and Yan, 2003; Fitzpatrick et al., 2004a):

$$(\tau/C)^n = (\sigma + T)/T \tag{4}$$

where τ is failure shear stress (kPa); C is cohesion (kPa); n is shear index (dimensionless); T is tensile stress (kPa); and σ is normal stress (kPa). An increase in cohesion can often be caused by the formation of liquid bridges between the particles due to the melting of lipids (Fitzpatrick et al., 2004b). DDGS contains relatively high fat content (Tjardes and Wright, 2002; Rosentrater and Muthukumarappan, 2006) and at higher temperatures, there is a possibility of fat melting to form liquid bridges between particles.

During handling and storage of granular solids, all particles of a given size range can stick together or to container walls. Particle adhesion can be caused by a number of factors, including surface and field forces (e.g., van der Waals, electrostatic, and magnetic forces), material bridges between particle surfaces (e.g., liquid and solid bridges, flocculants), and physical interlocking of the particles themselves (Tomas, 2007). To measure particle adhesion tendency, T_a, Pietsch (1969) developed an empirical relationship:

$$T_a = \frac{\sum_i B_i(x)}{\sum_j F_{jy}(x)} > 1 \tag{5}$$

where $B_i(x)$ are the binding forces (N), and $F_{jy}(x)$ are the components of the environmental forces (N) which are acting upon the particles. The relative effect of adhesion depends on the particle size; to cause adhesion, T_a must be bigger than 1.0. When adhesion is significant, the angle of repose is increased, and flow is reduced. Adhesion can be suppressed by the addition of flow conditioners (Craik and Miller, 1958). Tomas (2007) modelled single particle adhesion using stiff particles and developed equations for elastic-plastic particle contact behaviour with adhesion, load–unload hysteresis, and adhesion force functions.

3.4. Compressibility

Much attention has been given to the behaviour of bulk solids under compressive stress. Typically, a set of compression cells is used to obtain the pressure–density relationship for a given material; the test material is compressed using a compression testing machine, and the force-deformation data must then be converted to a pressure–density relation (Hollenbach et al., 1983; Barbosa-Canovas et al., 1987; Barbosa-Canovas and Yan, 2003). A number of authors have suggested empirical equations to describe these relationships. Three commonly used models are: Heckel, Kawakita and Ludde, and Sone (Malave et al., 1985; Barbosa-Canovas and Yan, 2003).

There are other ways to examine compressibility, however. Hausner ratio, the ratio between tapped and loose bulk density, is also used to quantify the compressibility of bulk solids. The compressibility of a material can also be computed by the following equation:

$$C = 100(P - A)/P \qquad (6)$$

where C is compressibility (%), P is packed bulk density (kg cm^{-3}); A is aerated bulk density (kg cm^{-3}). The greater the compressibility of a bulk solid, the less flowable it is. In general, the borderline between free flowing and non free flowing is approximately 20–21% compressibility (Carr, 1965b). Compressibility and bulk density are related, and have been correlated using the following empirical equation (Peleg and Mannheim, 1973; Peleg, 1977; Hollenbach et al., 1983; Malave et al., 1985):

$$BD = a + b \log P \qquad (7)$$

where BD is bulk density (kg cm^{-3}); a is extrapolated BD at 1 kg cm^{-2} pressure (kg cm^{-3}); b is the slope of the straight line (compressibility) (kg cm^{-3}); P is applied pressure (kg cm^{-2}). A decrease in compressibility has been observed with an increase in the particle size (Yan and Barbosa-Canovas, 1997). A decrease in compressibility of various powders and granular solids was observed when conditioners were added (Peleg and Mannheim, 1973; Hollenbach et al., 1983). DDGS is expected to gain moisture when exposed to higher humid conditions. This might increase the compressibility of DDGS and lead to flow problems.

4. Test methods for measuring bulk flow properties

Knowledge of physical and flow properties of bulk solids is essential for the design of reliable storage systems and equipment for handling these materials. As of now, however, there is very little information available on the test methods to measure the flow properties of DDGS. A review of the test methods available for other bulk materials would thus be useful. Generally, shear testers are used to measure the strength and flow properties of bulk solids (Schwedes, 2002). Several commonly used testers and their principles are discussed below.

4.1. Jenike shear cell

Jenike (1964) was the first to establish the fundamental methods for determining the flow characteristics of bulk materials. The procedures delineated by Jenike have become a standard method D6128 (ASTM, 2000). To analyze the flow of solids in bins and silos, and to develop a model of flow and no-flow, Jenike used the principles of plastic failure (Fig. 3) with the Mohr-Coulomb failure criteria (Thomson, 1997). Ideally, in free flowing powders, the resistance to flow is due to the result of friction; but in cohesive powders, the inter-particle forces are enhanced by compaction, which results in mechanical strength in the bulk (Peleg, 1983). Jenike's direct shear cell tester (Figs. 1 and 2), and procedure for the design of bins, have been commonly used in research and in industrial practice for characterizing a variety of granular materials (Ashton et al., 1965; Schrämli, 1967; York, 1975; Kamath et al., 1993, 1994;
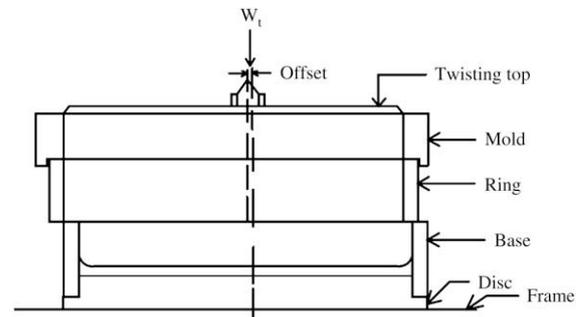
Fig. 1 – Schematic diagram of Jenike shear cell components.

Duffy and Puri, 1994, 1999; Schwedes, 1996; and Fitzpatrick et al., 2004b). The accuracy of the results depends upon the material being tested and the technician performing the procedures, and often has reproducibility problems.

To date, only one study has pursued Jenike shear testing of DDGS. Ganesan et al. (2007b) studied the flow behaviour of DDGS at four CDS (10, 15, 20, and 25% soluble solids) and five moisture (10, 15, 20, 25, and 30%) levels using Jenike shear testing. Unconfined yield strength varied from 0.05 to 15.96 kPa, angle of internal friction varied from 12 to 54°, and effective angle of internal friction varied from 25 to 58°. The authors found that the cohesiveness and compressibility of DDGS increased with an increase in moisture content and soluble solids levels.

4.2. Carr indices

The handling of granular materials is difficult without knowledge of how they flow in bins and hoppers. Carr (1965a) described a number of procedures that permit the evaluation of
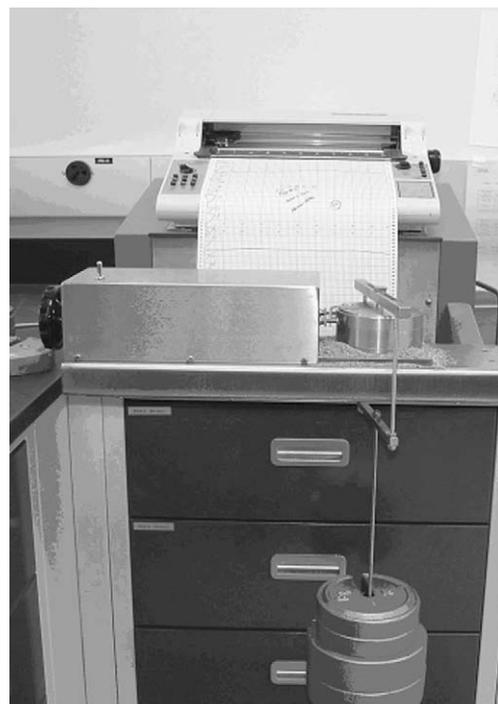
Fig. 2 – Jenike shear tester.
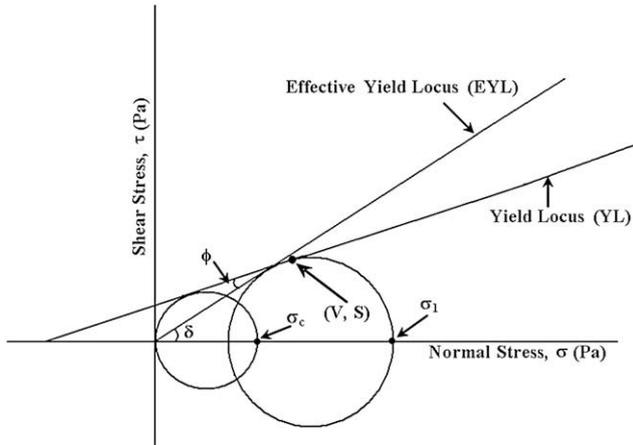
Fig. 3 – Typical Mohr circle failure plot used to analyze Jenike shear cell experimental data.

Fig. 4 – Semi-automated tester for Carr indices.

flow characteristics of such materials; and these procedures have become ASTM standard method D6393 (ASTM, 1999); it is widely used in powder and pharmaceutical industries (Kuchii and Tomita, 2002; Yang et al., 2005). The procedures described by Carr provide a realistic and straightforward method for assessing different aspects of flowability (Table 1) of any granular material. A tester used to evaluate the Carr flow properties is shown in Fig. 4. More detailed explanations of the Carr test procedures and resulting flow properties can be found in Ganesan et al. (2008b, c) and ASTM D6393 (ASTM, 1999).

4.3. Ring shear tester

The Schulze ring shear tester is also a widely used device to measure flow properties, including angle of internal friction, wall friction, and bulk density (Schulze, 1996; Röck and Schwedes, 2005). Detailed explanations of the test procedures for this shear tester can be found in Bromhead (1998) and ASTM method D6773 (ASTM, 2002a). Unlike the Jenike shear tester, this tester requires minimal operating skills and time. Moreover, results with low variability can be obtained with this tester (Schwedes and Schulze, 1990; Schulze, 1996; Schwedes, 2000). This tester, however, does not work well for particle sizes larger than powders.

4.4. Triaxial cell

The most widely used laboratory equipment for investigating the strength and deformation behaviour of soils at high stresses (i.e., >100 kPa) is the triaxial apparatus (Schwedes and Schulze, 1990). It was first developed by Bishop and Henkel (1962). For applications in powder storage problems, this method was found to be inadequate as it was designed for a relatively high stress range. Over the years, however, triaxial cells have been redesigned and have been successfully used to investigate agricultural grain properties (Bock et al., 1991). They have also been used to successfully measure powders at low stress ranges (Meerman and Knaapen, 1979; Kolymbas and Wu, 1990).

4.5. Direct shear cell

This apparatus has been used to measure the consolidated shear strength of soil in direct shear. Tsunakawa and Aoki (1982) used a direct shear tester with press loading to measure failure properties of granular materials. When compared to the Jenike shear cell test, the direct shear cell has the advantage that the yield locus can be obtained from only one shear test as a continuous line.

5. Modelling of bulk solids flow

Full scale silo experiments to determine material flow, and resulting effects on wall structures during flow are expensive and difficult to accomplish. Initial work in bulk solids flow by Jenike in the early 1960s was accomplished using numerical methods, which are relatively inexpensive and are amenable to extensive parametric studies. Today, numerical solutions of partial differential equations for stresses and flows are often

Table 1 – Carr classification of granular material flowability by Carr indices (based on Carr, 1965b)			
Property	Index value	Degree of flowability/floodability	Measures
Flow index	90–100	Very good	Bridge breaking measures not required
	0–19	Very bad	Special apparatus and techniques are required to break the bridge/cake/agglomerations
Flood index	80–100	Very high	Rotary seal must be used to prevent flushing
	0–24	Won't flush	Rotary seal is not required to prevent flushing

done using either the finite element method (FEM) or the discrete element method (DEM). Many studies have modelled the flow of granular solids and powders using FEM and DEM in the last few decades (see, for example, Langston *et al.*, 1996; Lu *et al.*, 1997; Gyenis *et al.*, 1999; Baxter *et al.*, 2000; Prescott and Barnum, 2000; Guines *et al.*, 2001; Vidal *et al.*, 2004; Zhang and Rosato, 2004). Both FEM and DEM are widely used for simulation of material flow in silos and hoppers, but they each have their own limitations. Most of the models have been used to describe the behaviour of cohesionless powders. Studies on particle mechanics, however, give a better physical understanding of the essential mathematical functions within a bulk solid's continuum. Tomas (2001a, b, 2004a, b) examined the fundamentals of cohesive powder consolidation and flow properties using both particle and continuum mechanics. Tykhoniuk *et al.* (2007) used continuum mechanical models along with DEM to relate macroscopic cohesion and friction to microscopic adhesion and contact friction for ultra fine cohesive powders, and observed that macroscopic cohesion was proportional to microscopic adhesion.

Because DDGS flowability is a multivariate problem, a comprehensive model to predict the flowability of DDGS would be very useful, as it could allow the prediction of when flow problems may occur. Ganesan *et al.* (2007c) developed an empirical model by combining results from Jenike and Carr testing, then using dimensional analysis and response surface modelling to predict the flowability of DDGS. This model was a nonlinear polynomial surface, and incorporated angle of internal frication, effective angle of internal friction, compressibility, dispersibility, and Hausner ratio, and fit the data well ($R^2 = 0.93$). This model, however, requires validation, and could be improved by accounting for other parameters associated with storage and flowability, including environmental conditions.

6.   Implications for DDGS

Today the growth of the DDGS market is limited by its caking/bridging tendency inside railcars and trucks during shipping, and to some extent bins and hoppers during storage. These occurrences make DDGS hard to unload and can lead to severe damage to shipping and storage containers. DDGS flowability problems may arise from a number of simultaneously interacting physical, flow, and chemical properties, environmental variables (i.e., temperature, relative humidity), external variables (i.e., vibration, compaction pressure), and storage time, to name a few. To date, only limited information is available for DDGS. The authors have investigated the flow behaviour of DDGS at various moisture contents, CDS levels, and flow agent levels using both Jenike and Carr test methods (Ganesan *et al.*, 2007b, c, 2008b, c), and have observed that increases in moisture content result in increases in cohesiveness and compressibility. Otherwise, there are no other known studies that have examined DDGS flowability. There are many things that must be known to thoroughly understand DDGS flowability. These include the chemical nature of particle surfaces (e.g., amorphous sugars, fats, and proteins which coat the particles), glass transition temperature of DDGS, denaturing of protein during production processes (because DDGS has high

protein content and high drying temperatures are typically used when processing DDGS), capillary condensation, and recrystallization (which may cause bonding at inter-particle contacts) over a period of time.

7.   Conclusions

During the last several years, many ethanol manufacturing plants have been established throughout the Midwest states of the United States, as maize is the major cultivated crop in these areas. Distillers dried grains (DDG) and DDGS have been widely used for cattle feed for several years, and are currently expanding into other major livestock segments as well, because they are an economical and effective replacement for maize, soybean meal, and dicalcium phosphate (especially in swine and poultry feeds). To date, most of the research work on ethanol co-products has focused on chemical and nutritional properties of distillers grains but not on the related physical or flow properties. Moreover, there is currently very little information available for storage and handling operations for these products.

To improve the use of these co-product feed materials, there is a vital need to understand their flow behaviour as well as storage and handling characteristics. This discussion should be an essential resource for future research aimed at examining and quantifying the flow properties of DDGS, as flow analysis of DDGS will play a significant part towards addressing flow problems associated with transport and storage. Remedies should be either economical modifications in current DDGS processing, handling, or storage, or DDGS formulation modifications to ensure reliable and uniform flow. Successful remedies will, in turn, reduce the limitations imposed by the caking/bridging tendency of DDGS. Additionally, this can help optimize utilization of these materials, and thus improve process economics for ethanol producers, livestock feeders, and ultimately the rural economy.

REFERENCES

ASTM D6128. (2000). Standard test method for shear testing of bulk solids using the Jenike shear cell. In: ASTM Standards. ASTM. W. ASTM International, Conshohocken, PA, USA.

ASTM D6393. (1999). Standard test method for bulk solids characterization by Carr indices. In: ASTM Standards. ASTM. W. ASTM International, Conshohocken, PA, USA.

ASTM D6773. (2002a). Standard shear test method for bulk solids using the Schulze ring shear tester. In: ASTM Standards. ASTM. W. ASTM International, Conshohocken, PA, USA.

ASTM E104. (2002b). Standard practice for maintaining constant relative humidity by means of aqueous solutions. In: ASTM

Standards. ASTM. W. ASTM International, Conshohocken, PA, USA.

Ashton M D; Farely R; Valentin F H H (1965). Some investigations into the strength and flow properties of powders. Rheologica Acta, **4**(3), 206–218.

Barbosa-Canovas G V; Lopez J M; Peleg M (1987). Density and compressibility of selected food powders mixtures. Journal of Food Process Engineering, **10**, 1–19.

Barbosa-Canovas G V; Yan H (2003). Powder characteristics of preprocessed cereal flours. In: Characterization of Cereals and Flours (Kalentunc G; Breslauer K J eds), pp. 173–209. Marcel Dekker, New York.

Baxter J H; Abou-Chakra; Tüzün U; Mills Lamptey B (2000). A DEM simulation and experimental strategy for solving fine powder flow problems. Transactions of Industrial Chemical Engineering, **78**, 1019–1025.

Bishop A W; Henkel D J (1962). The Measurement of Soil Properties in the Triaxial Test. Edward Arnold, London.

Bock R G; Puri V M; Manbeck H B (1991). Triaxial test sample size effect on stress relaxation of wheat en masse. Transactions of ASAE, **34**(3), 966–971.

Bradley M S A; Pittman A N; Bingley M; Farnish R J; Pickering J (2000). Effect of wall material hardness on choice of wall materials for design of hoppers and silos for the discharge of hard bulk solid. Tribology International, **33**(12), 845–853.

Bromhead E N (1998). Measurement of shear strength. In The Stability of Slopes (second ed.), pp. 99–102 Taylor and Francis Group, New York.

Carr Jr. R L (1965a). Evaluating flow properties of solids. Chemical Engineering, **72**(3), 163–168.

Carr Jr. R L (1965b). Classifying flow properties of solids. Chemical Engineering, **72**(3), 69–72.

Chen Y L; Chou J Y (1993). Selection of anticaking agents through crystallization. Powder Technology, **77**, 1–6.

Craik D J (1958). The flow properties of starch powders and mixtures. The Journal of Pharmacy and Pharmacology, **10**(2), 73–79.

Craik D J; Miller B F (1958). The flow properties of powders under humid conditions. Journal of Pharmacy and Pharmacology, **10**, 136–144.

Danish F Q; Parrott E L (1971). Effect of concentration and size of lubricant on flow rate of granules. Journal of Pharmaceutical Sciences, **60**(5), 752–754.

Duffy S P; Puri V M (1994). Effect of moisture content on flow properties of powders. ASAE Paper No. 944033.

Duffy S P; Puri V M (1999). Measurement and comparison of flowability parameters of coated cottonseeds, shelled maize and soybeans at three moisture contents. Transactions of the ASAE, **42**(5), 1423–1427.

Farely R; Valentin F H H (1967/68). Effect of particle size upon strength of powders. Powder Technology, **1**, 344–354.

Fitzpatrick J J; Barringer S A; Iqbal T (2004a). Flow property measurement of food powders and sensitivity of Jenike's hopper design methodology to the measured values. Journal of Food Engineering, **61**(3), 399–405.

Fitzpatrick J J; Iqbal T; Delaney C; Twomey T; Keogh M K (2004b). Effect of powder properties and storage conditions on the flowability of milk powders with different fat contents. Journal of Food Engineering, **64**(4), 435–444.

Fowler R T; Wyatt F A (1960). The effect of moisture content on the angle of repose of granular solids. Australian Journal for Chemical Engineers, **1**, 5–8.

Ganesan V; Rosentrater K A; Muthukumarappan K (2007a). Dynamic water adsorption characteristics of distillers dried grains with solubles (DDGS). Cereal Chemistry, **84**(6), 548–555.

Ganesan V; Muthukumarappan K; Rosentrater K A (2007b). Flow Properties of DDGS with Varying Soluble and Moisture Content Using Jenike Shear Testing. ASABE Paper No 076063. ASABE, St. Joseph, Mich.

Ganesan V; Rosentrater K A; Muthukumarappan K (2007c). Modeling the flow properties of DDGS. Cereal Chemistry, **84**(6), 556–562.

Ganesan V; Muthukumarappan K; Rosentrater K A (2008a). Sorption isotherm characteristics of distillers dried grains with solubles (DDGS). Transactions of the ASABE, **51**(1), 1–8.

Ganesan V; Muthukumarappan K; Rosentrater K A (2008b). Effect of flow agent addition on the physical properties of DDGS with varying moisture content and soluble levels. Transactions of the ASABE, **51**(2), 591–601.

Ganesan V; Rosentrater K A; Muthukumarappan K (2008c). Effect of moisture content and soluble level on the physical, chemical, and flow properties of distillers dried grains with solubles (DDGS). Cereal Chemistry, **85**(4), 464–470.

Guines D; Ragneau E; Kerour B (2001). 3D finite element simulation of a square silo with flexible walls. Journal of Engineering Mechanics, **127**, 1051–1057.

Guo A; Beddow J K; Vetter A F (1985). A simple relationship between particle shape effects and density, flow rate and Hausner ratio. Powder Technology, **43**, 279–284.

Gyenis J; Ulbert Zs; Szépvölgyi J; Tsuji Y (1999). Discrete particle simulation of flow regimes in bulk solids mixing and conveying. Powder Technology, **104**, 248–257.

Harwood C F (1971). Compaction effect on flow property indexes for powders. Journal of Pharmaceutical Sciences, **60**(1), 161–163.

Hodgman C D (1954/55). Handbook of Chemistry and Physics. Chemical Rubber Publications, Cleveland, Ohio. pp 2309–2310.

Hollenbach A M; Peleg M; Rufner R (1982). Effect of four anticaking agents on the bulk characteristics of ground sugar. Journal of Food Science, **47**, 538–544.

Hollenbach A M; Peleg M; Rufner R (1983). Interparticle surface affinity and the bulk properties of conditioned powders. Powder Technology, **35**, 51–62.

Iqbal T; Fitzpatrick J J (2006). Effect of storage conditions on the wall friction characteristics of three food powders. Journal of Food Engineering, **72**(3), 273–280.

Irani R R; Callis C F (1960). The use of conditioning agents to improve the handling properties of cereal products. Cereal Science Today, **5**(7), 198–201, 214.

Irani R R; Callis C F; Liu T (1959). Flow conditioning and anticaking agents. Industrial and Engineering Chemistry, **51**(10), 1285–1288.

Jaya S; Das H (2004). Effect of maltodextrin, glycerol monostearate and tricalcium phosphate on vacuum dried mango powder properties. Journal of Food Engineering, **63**, 125–134.

Jenike A W (1964). Storage and flow of solids. Bulletin No. 123, Utah Engineering Station. Bulletin of the University of Utah.

Johanson J R (1971/72). Modelling flow of bulk solids. Powder Technology, **5**, 93–99.

Johanson J R (1978). Know your material-how to predict and use the properties of bulk solids. Chemical Engineering9–17, (Desk book issue).

Kamath S; Puri V M; Manbeck H B; Hogg R (1993). Flow properties of powders using four testers – measurement, comparison and assessment. Powder Technology, **76**, 277–289.

Kamath S; Puri V M; Manbeck H B (1994). Letter: flow property measurement using the Jenike cell for wheat flour at various moisture contents and consolidation times. Powder Technology, **81**(3), 293–297.

Kolymbas D; Wu W (1990). Recent results of triaxial tests with granular materials. Powder Technology, **60**(2), 99–119.

Kuchii S; Tomita Y (2002). Flushing phenomenon of fine powder. Powder Technology, **126**(3), 275–282.

Langston P A; Tüzün U; Heyes D M (1996). Distinct element simulation of interstitial air effects in axially symmetric granular flows in hoppers. Chemical Engineering Science, **51**, 873–891.

Lu Z; Negi S C; Jofriet J C (1997). A numerical model for flow of granular materials in silos. Part 1: model development. Journal of Agricultural Engineering Research, **68**(3), 223–229. doi:10.1006/jaer.1997.0196.

Malave J; Barbosa-Canovas G V; Peleg M (1985). Comparison of the compaction characteristics of selected food powders by vibration, tapping and mechanical compression. Journal of Food Science, **50**, 1473–1476.

Marinelli J; Carson J W (1992). Solve solids flow problems in bins, hoppers and feeders. Chemical Engineering Progress, **88**(5), 22–28.

Meerman W C P M; Knaapen A C (1979). A high pressure triaxial testing cell. Powder Technology, **22**(2), 271–278.

Mohsenin N N (1986). Friction. In: Physical Properties of Plant and Animal Materials, **Vol. 1**. Gordon and Breach Publishers, New York. 556–642.

Moreyra R; Peleg M (1981). Effect of equilibrium water activity on the bulk properties of selected food powders. Journal of Food Science, **46**, 1918–1922.

Nash J H; Leiter G G; Johnson A P (1965). Effect of antiagglomerant agents on physical properties of finely divided solids. Industrial and Engineering Chemistry, **4**, 140–145.

NCGA (2007). World of Corn-production. National Corn Growers Association, Washington D.C. <http://www.ncga.com/WorldOfCorn/main/production1.asp> (accessed 23.03.07).

Onwulata C I; Konstance R P; Holsinger V H (1996). Flow properties of encapsulated milk fat powders as affected by flow agent. Journal of Food Science, **61**(6), 1211–1215.

Peleg M (1977). Flowability of food powders and methods for its evaluation – a review. Journal of Food Process Engineering, **1**, 303–328.

Peleg M (1983). Physical characteristics of food powders. In: Physical Properties of Foods (Peleg M; Bagley E eds), pp. 293–323. AVI, New York.

Peleg M; Hollenbach A M (1984). Flow conditioners and anticaking agents. Food Technology, **38**(3), 93–102.

Peleg M; Mannheim C H (1973). Effect of conditioners on the flow properties of powdered sucrose. Powder Technology, **7**, 45–50.

Perez M F; Flores R A (1997). Particle size of spray dried soymilk. Applied Engineering in Agriculture, **13**(5), 647–652.

Pietsch W B (1969). Adhesion and agglomeration of solids during storage, flow and handling-a survey. Journal of Engineering for Industry, **5**, 435–449.

Prescott J K; Ploof D A; Carson J W (1999). Developing a better understanding of wall friction. Powder Handling and Processing, **11**(1), 19–26.

Prescott J K; Barnum R A (Oct 2000). On powder flowability. Pharmaceutical Technology 60–84.

Rao M A (1992). Transport and storage of food products. In: Handbook of Food Engineering (Heldman D R; Lund D B eds), pp. 199–246. Marcel Dekker, New York.

Röck M; Schwedes J (2005). Investigations on the caking behaviour of bulk solids-macroscale experiments. Powder Technology, **157**(1–3), 121–127.

Rockland L B (1960). Saturated salt solutions for static control of relative humidity between 5 °C and 40 °C. Analytical Chemistry, **32**(10), 1375–1376.

Rooda E J (1975). A numerical method for the calculation of the powder flow properties obtained with the Jenike flow factor tester. Powder Technology, **12**, 97–102.

Rosentrater K A; Muthukumarappan K (2006). Corn ethanol coproducts: generation, properties, and future prospects. International Sugar Journal, **108**(1295), 648–657.

Rosentrater K A (2006). Physical Properties of Distillers Grains with Solubles (DDGS). ASABE paper No: 066164. ASABE, St. Joseph, MI.

Savage S B (1967). Gravity flow of a cohesionless bulk solid in a converging conical channel. International Journal of Mechanical Science, **9**(9), 651–659.

Schrämli W (1967). On the measurement of the flow properties of cement. Powder Technology, **1**, 221–227.

Schulze D (1996). Flowability and time consolidation measurements using a ring shear tester. Powder Handling and Processing, **8**(3), 221–226.

Schwedes J (1996). Measurement of flow properties of bulk solids. Powder Technology, **88**, 285–290.

Schwedes J (2000). Testers for measuring flow properties of particulate solids. Powder Handling and Processing, **12**(4), 337–354.

Schwedes J (2002). Consolidation and flow of cohesive bulk solids. Chemical Engineering Science, **57**, 287–294.

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

Sjollema A (1963). Some investigations on the free flowing properties and porosity of milk powders. Netherlands Milk and Dairy Journal, **17**, 245–259.

Spencer H M (1926). Laboratory methods for maintaining constant humidity. In: International Critical Tables of Numerical Data, Physics, Chemistry and Technology, **Vol. 1**. McGraw-Hill Publications, New York, NY. 67–68.

Stanford M K; Corte C D (2002). Effects of humidity on the flow characteristics of PS304 plasma spray feedstock powder blend. NASA/TM-2002-211549. Ohio.

Teunou E; Fitzpatrick J J (1999). Effect of relative humidity and temperature on food powder flowability. Journal of Food Engineering, **42**(2), 109–116.

Teunou E; Fitzpatrick J J; Synnott E C (1999). Characterisation of food powder flowability. Journal of Food Engineering, **39**(1), 31–37.

Thomson F M (1997). Storage and flow of particulate solids. In Handbook of Powder Science and Technology, pp. 389–486. Chapman and Hall Publications, New York, NY.

Tjardes K; Wright C (2002). Feeding corn distiller's co-products to beef cattle. Extension Extra – SDSU Extension Cooperative Service. Available from: http://agbiopubs.sdstate.edu/articles/ExEx2036.pdf.

Tomas J (2001a). Assessment of mechanical properties of cohesive particulate solids. Part 1: particle contact constitutive model. Particulate Science and Technology, **19**, 95–110.

Tomas J (2001b). Assessment of mechanical properties of cohesive particulate solids. Part 2: powder flow criteria. Particulate Science and Technology, **19**, 111–129.

Tomas J (2004a). Fundamentals of cohesive powder consolidaton and flow. Granular Matter, **6**, 75–86.

Tomas J (2004b). Product design of cohesive powders-mechanical properties, compression, and flow behavior. Chemical Engineering and Technology, **27**(6), 605–618.

Tomas J (2007). Adhesion of ultra fine particles: a micromechanical approach. Chemical Engineering Science, **62**, 1997–2010.

Tsunakawa H; Aoki R (1982). Measurements of the failure properties of granular materials and cohesive powders. Powder Technology, **33**, 249–256.

Tykhoniuk R; Tomas J; Luding S; Kappl M; Heim L; Butt H J (2007). Ultrafine cohesive powders: from interparticle contacts to continuum behaviour. Chemical Engineering Science, **62**, 2843–2864.

Vidal P; Guaita M; Ayuga F (2004). Simulation of discharging processes in metallic silos. ASAE Paper No. 044151.

Weber M W; Hoffman D K; Hrenya C M (2004). Discrete particle simulations of cohesive granular flow using a square-well potential. Granular Matter, **6**(4), 239–254.

Yan H; Barbosa-Canovas G V (1997). Compression characteristics of agglomerated food powders: effect of agglomerate size and water activity. Food Science and Technology International, **3**(5), 351–359.

Yang J; Sliva A; Banerjee A; Dave R N; Pfeffer R (2005). Dry particle coating for improving the flowability of cohesive powders. Powder Technology, **158**(1–3), 21–33.

York P (1975). The use of glidants to improve the flowability of fine lactose powder. Powder Technology, **11**, 197–198.

Zhang N; Rosato A D (2004). Analysis of instantaneous dynamic states of vibrated granular materials. Mechanics Research Communications, **31**, 525–544.