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Flowability and Handling Characteristics of Bulk Solids and Powders – A Review

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Abstract. *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 flow and storage behavior, and are therefore essential to design appropriate, efficient, and economic bulk solids handling and storage equipment and structures. Distillers Dried Grains with Solubles (DDGS) are 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 dense as they contain high fat levels. With the exponential growth of the fuel ethanol industry in the past several years, significant quantities of distiller's grains are now being produced. To effectively utilize these feeds in the domestic market, however, these coproduct streams are increasingly being transported greater distances, and must be stored until final use. DDGS flow is often problematic as it can become restricted by caking and bridging which occurs during transportation and storage. This issue probably results from storage moisture, temperature, relative humidity, particle size, time, or temperature variations. The objective of this study is to review the primary factors affecting flowability, handling, and storage of granular solids and powders, as well as appropriate test methodologies for these materials. Considering these will be helpful when examining granular flowability and storage challenges, including those surrounding the use of DDGS.*

Keywords. Bridging, Caking, DDGS, Granular Powders, Moisture, RH, Storage, Temperature.

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Introduction

Distillers' grains are the corn fraction remaining after the starch has been converted to ethanol in corn dry mill processing. Distillers dried grains with solubles (DDGS) have been widely used as protein (approx. 30%) sources for ruminants and non-ruminants for more than two decades. Distillers' grains are energy dense as they contain high fat (10-12%) content. With the tremendous growth of the U.S. ethanol industry in the past decade, significant quantities of distiller's grains are now produced. Currently, almost 5.0 million tons of distillers dried grains are created in domestic dry grind ethanol production, and this number is expected to increase to 9 million tons by the year 2006. Moreover, exports of DDGS to Europe, a major outlet for these feed materials, might decrease in coming years. As a consequence, it is important to increase the use of distillers' grains in domestic market. To achieve this, however, they will have to be economically hauled greater distances, and will have to be stored in bins and silos until use; sometimes this may be a relatively long time. The storability and resulting flowability of DDGS is currently becoming very problematic.

Furthermore, marketing of distillers' grain products is hampered by inconsistencies in physical properties, both within a single plant over time, as well as between plants. Quantification of physical properties is important, because DDGS storage and flow behavior depends on the physical properties of DDGS, as well as external conditions such as temperature, relative humidity, and compression. At times, small differences in moisture content, particle size, storage time, temperature, and even relative humidity can cause caking / bridging of granular materials. This results in a great disparity in flowability. The flowability of DDGS and their flow behavior under various pressures, temperatures and humidities are important in handling operations such as storage in silos or hoppers, transportation and packaging.

As there is currently no information available regarding the handling and flow behavior of DDGS, there is a critical need for this data. This review discusses the various factors affecting the flowability and handling of granular solids and powders, as well as appropriate test methods, and thus should be helpful in examining DDGS as well as other byproduct feed materials.

Factors Influencing the Flowability of Granular Solids and Powders

Flowability is defined as the ability of granular solids and powders to flow. Flow behavior is multidimensional in nature, and it depends on many physical characteristics. Because of this, no single test can quantify a product's flowability. Flowability, in fact, is not a natural material property at all. It is the consequence of the combination of material physical properties that influence material flow, environmental conditions, and the equipment used for handling, storing, and processing the material (Prescott and Barnum, 2000). Some of the factors that affect flowability are discussed below, and include moisture content, humidity, temperature, pressure, fat, particle size, and addition of flow agents.

Moisture Content

Amid all factors affecting product storage, moisture is a key, as it influences microbial growth. Most organic granular materials are hygroscopic in nature, so they gain or lose moisture when they are exposed to various humidity conditions. This leads to physical and chemical changes in the material itself. Moisture sorption is coupled with increased cohesiveness, chiefly because of interparticle liquid bridge formation. Moisture content is a significant variable that 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 affects the frictional properties (wall friction angle, internal angle of friction) of material significantly (Marinelli and Carson, 1992). Physical properties are highly dependent on the material's moisture content, and that each material behaves differently. For example, the angle of friction of zinc ore at 18% moisture was found to be 32°. But when the moisture was increased to 23%, the friction angle reached 56°. This showed that the material adhered strongly to the steel bin and would undoubtedly have caused a severe build up problem (Johanson, 1978). Duffy and Puri (1994), studied the flowability parameters of confectionary sugar and detergent at two moisture contents (0.3% and 3.3% for sugar; 1.4% and 4.4% for detergent). As the moisture content increased, the internal angle of friction of both the sugar and detergent decreased. This is totally different from Johanson's (1978) case. Also the unconfined yield strength of sugar increased seven fold as the moisture increased by 3%. It has also been found that with an increase in moisture, bulk density of granular solids decreases and the compressibility increases (Moreyra and Peleg, 1981; Yan and Barbosa, 1997). Moisture at higher levels can possibly alter the surface properties of particles to such an extent that the adherence pattern may also be modified (Hollenbach et al, 1983).

Humidity

Relative humidity of the air (interstitial as well as head space) in a storage container, such as a bin or silo, also affects a bulk material's properties. Many bulk materials are hygroscopic, and thus the exposure to humid conditions results in increased moisture content of the material. This can lead to the particles gaining strength (Marinelli and Carson, 1992), but also to an increase in angle of repose. Flowability reduces with increase in angle of repose, and increase in humidity increased the angle of repose of starch, sucrose and sodium chloride (Craik and Miller, 1958).

Caking problems were observed when samples of DDT were stored at 60 or 75% RH (Irani et al, 1959). The angle of internal friction was found to decrease with the powder humidity (Peleg and Mannheim, 1973). When prilled urea was tested in a shear cell at 70°F and 50%RH, it showed no arching, whereas prilled urea tested at 90°F and 95%RH showed a central core with a pond of urea-saturated water surrounding it (Johanson, 1978). The consequences of atmospheric humidity (2-100%RH) on the flow characteristics of PS304 plasma spray feedstock powder blend were studied. The flow was more affected when the RH was above 66%; and, in fact, there was no flow observed at 88%RH (Stanford and Corte, 2002). Fitzpatrick et al- (2004b) noticed a greater effect on the cohesiveness of skim milk powder when it is exposed to 46%RH and 20°C. This may be due to the glass transition of lactose which in turn forms solid crystal bridges between powder particles.

Controlled humidity chambers are employed in many laboratories for studying the physical properties and stability of foods and feeds. Sulfuric acid, glycerol or saturated salt solutions are often employed for controlling the humidity (Rockland, 1960). Saturated salt solutions are most useful, as the three phase (vapor-liquid-solid) systems are independent of changes in their total moisture content. A saturated aqueous solution in contact with an excess of a definite solid phase at a given temperature will maintain a constant humidity within any enclosed space around it. A number of salt solutions suitable for sustaining a wide range of specific relative humidities at various temperatures were displayed in tables and charts (Spencer, 1926; Hodgman, 1954/55). For example, $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ at 5°C will maintain a RH of 39.8% and at 20°C, 32.3% RH.

Temperature

Temperature also has a substantial effect on granular solid and powder flowability. The most drastic temperature effect is the freezing of moisture contained within the granular

materials and on particle surfaces. The resulting ice bond weakens 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). Johanson (1978) found that the coal at 14°F and adipic acid at 150°F are more free flowing than at room temperature. Severe caking occurs whenever a granular material undergoes a change in crystallinity or other physical 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). 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). They found that the cohesiveness of SMP and WMP tended to increase as the temperature increased from 5 to 20°C. But for HFP, the cohesiveness increased from 5 to 20°C and then it is decreased from 30 to 40°C.

Pressure

Compacting pressure is also one of the significant factors affecting the flow properties of bulk solids. Additionally, the solids may be subjected to further compaction due to vibration, impact from a falling stream of solids, or external loading. The effect of increased pressure on flowability, and on caking in particular, is twofold. It leads to a larger number of contact points between particles, thus causing more interparticle adhesion (Irani et al, 1959). 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).

Fat

Surface free fat content is expected to play a key role in determining granular flowability, but has not been extensively researched. High fat (20%) content spray dried soymilk led to worse flow of the resulting powder (Perez and Flores, 1997). 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).

Particle Size

Particle size, and particle size distribution, plays a significant role in flowability, bulk density, angle of repose, and compressibility of powders and granular solids. In fact, particle size measurements are often made to control final product quality. Even a small change in particle size will cause a significant difference in the resulting flowability. A powder is considered as having a particle size less than 200µm; a reduction in this size will make flowability worse and will increase particle cohesion. This is due to the increased surface area per unit mass (Fitzpatrick et al, 2004a, 2004b). Farely and Valentin (1967/68) investigated the influence of particle size distribution on bulk powder properties. They correlated the shear index n , in the yield locus equation:

$$\left(\frac{\tau}{C}\right)^n = \frac{\sigma}{T} + 1 \quad (1)$$

with the volume surface mean diameter (in microns) by means of a general equation:

$$n = 1 + \frac{B}{(d)^{2/3}} \quad (2)$$

where τ is shear stress (g/cm²); T is tensile strength (g/cm²); σ is normal stress (g/cm²); C is cohesion (g/cm²); n is the shear index (-); B is a constant (-); d is volume/surface mean diameter (μ m). It was found that the particle size was the most important factor governing the “structure” of the powder compact; at the same time the interparticulate forces govern the strength of this “structure”.

Particle size also plays an important role in the compressibility of food powders. An increase in particle size leads to an increase in compressibility, and thus a decrease in bulk density (Yan and Barbosa, 1997). In mass flow bin, if the particles are less than 4 in. in size, then cohesive arching will occur. The finer the particle size and greater the range of particle sizes, the greater it's cohesive strength, and the lower the flow rate (Marinelli and Carson, 1992). Reduction in size increases the contact area between the particles allowing greater interaction between the cohesive forces.

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 modes, contact and interact to form a conglomerate in which the particles are incapable of independent translations (Barbosa and Yan, 2003). Flow conditioners and anticaking agents, also called glidants, antiagglomerants, lubricants, dispersion agents, and free flowing agents, are commonly identified as additives that will assist a powder in maintaining a steady flow and/or increase its flow rate. Inter- and intra-particle forces, particle size, and shape, as well as moisture and fat contents, are the sources of most flow problems. 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. A significant caking inhibition was found when surfactants such as lauryl amine and sodium dodecyl sulfonate were added to ammonium perchlorate (Chen and Chou, 1993). Onwulata et al. (1996) studied the effect of three flow conditioners (calcium stearate, aluminum silicate, and silica) at three levels of concentration (0, 1, and 2%) on the bulk and flow properties of sucrose, lactose, and modified corn starch as well as butter oil powders encapsulated with the same materials. They found that silica and silicate as flow conditioners were effective in improving the flowability of unencapsulated powders as well as lactose encapsulated butter oil powders, whereas the stearate flow conditioner resulted in flow retardation of all powders. Two dispersion agents, Cab-o-Sil and Zeofree 80, have been found to have a significant effect on the flowability of spray dried soymilk (Perez and Flores, 1997).

To be effective, the conditioning agent must be finer than the material to be conditioned. The finer the particle size of the conditioner, the less severe is the caking of the original material (Irani et al, 1959). 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). For example, dolomitic limestone had an arching dimension of 3.2 ft in a mass flow bin, whereas with a fractional addition of flow additive showed a zero arching dimension. The flow aid reduced the permeability of limestone by 100 times and manifestly smoothed the surface of the particles thereby prevented interlocking (Johanson 1978). Addition of tricalcium phosphate,

magnesium carbonate, and Santocel®C up to 4% to barely malt flour, bread flour, and cake flour improved their flow properties (Irani and Callis, 1960). Addition of magnesium oxide of concentration 1% or less (Craik, 1958) and tricalcium phosphate (Sjollesma, 1963) was found to be effective for improving the flow properties of maize starch and milk powder respectively. Flow properties of maize starch, sucrose and sodium chloride were found to be increased on the addition of magnesium oxide. This improvement was due to the reduction of adhesion between the particles (Craik and Miller, 1958).

Above a certain inclusion rate, however, the conditioner can retard the overall flow of the material (Hollenbach et al, 1982; Nash et al, 1965; Irani et al, 1959). 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 of 0.1 to 0.5%. When there is a little affinity, the effects become noticeable only at 1 to 2% concentration (Hollenbach et al, 1983). Danish and Parrott (1971) investigated the effect of size and concentration of lubricants (hydrogenated castor oil, glycerol monostearate, polyethylene glycol 4000, and stearic acid) on the flow rate of sodium chloride and lactose granulations. With both sodium chloride and lactose granulation, the maximum flow rate increased when the lubricant's concentration was 1% or less and had a diameter of 0.0213 cm. Peleg and Mannheim (1973) found that two conditioners, calcium stearate and aluminum silicate, inhibited the caking tendency and improved the flowability of powdered sucrose. It seemed that calcium stearate gave a better effect, however. It was observed that an increase in the amount of tricalcium phosphate, maltodextrin, and glycerol monostearate decrease the degree of caking of dried mango powder (Jaya and Das, 2004).

From many research studies, it has been found that the host powder and the conditioner particles should have a surface affinity. Hollenbach et al. (1983) found that calcium stearate and silicon oxide had no effect on improving the flowability of soy protein powder. This was due to the poor affinity between the conditioner and the host powder. If there is no attraction between the particles, then the conditioner particles themselves will segregate together, and instead of reducing overall cohesiveness, will fill the interparticle voids (Peleg, 1983).

Flowability Related Properties

The handling, storage, and flow of particulate materials is important in industries associated with agricultural, food, chemical, ceramic, pharmaceutical and metallurgical bulk solids and powder processing. Flow is defined as the relative movement of a bulk of particles among neighboring particles, or along a container wall surface (Peleg, 1977). Flow characteristics are of immense significance in bulk material handling and processing, since the ease of conveying, blending, and packaging depends on them. Reliable flow optimizes designs and maximizes profits. To ensure steady and reliable flow, it is crucial to accurately characterize the flow behavior of these materials (Kamath et al, 1994).

In a simple flow test, a granular material is allowed to flow through a laboratory bin or a conical funnel. The flowability is evaluated based on the mass flow rate. The mass flow rate V_m is denoted as (Barbosa and Yan, 2003):

$$V_m = \alpha \rho_b (D - \phi d) \quad (3)$$

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 (-). Material flowability can also be quantified via several additional parameters, including angle of repose, bulk density, angle of internal friction, cohesion, adhesion, and compressibility.

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 elevation. Angle of repose corresponds qualitatively to the flow properties of that material, and is a direct indication of the potential flowability. Angle of repose of solids can be computed using the following equation (Fowler and Wyatt, 1960; Mohsenin, 1986; Rao, 1992):

$$\tan \Phi_r = an^2 + b \frac{M}{D_{av}} + cs_g + d \quad (4)$$

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 constants (-).

High angle (50° to 60°) represents a material with flow difficulty, while a low angle (30° to 40°) represents a material with relatively easy flow. Angle of repose gives a reproducible numerical value, so it has been adopted as a standard measurement of flow properties (Craik and Miller, 1958). Typically, the lower the angle of repose of a dry material, the more flowable is the material, and vice versa (Carr, 1965a). The magnitude of angle of repose increases with increasing moisture content.

Bulk Density

Bulk density of granular solids and powders is considered a highly significant physical property. It plays an important role in storage, transportation, and marketing. 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 the particles that occupies a unit volume of a container. Particle density, on the other hand, is defined as the reciprocal of a particle's actual mass to its actual volume. Bulk and particle densities are related by the following equation (Zuilichem et al., 1974; Barbosa and Yan, 2003):

$$\rho_b = (1 - \varepsilon_p)(1 - \varepsilon_b)\rho_s = (1 - \varepsilon)\rho_s \quad (5)$$

where ρ_b is bulk density (g/cm^3); ρ_s is particle density (g/cm^3); ε_p is particle porosity (-); ε_b is bulk porosity (-); ε is porosity (-).

Zuilichem et al. (1974) carried out experiments with several bulk solids to determine the density patterns in a flow mechanism using gamma absorption techniques. It was observed that the density profiles measured in the plane of the aperture could be described with eight degree polynomials. They concluded that the method described was very suitable for bunker research, which was related to density behavior. This method offered a strong tool for calculating mathematical relations of bulk density variations and their overall influence on the mass flow rate of bulk solids flowing through orifices. Increases in bulk density of various food powders were observed when conditioners were added (Peleg and Mannheim, 1973; Hollenbach et al, 1983). This resulted in a modification of density via lowering the intensity of interparticle interactions. Bulk density was observed to decrease with an increase in the particle size and with the moisture of the powder (Yan and Barbosa, 1997).

The ratio between tapped and loose bulk density is known as the Hausner ratio, and it is used as an internal friction index in cohesive powders (Guo et al, 1985; Malave et al, 1985). If the blends of the conditioning agents result in the filling of interparticle void space only, then the conditioner's bulk density is given by (Hollenbach et al, 1982):

$$\rho_{BT} = \rho_{BU}(1 + X_A) \quad (6)$$

where ρ_{BT} is the bulk density of conditioned powder (g/cm^3); ρ_{BU} is the bulk density of the unconditioned powder (g/cm^3); and X_A is weight fraction of the conditioning agent (-).

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

$$P = [(V - V_p)/V] 100\% \quad (7)$$

where P is porosity (%); V is bulk volume of the powder (cm^3); and V_p is particle volume of the powder (cm^3). P is affected by the free-flowingness of the powder. So, as porosity decreases, bulk density increases (Sjollema, 1963).

Guo et al. (1985), correlated density, flow rate, and Hausner ratio empirically with the non-roundness of particles. It can be expressed in a simple form as:

$$P \text{ (bulk property)} = P \text{ (ideal)} + KP \text{ (deviation)} \quad (8)$$

where P (bulk property) is a bulk solids property (e.g., bulk density, porosity, flow rate etc.); P (ideal) is the ideal state property (e.g., for perfect spheres); P (deviation) is the deviation from an ideal state; and K is a proportionality constant. It was found that the bulk density decreases as the non-roundness of the particles increased. The Hausner ratio, on the other hand, increases with an increase in the non-roundness of the cross-sectional shape.

Angle of Internal Friction

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, size distribution, etc. It is needed for calculating the lateral pressure on walls of storage bins and in the design of gravity flow bins and hoppers (Mohsenin, 1986; Rao, 1992). The Jenike Flow Factor Tester is used to measure the angle of internal friction (Peleg and Mannheim, 1973; Teunou et al, 1999; Fitzpatrick et al, 2004b), and will be discussed in more detail subsequently. Savage (1967) carried out an approximate analysis of gravity flow of cohesionless bulk solids in a vertical converging channel using a perturbation method. The flow rate was then related to the angle of friction between the flowing solid and the channel wall. They estimated the wall friction angle to be equivalent to one-half of the internal friction angle. It was observed that the wall friction was more important in reducing the flow rate for small values of cone wall half angle.

Cohesion

Cohesion is the adhering of particles together in a bulk solid. Cohesive forces occur from a variety of sources, such as liquid bridges, van der Waals forces, electrostatic forces, and magnetic forces. The most prevalent inter-particle forces in systems composed of solid particulates are the liquid bridging force and the van der Waals force (Weber, 2004). Cohesion increases with a decrease in particle size, and with an increase in moisture (Fitzpatrick et al, 2004a). Cohesion is measured using a Jenike shear cell. A yield locus plot of failure shear stress versus normal stress for a given consolidating stress has been successfully fitted by the Warren Spring equation (Farely and Valentin, 1967/68; Harwood, 1971; Peleg and Mannheim, 1973; Rooda, 1975; Peleg, 1977; Moreyra and Peleg, 1981; Barbosa and Yan, 2003; Fitzpatrick et al, 2004a):

$$\left(\frac{\tau}{C}\right)^n = (\sigma + T) / T \quad (9)$$

where τ is failure shear stress (KPa); C is cohesion (Kpa); n is shear index (-); T is tensile stress (Kpa); and σ is normal stress (KPa). An increase in cohesion can often be attributed to fat liquefaction resulting in the formation of liquid bridges between the particles (Fitzpatrick, 2004b).

Adhesion

During storage, flow and handling of granular solids, all particles in the micron size range tend to stick together, or to container walls. This may cause severe process and storage disturbances, require the shutdown of whole plants, or costly reconditioning of caked products. Environmental forces must be less than the binding forces between the particles to cause adhesion. To measure the adhesion tendency, T_a , Pietsch (1969) developed:

$$T_a = \frac{\sum_i B_i(x)}{\sum_j F_{jy}(x)} > 1 \quad (10)$$

where $B_i(x)$ are the binding forces (N), and $F_{jy}(x)$ are the active components of the environmental forces (N). The relative effect of adhesion depends on the particle size. To cause adhesion, T_a has to be bigger than 1 (-). When adhesion is significant, the angle of repose is increased and thereby the flow of is reduced. Adhesion can be suppressed by the addition of small concentrations of conditioners (Craik and Miller, 1958).

Compressibility

Much attention has been given to the behavior 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; to obtain compressibility information, the force-deformation data must be converted to a pressure-density relation (Hollenbach et al, 1983; Barbosa et al, 1987; Barbosa and Yan, 2003). A number of authors have suggested empirical equations to describe these relationships during compression testing. The three models most commonly used include:

1) *Heckel model* (Barbosa and Yan, 2003):

$$\ln \frac{1}{1-D} = aP + b \quad (11)$$

where D is relative density (-); P is applied pressure (kg/cm^2); a (kg/cm^2)⁻¹ and b (-) are constants. The two constants can be determined from the slope and intercept, respectively, from the plot of $\ln [1/1-D]$ versus P .

2) *Kawakita and Ludde model* (Barbosa and Yan, 2003):

$$\frac{P}{C'} = \frac{1}{A'B'} + \frac{P}{A'} \quad (12)$$

where C' is relative volume change (-); A' is the initial porosity (-) and $1/B'$ (Pa) is qualitatively related to the yield stress of the compacted particles.

3) *Sone's model* (Malave et al, 1985; Barbosa and Yan, 2003):

$$\gamma(n) = \frac{V_o - V(n)}{V_o} = \frac{a'b'n}{1 + b'n} \quad (13)$$

where V_o and $V(n)$ are the initial and final volume (cm^3) after n cycles of tapping, respectively. As said before, Hausner ratio is the ratio between tapped and loose bulk density and it can be also used to quantify the compressibility of any given food powder.

The compressibility percentage of a material can be computed by the following equation:

$$100 (P-A) / P = \% \text{ Compressibility} \quad (14)$$

where 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. The borderline between the free flowing and non free flowing is approximately 20 to 21% compressibility (Carr 1965b).

A decrease in compressibility of various powders and granular solids were observed when conditioners were added (Peleg and Mannheim, 1973; Hollenbach et al, 1983). Compressibility and bulk density were correlated using the equation (Peleg, 1977; Peleg and Mannheim, 1973; Hollenbach et al, 1983; Malave et al, 1985):

$$\text{BD} = a + b \log P \quad (15)$$

where BD is bulk density (kg/cm^3); a is extrapolated BD at $1 \text{ kg}/\text{cm}^2$ pressure (kg/cm^3); b is the slope of the straight line (compressibility) (kg/cm^2)⁻¹; P is applied pressure (kg/cm^2). An increase in compressibility was observed with an increase in the particle size of the powder (Yan and Barbosa, 1997).

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 the handling of these materials. Substantial work has been accomplished in developing models of flow based on the properties of particles. Toward that end, shear testers are used to measure the strength and flow properties of bulk solids. A shear test always consists of two components: measurement of consolidation and of strength. The measured strength depends on the degree of consolidation, and how it was achieved. Each of these aspects are highly dependent upon each other (Schweddes, 2002). Additionally, it has been found that stress history and anisotropic behavior has a strong influence on the strength of a bulk solid. It has also been concluded that a reliable prediction of the strength of a bulk solid can be achievable only if the stress history and the directions of the major principal stresses during consolidation and failure are known for the specific application.

Jenike's Shear Cell Test

Jenike (1964) was the first to establish the fundamental methods for determining the flow characteristics of powders. To analyze the flow of solids in bins and hoppers, and to develop a model of flow-no-flow criterion, Jenike used the principles of plastic failure with the Mohr-Coulomb failure criteria (Thomsan, 1997). From a physical point of view, the general principle is that the powder flow is equivalent to solid failure in shear. In ideal, free flowing powders, the resistance to flow is only the result of friction, but in cohesive powders, the interparticle forces

are enhanced by compaction, which can develop mechanical strength in the powders (Peleg, 1983). Until now, Jenike's direct shear cell tester (Figure 1) and his proven procedure for the design of bins for flow has become a benchmark in research and in industrial practice. The test actually consists of three main steps:

- 1) Preconsolidation – To ensure the uniformity between samples;
- 2) Consolidation – Reproduces flow with the given stress at steady state conditions;
- 3) Shearing of the material – To measure the shear stress (τ) at failure.

This procedure is shown in Figure 2. Experimental yield locus is obtained from the plot of normal stress versus shear stress (Figure 3) at a specific powder porosity. Yield locus is the locus of the values of normal stress and shear stress at which irreversible deformation, or yield, occurs. The stress condition of each point on the yield locus is described by Mohr stress circles, which are used to identify the strength and frictional properties of the powder from the yield locus. The yield loci curves of many food materials can be approximated by a straight line (Peleg, 1977).

Figure 1. Jenike Shear Cell (Thomson, 1997).

After the Jenike Shear Test has been completed, the granular material can be characterized via several parameters. These characteristics which are used in the analysis of flowability of bulk solid are determined from the shear test and the yield loci.

1) Cohesion (C)

Cohesion is the sticking together of particles in a bulk solid. The yield locus intersects the shear stress (τ) axis at a value of τ called the cohesion (C) of the powder at an internal friction angle (ϕ) (Thomson, 1997).

2) Effective Yield Locus (EYL)

The ratio between the major consolidating stress σ_1 and the minor consolidating stress σ_2 during steady flow approaches a constant value, called the EYL:

$$\frac{\sigma_1}{\sigma_2} = \frac{1 + \sin \delta}{1 - \sin \delta} \quad (16)$$

σ_1 and σ_2 are the major and minor consolidating stress (KPa), respectively; δ is the angle of internal friction (degrees). EYL is a measure of the inner friction at steady state flow and is very important in the design of storage silos (Schwedes, 1996).

3) Effective Angle of Friction (δ)

This is a measure of resistance of the solids to flow in a steady flow condition. This can be calculated from the EYL.

4) Unconfined Yield Strength (f_c)

It can be obtained by inscribing a Mohr yield circle through the origin, tangential to the yield locus. This is responsible for failure at a friction-free surface.

5) Flow Function (FF)

Flow function, also called failure function, characterizes the flowability of a bulk solid. It can be defined as:

$$FF = \sigma_1 / f_c \quad (17)$$

where σ_1 is the major consolidating stress (KPa); f_c is the unconfined yield strength (Kpa). Flowability can best be described by using the flow function. The exact measurement of the flow function is possible only with Jenike shear testers and requires substantial time investment (Schwedes, 1996). Instantaneous flow functions are determined at zero consolidation time. Time flow function is determined during time consolidation. The inverse of FF's slope is the flow index (i), which is used as an index of the flowability of a powder (Table 1).

Table 1: Jenike classification of powder flowability by flow index (i).

Flowability	No-flow	Cohesive	Easy flow	Free flow
Flow index (i)	<2	<4	<10	>10

6) Angle of Internal Friction (ϕ)

The slope of the yield locus, when it is tangential to the Mohr circle passing through the origin, is defined as the angle of internal friction, or kinematic angle of internal friction.

7) Static Angle of Internal Friction (ϕ_t)

The slope of the time yield locus when it is tangential to the Mohr circle passing through the origin is defined as static angle of internal friction. This is used in the analysis of funnel flow.

Jenike's shear cell has been used by very few researchers for characterizing various granular food materials. The Jenike shear test method is an extremely useful quantitative method for designing storage bins for gravity flow of solids. Ashton et al (1965) investigated the strength and flow properties of more than 30 powders using the consolidating procedure

recommended by Jenike. The Jenike shear cell was used to study the flow properties of cement (Schrämli, 1967), fine lactose powder with and without conditioners (York, 1975), wheat flour and sugar (Kamath et al, 1993), wheat flour at three moisture contents (Kamath et al, 1994), confectionary sugar and detergent (Duffy and Puri, 1994), grains (Duffy and Puri, 1999), and milk powders with different fat contents (Fitzpatrick et al, 2004b).

Jenike's method does not lead to any information regarding the influence of the stress history (i.e., the way in which the bulk solid has reached its actual state). In addition, the method does not provide any information on the relationship between stresses and strains (Schwedes and Schulze, 1990). The accuracy of the results depends on the material being tested, and the technician performing the procedures. The ease of operation requires a skilled operator with knowledge of Mohr's circle interpretation, and how the yield locus curve fits the data.

Figure 2. Testing Procedure: (a) Preconsolidation, (b) Removal of twisting top and packing mold ring, (c) Consolidation, (d) Shear, and (e) Time consolidation (Thomson, 1997).

Figure 3. Typical plot of normal stress versus shear stress (Thomson, 1997).

Bulk Solids Characterization by 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 standard procedures that permit the evaluation of flow characteristics of any such materials. The evaluation of the flow characteristics of dry material involves the determination of four main properties, as described below.

1) Angle of Repose

This is defined as the constant angle to the horizontal of a cone pile formed by the material. The pile is built up by dropping the material from a point above the horizontal using an apparatus (Fig 4), until a constant angle is measured. This method is a direct simulation of the potential flowability of the material. This procedure is a simple means to indirectly measure the physical properties (size, shape, porosity, cohesion, fluidity and surface area) affecting the flow of the material.

2) Compressibility

The percentage compressibility is computed as follows:

$$100(P-A)/P = \text{compressibility}\% \quad (18)$$

where P is the packed bulk density, and A is the aerated bulk density. Compressibility can be used to indirectly assess properties such as uniformity in size and shape, deformability, surface area, cohesion and moisture content of the material.

Figure 4. Powder characteristics tester for Carr indices.

3) Angle of Spatula

This is an easily determined property which gives a relative angle of internal friction, or angle of rupture, for a dry material. It is an indirect measurement of cohesion, surface area, size, shape, uniformity, fluidity, deformability and porosity of the material.

4) Cohesion or Coefficient of Uniformity

Cohesion is used with powders and fine particles, or with materials on which an effective cohesive force can be measured. Cohesion tests yield a direct determination of this important flow factor. The coefficient of uniformity is used with granular materials on which an effective surface cohesion cannot be measured. Uniformity coefficient is an indirect measurement of size, shape and compressibility of the material.

The detailed procedure for measuring all the above properties is found in Carr (1965a). The procedure described by Carr provides a realistic and straightforward method for computing the flow factor, and assessing the flowability of any granular material.

Triaxial Cell

The most widely used laboratory equipment for investigating the strength and deformation behavior of soils at high stresses ($> 100\text{Kpa}$) 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. In recent years, though, triaxial cells have been redesigned, and have been used to investigate agricultural grain properties (Bock et al, 1991). It has also been used successfully to measure powders at low stress ranges (Meerman and Knaapen, 1979; Kolymbas and Wu, 1990). The testing procedure has been explained in depth by Bishop and Henkel (1962). From the triaxial tester, it is possible to obtain accurate information about strain conditions (Schwedes and Schulze, 1990).

Direct Shear Cell

This apparatus is designed to measure the consolidated shear strength of a soil material in direct shear. Tsunakawa and Aoki (1982) used a direct shear tester with press loading to measure the failure properties of granular materials. When compared to the Jenike shear cell test, this had an advantage that the yield locus can be obtained from only one shear test as a continuous line. Direct shear cell equipment and testing procedure have been described in detail by Tsunakawa and Aoki (1982).

Modeling of Bulk Solid Flow

The breakthrough work in solids flow by Jenike in the early 1960's was accomplished using numerical methods for the solution of respective partial differential equations, namely the method of characteristics. Today, numerical solutions of partial differential equations for stresses and flows is done using the finite element method (FEM). Currently, no universal mathematical model exists to predict granular flow behavior in every situation, nor is such a universal model anticipated. In the past two decades, the discrete element method (DEM) has gained an equal importance in the field of bulk solids handling. It is a promising approach, but still relies on physical measurements of individual particles and those surfaces with which they interact. Additionally, it requires precise numerical models and intensive computational power by current standards (Prescott and Barnum, 2000). In general, the DEM approach considers every particle in an assembly as a separate body, and follows its movement by describing interactions between each particle and its environment by solving its equations of motion.

Langston et al (1996) modeled two phase flow of interstitial air in a moving packed bed of granular solids using a distinct element (DE) technique. The air flow was assumed to be incompressible at relatively low velocities associated with the hopper discharge rates. The mass flux of air at any height within the hopper was assumed to be constant. With these assumptions they simulated air-retarded and air-assisted flows in mass flow hoppers without the development of momentum-based calculations for a fixed Eulerian grid. The interstitial air velocity around each particle could be calculated from the following equation:

$$U_{iz} = U_{oz} / \varepsilon_i \quad (19)$$

The superficial air velocity was given by:

$$U_{o0} = Q_a / A_0 \quad (20)$$

where U_{iz} is the interstitial air velocity (m/s) at height z ; ε_i is the local voidage around the particle (-); U_{o0} is the superficial air velocity (m/s) at orifice 0; Q_a is the volumetric flow rate of solid or air (m^3/s); A_0 is the cross sectional area (m^2). These DE simulation results show that air-assisted flow leads to increased wall stresses, which reduce bulk solids discharge through small orifices.

Silos and bins are extensively used in agriculture and many other industries for the storage and handling of bulk solids. Full-scale silo experiments to determine wall pressures and loads exerted during flow of cohesionless materials, however, are expensive and difficult to accomplish. As more powerful computers have become available, numerical methods have become very useful in research on the flow of these solids. Numerical methods are relatively inexpensive and are amenable to extensive parametric studies. For example, Meng et al.

(1997a) developed secant constitutive relationships for a transient finite element analysis (FEA) of displacements, velocities and stresses during discharge of cohesionless material based on elasto-plastic theory. The secant constitutive relation that was used in the finite element analysis was:

$$\{\sigma\} = [D^{ep}] \{\varepsilon\} - \{\sigma^p\} \quad (21)$$

where σ is the mean stress (N/m²); $[D^{ep}]$ is the matrix linking stress to strain; ε is mean strain (-); and $\{\sigma^p\}$ is the plastic stress vector (N/m²). In order to use this secant constitutive relation, approximately 150 experiments were carried out on corn and soybeans to find their material properties. Experiments were performed using triaxial tests. The constitutive relationship in equation (20) was then incorporated in a standard finite element formulation of the form:

$$[K]\{U\} + [M]\{\ddot{U}\} = \{F\} + \{P\} \quad (22)$$

where $[K]$ is the stiffness matrix; $[M]$ is the mass matrix (kg); $\{U\}$ is displacement vector (m); $\{\ddot{U}\}$ is acceleration vector (m/s²); $\{F\}$ is force vector (N); and $\{P\}$ is the plastic force vector (N). For axisymmetric problems, the constitutive relation can be written as:

$$[K_{ij}] = \iiint_v [B_i]^T [D^{ep}] [B_j] r d\theta dr dz \quad (23)$$

where $[B]$ is the matrix relationship between strain and displacement.

Meng et al. (1997b) conducted a small parametric study consisting of five analyses using an axisymmetric model of a full scale bin, which was approximately ten times the size of the lab scale bin, for verification of the FEA program. The elastic deformations of the bin and hopper walls were modeled by elastic spring supports at each boundary node with stiffness:

$$k = (2\pi E_w t_w h) / R \quad (24)$$

where k is the stiffness of the elastic spring (N/m); E_w is Young's modulus of the silo wall material (N/m²); t_w is the wall thickness (m); h is the wall height covered by the spring support (m); and R is the radius of the silo (m). They found that the model had a very fast convergence rate. More than that, there was no numerical instability as the bulk material behavior moved from the elastic into plastic range. They concluded that this approach was relatively easy to determine the parameters in the constitutive relations.

A hybrid numerical model based on the finite element method and the discrete element method has been developed by Lu et al. (1997) to predict the stress and velocity for particulate materials during silo discharge. Both FEM and DEM are widely used for simulation of particulate material flow in silos, but they have their own limitations. FEM modeling can be used only when there is a continuum approach; on the other hand, DEM cannot deal with a very large number of particles and it can be exceedingly computationally intensive. To accommodate these approaches, Equation (21) can be modified into:

$$[K + K']\{U\} + [M]\{\ddot{U}\} = \{F\} + \{P\} + \{R\} + \{R'\} - \{Q\} \quad (25)$$

where $[K] = (H/\Delta t_1)[B]$ and $\{R\} = (H/\Delta t_1)[B]\{U^{N-1}\}$; H is the height from where the particles are falling; $\{U^{N-1}\}$ is the nodal displacement at $(N-1)^{th}$ time step; Δt_1 is the time step of FEM analysis; $\{Q\}$ is the residual force vector from volume strain; $\{R\}$ is the boundary reactions. The model was found to be capable of predicting flow velocities, stresses and wall pressures during emptying. It has been concluded that the two dimensional numerical model can be used for uniform size particles and mass flow conditions in full scale bins or silos. Furthermore it can be used for three dimensional applications and for simulating silo filling with some modifications.

Negi et al. (1997) verified the hybrid numeric model developed by Lu et al. (1997) for modeling the gravity flow of granular materials in silos and bins. Their computer simulations successfully matched most of the observed features of the physical tests. They observed a good correspondence between the wall pressures measured in the model silo and calculations from the numerical model based on FEM and DEM. Jofriet et al. (1997) also used the hybrid numeric model developed by Lu et al. (1997) for the analysis of flow in symmetric and asymmetric rectangular bins.

Discrete particle simulation (DPS), also called DEM, based on the Lagrange method was applied by Gyeenis et al. (1999) to simulate gravity flow of particles and gas-solids two-phase flow in tubes containing static mixer elements. It was observed that this method corresponded well to the discontinuous nature of particulate systems. The vast computational potential of the DPS method could be used advantageously either for simple gravity flow of particles, or for dense or lean gas-solids two phase flows. They also found that the DPS simulation method proved to be an appropriate tool to reproduce theoretically the main characteristics of the distinct flow regimes observed experimentally.

Handling problems, such as “rat holing” and arching, arise when there is an impairment to flow or discharge of granular materials from storage vessels. Most of the measuring methods and models have been applied to describe the behavior of cohesive powders, and are applicable for the design of silos. Studies on particle mechanics, however, give a better physical understanding of the essential constitutive functions within a bulk solid’s continuum. Powders below 20 μm in diameter exhibit strong surface active forces which lead to adhesion. DEM allows one to take into account the contact and adhesive forces in the equations of motion for the particles. For instance, Baxter et al (2000) approached the problem with DEM. Interaction forces (elastic and dissipative) on particles were summed and the resultant forces were used to integrate the classical equations of motion over small, finite time steps. For realistic representations of cohesionless particles flow and internal structures, they used the following equation:

$$\frac{F_N(r)}{M} = \left(\frac{d}{r}\right)^n \rightarrow F_N^*(r^*) = \left(\frac{1}{r^*}\right)^n \quad (26)$$

where F_N is the normal force (N); d is particle diameter (m); M is particle mass (kg); r is center to center distance (m), and n is elasticity index (-). When there is interparticle attraction, this can be rewritten as:

$$F_N^*(r^*) = \left(\frac{1}{r^*}\right)^n - \left(\frac{1}{r^*}\right)^m \quad (27)$$

Guines et al (2001) used a nonlinear finite element method for 3D modeling of filling and discharge from a full scale square silo. Both the nonlinear bulk properties, and the structural

behavior of the cells, including the contact conditions between the bulk material and the wall, the flexibility of the wall, and the presence of stiffeners and ties, were taken into account for the simulation. The elastic behavior of the bulk material was based on the Hujieux model:

$$K_T = K_{ref} \left[\frac{p}{p_{ref}} \right]^n ; G_T = G_{ref} \left[\frac{p}{p_{ref}} \right]^n \quad (28)$$

where K_T is the tangent bulk modulus (KPa); G_T is the tangent shear modulus (KPa); K_{ref} is the tangent bulk modulus at reference pressure p_{ref} (KPa); G_{ref} is the tangent shear modulus at reference pressure P_{ref} (KPa); p is the spherical stress invariant (KPa); n is the elastic exponent (-); and p_{ref} is the reference mean pressure (KPa).

Additionally, the behavior of noncohesive materials can be represented by the modified Cam-Clay model:

$$F(p, q, \varepsilon_v^p, \varepsilon_q^p) = \frac{q}{Mp} + \left(b \ln \frac{p}{p_{ppf}} - 1 \right) r(\varepsilon_q^p) \quad (29)$$

where q is the deviatoric stress invariant (KPa); ε_v^p is volumetric plastic strain (-); ε_q^p is deviatoric plastic strain (-); M is characterization of failure stress rate (-); b is the second plastic constant of Hujieux's model (-); p_{ppf} is mean pressure at strain state ε_v^p (KPa); $r(\varepsilon_q^p)$ defines the domain of deformation (-). It was found that the flexibility of the silo structure has a significant influence on the normal pressure distribution along the wall. The wall stiffness variation due to vertical stiffeners and horizontal ties were taken into account in this FEM analysis. The localization of the maximum pressure in this analysis was very sensitive to the wall deformation and it was in agreement with experimental measurements.

Xu et al (2002) studied the effects of material modulus and adhesion on flow behavior from both a microscopic as well as a macroscopic viewpoint using DEM. They used Aston-TRUBAL code, and assumed that the particles were elastic, soft or hard spheres, with or without adhesion. The movement of each particle followed Newton's law of motion. Over a time step Δt , the translational movement of a given particle was given by:

$$F_i - \beta_g V_i = m \Delta V_i / \Delta t_i \quad (30)$$

where $i=1, 2, 3$ is the index of x, y, z coordinate components, respectively (-), F_i is the out of balance force (N), V_i is transitional velocity of the sphere center (m/s), m is mass of a particle (kg), β_g is a global damping coefficient (-). The rotational movement was described by:

$$M_i = \beta_g \omega_i = I \Delta \omega_i / \Delta t \quad (31)$$

where M_i is the out of balance moment (N-m); ω_i is rotational velocity components (rad/s); I is the rotational inertia (N/m²). Both the incremental translational and rotational displacement components were given by:

$$\Delta x_i = V_i \Delta t \quad \text{and} \quad \Delta \Phi_i = \omega_i \Delta t \quad (32)$$

As a result of their study, they concluded that there is a need for a combined investigation using DEM with computational structural mechanics.

DEM was found to be useful when traditional heuristic methods are proven to be inadequate in explaining granular flow problems. Tykhoniuk et al (2003) discussed a realistic and flexible microscopic model for contact laws with elastic, permanently plastic, and adhesion forces, based on macroscopic observations from bulk experiments. In order to show that there is a possibility of some qualitative agreement between numerical experiment and reality with DEM, the model was applied to the Jenike shear test.

FEM was used to study the pressures exerted in cylindrical silos with flexible walls (Vidal et al, 2004). A model has been developed using the commercial FEM software ANSYS. The FEM procedure developed used a transient, dynamic point of view that comprised time, a nonlinear material, and a flexible wall. It is not recommended to use elastic models, however, because they cannot consider the behavior of the granular material correctly. Vidal et al. (2004) used the Drucker-Prager criterion model, which offers the best approximations when compared with experimental results. Observing the influence of the internal friction coefficient, it has been concluded that there is not important differences in plastic areas.

Rapid granular shear flow was simulated using discrete element simulation for a two particle system as well as for a many particle system (Weber, 2004). Cohesive interactions of the particles were modeled using a square-well potential. For the two particle simulations in which agglomerate did not occur, an effective coefficient of restitution (e_{eff}) was calculated based on approaching and departing normal relative velocities:

$$e_{\text{eff}} = -\frac{\vec{k}_{ij,3} \cdot \vec{v}_{ij,d}}{\vec{k}_{ij,1} \cdot \vec{v}_{ij,a}} \quad (33)$$

where $\vec{k}_{ij,3}$ is the unit vector pointing from the center of the i^{th} particle to the center of the j^{th} particle when the departing particles are separated by $2r_{\text{inner}}$; $\vec{v}_{ij,d}$ is the relative velocity of the particles after escaping the square well; $\vec{k}_{ij,1}$ is the unit vector pointing from the center of the i^{th} particle to the center of the j^{th} particle when the approaching particles are separated by $2r_{\text{outer}}$; $\vec{v}_{ij,a}$ is the relative velocity of the particles before the cohesive interaction. When $r_{\text{outer}}/r_{\text{inner}}$ approaches 1 (-), then the effective restitution coefficient becomes:

$$e_{\text{eff}, r_{\text{outer}}=r_{\text{inner}}} = \sqrt{e^2 + \frac{4(e^2 - 1)D}{m(\vec{k}_{ij,1} \cdot \vec{v}_{ij,a})^2}} \quad (34)$$

where e is the restitution coefficient (-); D is well depth (m); m is mass of the particle (kg). The range of validity of the effective restitution coefficient was narrow when compared with the simulations, however. This approach does not seem to be a practical simplification of the more complete square well potential model.

Typically there are two different flow regimes present for simulations involving a large number of particles. It has been found that the effect of cohesive forces on stresses was minimal at low solids fractions, but it did decrease the stress on high solid fractions. This decrease in stress becomes more significant as the strength of the cohesive forces increases.

Simulation results indicate that the square-well potential have been observed to be a viable method for incorporating cohesive forces into rapid granular flow (Weber, 2004).

The aerated flow discharge technique is considered a valuable method for improving the flow properties of powders. The mechanism of gas particle interaction during flow is not fully understood due to complex phenomena such as drag, friction, and cohesion. Moreover, the difficulty in representing the gravity flow of fine particles through a continuum model has led to the development of semi-empirical relationships for predicting discharge rates. These predictions can only be used for the rough estimation of discharge rates. Donsi and Ferrari (1991) carried out experiments on different fine materials of various cohesiveness to elucidate the complex phenomena occurring in aerated discharge of solids. They noticed a progressive transition from gravity flow to aerated gravity flow and to fluidized-bed discharge. The gravity discharge velocity was compared with the existing correlation developed by Beverloo et al for coarse solids, which is:

$$W = 0.58 \rho_p (1-\varepsilon) g^{0.5} D_f^{2.5} \quad (35)$$

where W is the mass flow rate of discharge (g/s); D_f is the orifice diameter (cm); ρ_p is the particle density (g/cm³); ε is the void fraction of the flowing solid (-).

For finer particles discharging under gravity conditions and various gas pressures, this equation can be modified to:

$$W = \lambda \left(g + \frac{1}{\rho_b} \frac{dp}{dz} \right)^{0.5} \rho_p (1-\varepsilon) D_f^{2.5} \quad (36)$$

where ρ_b is the bulk density (g/cm³); g is the acceleration due to gravity (cm/s²); dp/dz is the pressure gradient at the outlet in the direction of particle motion (N/m³).

Additionally, the correlation for the efflux of free flowing materials from fluidized beds can be given by the following relation:

$$W = 0.5 \rho_p (1-\varepsilon) A (2gH)^{0.5} \quad (37)$$

where H is the height of the draining bed (cm). Donsi and Ferrari (1991) found that their experimental data refer to conditions that are intermediately between gravity and fluidized efflux. Also they detected discrepancies related to the relaxation energy of the particle structure. They concluded that the existing correlations both for gravity flow and for efflux from fluidized beds are unable to predict correctly the effect of gas velocity and orifice diameter.

Erdész and Szalay (1988) investigated the sliding regime in vibrational transport on a laboratory scale vibrating conveyor driven by a pneumatic ball vibrator. Vibrational transport of solids is extensively used in industries where cost-effective transport of granular materials is required. It has its own merits and drawbacks. A vibrated system can be divided into an exciting system (vibrational mechanism) and excited system (granular medium). The dynamic model of the exciting system is based on the mathematical methods of oscillation theory. The amplitude amplification is of great importance to the speed of vibrational transport. For the ball vibrating conveyor, the differential equation of motion is given by:

$$M\ddot{x} + K\dot{x} + \frac{x}{c} = m_0 r \omega^2 \sin \omega t \quad (38)$$

where M is the total mass of the vibrating system (kg); x is the displacement of vibrating system (m); m_0 is the mass of the vibrator ball (kg); r is the radius of rotation of the vibrator ball (m); ω is the angular frequency (1/s); t is time (s). It was found that the transport of a granular medium in a vibrated bed is a dynamic process which occurs in the common region of the exciting and excited systems. They concluded that the vibrational transport can be easily and continuously controlled even under the condition of sliding regime by setting the frequency of the exciting vibration.

Furthermore, a bulk solid can attain an increase in density, after certain exposure to vibrations or taps. This phenomenon is referred to as density relaxation or densification. Understanding the densification process is important to solids handling in industries where vibrations are often used to enhance the processing of large quantities of bulk materials. Zhang and Rosato (2004) carried out experiments to classify the instantaneous dynamic states of granular materials to understand flow regimes that promote densification. They employed DEM to simulate the dynamic state of a granular material in which the particles are represented as inelastic, frictional spheres. It was observed that the use of more frictional particles tend to hinder thermalization, while the particle restitution coefficient plays a role when the flow is collision dominated. The structure, before vibrations are applied, plays an important role in determining the depth profiles and the phase pattern only at low accelerations. At the same time, large accelerations can easily break up the poured structure very quickly, so that the initial state does not play a major role in computed profiles, and hence the phase pattern.

In the last few years, the field of bulk solids handling has experienced many advances, which has been especially due to computer modeling and simulation studies. Many investigations have been conducted on silo stresses and hopper designs that affect bulk solids flow. Developments in these areas are indicative of the many significant accomplishments in the field of silo technology. Even so, only a few studies are available that specifically examine the effect of physical properties on the flow of bulk solids. Thus, more work is needed for the prediction of flowability problems, such as caking behavior, interactions between the stored materials, and temperature fluctuations.

Conclusions

During the last several years, many ethanol manufacturing plants have been established in the Midwest, as corn is the major cultivated crop in these areas. Distillers dried grains (DDG) and distillers dried grains with solubles (DDGS) have been widely used as cattle diets for more than two decades, and are currently expanding into the other major livestock segments, because they are an economical partial replacement for corn, soybean meal, and dicalcium phosphate in livestock and poultry feeds. To date, most of the research work in this area has focused on chemical analysis of distillers grains, but not on the related physical properties. Also, there is currently no information available for appropriate distillers grains storage and handling operations. To improve the domestic use of these coproduct feed materials, there is an urgent need to study their flow behavior as well as storage and handling characteristics. This can help optimize utilization of these materials, and thus improve process economics for ethanol producers, use by livestock feeders, and ultimately the real economy. This review of flow properties, and techniques for their quantification, will be essential to that effort. Moreover, this paper will be an essential resource for efforts focused on analyzing and quantifying other granular solids as well.

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