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Towards an Understanding of DDGS Flowability Characteristics

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***Abstract*.** Distillers dried grains with solubles (DDGS), a major coproduct from the corn-based fuel ethanol industry, is primarily used as livestock feed. Due to high protein, fiber, and energy contents, there is a high demand for DDGS. Flowability of DDGS is often hindered due the phenomenon of “caking”. Shipping and handling of DDGS has thus become a major issue due to bridge formation between the DDGS particles. The objective of this investigation was to measure flowability of DDGS samples from five ethanol plants in the north central region of the U.S. Carr and Jenike tests were performed, and the resulting data will be presented and discussed. Quantifying DDGS flowability is a first step toward overcoming this challenge facing the industry.

Keywords. Caking, Carr, DDGS, Flowability, Jenike, Properties

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Introduction

Distillers dried grain with solubles, commonly known as DDGS, is extensively used as a source of protein for ruminants and non-ruminants for more than two decades. With the exponential growth of corn based bioethanol industry, it is expected that there will be an increase in supply as well as in demand of DDGS with coming years. It is roughly estimated that for every one bushel (56 lbs) of corn being converted to ethanol approximately 17 lbs of DDGS are being produced along with 17.6 lbs of ethanol, 18.4 lbs of carbon dioxide (Jaques et al., 2003). DDGS is found to be a storehouse of energy for livestock as it has nearly 35% protein, 30% fiber, some traces of non fermentable starch, and about 10-12% of fat which accounts for its high energy. DDGS is also found to have significant amount of minerals (calcium, phosphorous, etc.) and some key essential amino acids like methionine, leucine, etc. (Spiehs et al., 2002). This makes DDGS a very promising livestock feed. Due to its increasing demand and benefits it will be essential to ship and to handle this product large distances through railway cars and trucks. It will be also essential to store DDGS in large tanks, silos or storage bins for relatively long time periods.

Storage and handling of DDGS is found to be troublesome due to the poor flowability of DDGS. Restriction commonly occurs due to the familiar “caking” phenomenon between two particles or a group of particles. Due to this caking, which is also known as “bridging”, there is substantial economic loss during shipping of DDGS. The particles tend to stick with each other which results in unwanted agglomeration and adds to cost of DDGS market since manpower, machinery, and time is required to break those agglomerates (Rock and Schwedes, 2005). It has also been reported that due to the flowability problem in DDGS, shipping it through railway cars or trucks is very problematic during unloading of it.

Enormous amount of research has been done with the flowability, handling, and storage characteristics of granular powders and bulk solids. Apart from solving the caking problem in the flowability of DDGS it is useful to know the physical and flow properties of DDGS for long term handling, storage and shipping. Flow is defined as the relative movement of bulk particles in proximity to neighboring particles or along the wall of the container or storage tanks (Peleg, 1977). Flowability studies are important to understand and ensure steady and reliable flow of a particular powder or granular solid (Kamath et al., 1994).

There is a great need to understand flowability behavior of DDGS as there is very little information available to date. Understanding flowability properties, storage properties, physical properties, and related chemical properties, along with their inter relationship would be an important place to study to solve flow problems associated with DDGS.

Flowability problems are often related to physical properties of granular solids. It has been reported that there can be differences in most of physical properties among the DDGS samples obtained from commercial plants, and also between batches (collection period) in a particular plant (Bhadra et al., 2007). Thus, it can be summarized that not only understanding the flowability and physical properties would be helpful in solving the flow problem in DDGS, but also inconsistencies in DDGS samples may be an important issue while dealing with flowability of DDGS.

Flowability is not a natural material property of a particular product but being a multidimensional problem, not single set of test can determine it. Flowability is a combination of the physical properties of materials, environmental factors, processing techniques used for that material’s production, and storage equipment used to store and handle that material (Prescott and Barnum, 2000). Some key factors that influence flowability are moisture, humidity, temperature, pressure, fat, particle size and shape and addition of flow agents.

Moisture is a key parameter when considering flowability of any organic material. Most agricultural and organic materials have a tendency to lose or to gain moisture with changing environmental factors being hygroscopic. Moisture content is an important variable that affects cohesive strength and arching of bulk solids (Johanson, 1978). It was reported that small amount of change in the moisture help to change the frictional properties of the bulk solids very significantly (Marinelli and Carson, 1992). With the increase in moisture it has been reported that compressibility increases, causing flowability problems (Moreyra and Peleg, 1981; Yan and Barbosa, 1997). Moisture can also be coupled with surface properties, and change or influence adherence properties between two particles or between the particles and the storage tanks (Hollenbach et al., 1983). Moisture migration and liquid bridge formation would lead to such flowability problems in DDGS. Like moisture content, humidity can also an important factor for flowability in DDGS. It has been found out that humidity increases the angle of repose for starch, sucrose and sodium chloride powders (Craik and Miller, 1958).

Temperature also plays an important role in terms of the flowability of powders. Freezing temperature may result in formation of ice bridges between the particles which restricts the flow of particles. Ice bridges are formed due to the presence of moisture and low temperatures between the particles (Irani et al., 1959; Johanson, 1978; Fitzpatrick et al, 2004b). Fat has been found to play an important role in flow problems too. It was found that high fat content leads to worse flow condition for dried soy milk powders (Perez and Flores, 1997). One of the reasons for this could be higher fat content in presence of a higher temperatures may liquefy and act as a glue between particles. It may be also possible that fat content may itself cause stickiness among the DDGS particles without even changes in temperatures.

Particle size and shape plays a vital role in predicting flowability of powders. Particles shapes and size are more often adjusted to suit the final requirement and quality of the product. Lower the size of the particle higher is the ease of flow. However it has found been found that a reduction in the particle size of powders makes the flowability worse and increases particle cohesion due to increase in surface area per unit mass (Fitzpatrick et al., 2004a, 2004b). It has been found that shear index for general powders, mainly inorganic materials like ceramics was inversely proportional to volume/surface mean diameter (Farely, 1967 and Valentin, 1968). Finer the particle size more is the contact area between particles which leads to greater cohesive forces among the particles and thus causes flowability problems, having lower flow rate (Marinelli and Carson, 1992).

Again it has been found that larger particle size will increase compressibility in the bulk solid and thus flow problems (Yan and Barbosa, 1997). Particle shape parameters which include roundness, sphericity, surface roughness etc. leads to flow related problems. Smooth surface with higher roundness ratios would give us better flowability in DDGS than surfaces with rough edges. Rough edges on the DDGS particles may form a lock and key model and thus interlock the neighboring particles and therefore cause flowability problems. Small particles with higher roughness on surface may cause more flow problems than larger particles with smooth edges.

Flowability problems may arise due to combined or synergistic affects of influencing factors like moisture, humidity, time of storage, fat composition, particle size and shape, compaction pressure distribution, and vibrations during transport process of powders. Variation in the levels of these above mentioned factors also leads to flowability problems (Rosentrater, 2006b).

Parameters Associated with Flowability and Handling of DDGS

Carr Indices Flow Properties

Angle of Repose

Angle of repose is defined as the angle formed between the slope of the pile of DDGS with a horizontal plane; this pile has been formed when DDGS or other such powders are dropped from an elevation. These properties affect flowabity of DDGS. Angle of repose of between 25° to 35° are generally considered free flowing substances (Carr, 1965). Two categories of angle repose can be formed: one during filling, and the other during emptying. The two forms of angle of repose are also important while considering design parameters related to handling and shipping of DDGS. Higher the angle of repose, the greater flow problem for DDGS.

Angle of repose related to flowability of powders or bulk solids can be summarized categorically and in given in table 1 (Carr, 1965):

Bulk Density

Bulk density gives the measure of the effective capacity for storage bins and silos. This parameter is determined as the mass of granular material that will occupy a specific volume of the storage space. Bulk densities include not only the material volume but also air space entrapped between the particles. The two categories of bulk density are aerated bulk density (or loose bulk density) and packed or (tapped) bulk density. The latter category of bulk density occurs when an external force or pressure has been applied to the mass of the granular solid and it compresses, displacing the entrapped air between particles. Packed or tapped density is an actual representation of material bulk density when they are stored in bins and being transported over large distances.

Hausner Ratio

This is defined as the ratio of tapped density to the aerated or apparent density. Value less than 1.25 indicates good flow whereas values greater than 1.25 indicate poor flow (Michael, 2001). Bulk density or hausner ratio influences the functions and design parameters like arching, ratholing, limiting flow rate from hooper and equipment structural design (Johanson, 1978).

Compressibility

The compressibility of granular solids is calculated as:

$$C = 100\,(PD-AD) / PD \qquad (1)$$

Where PD is denotes the packed density (kg^3/cm) and AD (kg^3/cm) is denotes the aerated density for the granular solids, and C is denoted as compressibility (%). Compressibility less than 18% approximately gives good free flowing solids (Carr, 1965). It gives the idea of cohesion among the particles.

Angle of Spatula

Angle of spatula gives the indication of the internal angle of internal friction for granular solids. It is measured by inserting a flat blade into a pile of solid powder and then lifting is up. The new angle of repose which the material forms relative to the horizontal plan of the blade gives the measure of the angle of spatula. This simulates movement of supporting surface structure during material handling and shipping. Angle of spatula less than 40° in a solid powders, show less flow problems. Lower the angle of spatula better is flow of the material (Carr, 1965).

Uniformity

Uniformity is the ratio obtained between the width of sieve opening that will pass 60% of the sample and width of sieve opening that will pass only 10% of the sample. Uniformity, gives a relative measure of homogeneity of the size and shape of the material, and has a direct affect on the material ability to flow (Carr, 1965). Smaller the uniformity value, the more homogenous the particle shapes are, and typically less the flow problem.

The evaluation of the above properties from angle of repose to uniformity (excluding Hausner ratio) as mentioned, are combined to provide the flowability index value for powders or bulk solids (Carr, 1965).

Angle of Fall

This is the new angle of repose that is formed after impaction has been applied to the material. Materials, when piled up, give an angle of repose while it may dislodge or get disturbed due to vibration and environmental effects (Carr, 1965).

Angle of Difference

Angle of difference is calculated by subtracting angle of fall from angle of repose. Larger the angle of difference, more flowable the material is (Carr, 1965).

Dispersibility

Dispersibility is related to ability of the material to flood or to disperse. Higher the dispersibility of the material, the more floodable the material is, it tends to flush easily. Tends to flush means the powder or the solid material flow abruptly and sporadically, which is not desired in a good flow material.

The immediate above properties (angle of fall, angle of difference, and dispersibility along with flowability index) accounts for the total floodability index of bulk solids (Carr, 1965).

Jenike Shear Testing Properties

Yield Locus (YL) and Effective Yield Locus (EYL)

Yield locus (YL) is a plot of failure shear stress versus normal stress for a given consolidating stress, for any kind of general cohesive solid (Fitzpatrick et al., 2004a). For free flowing materials, like sand and gravel, the Mohr stress circle shows a straight envelope which passes through the origin. This envelope is called effective yield locus (EYL) (Jenike, 1964).

Angle of internal friction (Φ)

This is the inter particle friction measurement, in degrees, as the bulk solids tends to slide on itself at the onset of flow (Jenike, 1964). Pressure arises in the solid due to superimposed mass when the solids are placed in channels. At higher pressure, the particles are brought closer as molecular forces develop causing the solids to consolidate and gain strength. In order to shear such solid systems the angle of internal friction must be exceeded (Jenike, 1964).

Effective angle of internal friction (δ)

During flow process, solids are constantly exposed to pressures. The major pressure acting on a particle element is denoted by σ_1 while the minor pressure is called σ_2.The relationship between the above two pressures varies very little with changes in temperatures and pressure for most bulk solids (Jenike, 1964). The relationship is given as:

$$\frac{\sigma_1}{\sigma_2} = \frac{1+\sin \delta}{1-\sin \delta} \quad (2)$$

This equation is called the effective yield function, and the angle is called the effective angle of internal friction. It is the measure of interparticle kinematic particle friction which exists during steady flow. Generally, this value lies between 30° to 70°. For noncohesive solids, like sand, which practically have no flowability problem, have the same angle of friction and effective angle of friction (□=δ) (Jenike, 1964). Usually it is found that the value of angle of internal friction is less than effective angle of friction.

Unconfined Yield strength (σ_c)

This is the measure of compressive strength (kPa) of granular solids (Schulze, 2006). For an exposed particle, the forces acting on that particle are zero, but the major pressure acting on the solid particle is tangential to the particle. If this pressure causes yield it is termed as unconfined yield pressure (Jenike, 1964). A free flowing noncohesive solid shows an unconfined yield strength value of zero.

Major consolidation stress (σ_1)

A circle which passes through the steady state point (V, S) where V is the normal load and S is the shear force applied in each consolidation during shear test, and is tangent to YL, is called a Mohr circle (Jeneki,1964). The point of the intersection of Mohr circle to the stress axis gives the value of major consolidating stress.

Flow functions

The ratio of the major consolidation stress (σ_1) to unconfined yield strength (σ_c) is called the flow function of bulk solids which is represented in equation 3. Flow function is a dimensionless quantity. Jenike (1964) classified flow functions and is elucidated in table 2

$$F= \sigma_1 /\sigma_c \quad (3)$$

Jenike compressibility testing (β)

Compressibility is measured using material bulk density for the various predetermined normal loads as described by Jenike (1964). The relationship between bulk density (γ, kg/cm^3), net weight of the material (M, g) and height measured (H, mm) by the compressibility indicator is given as:

$$\gamma = (0.3157\ M) / H \quad (4)$$

The compressibility of the material was calculated graphically from the linear plot of normal load versus bulk density (γ, g/cm^3). The slope of the line of this plot directly gives the compressibility of material. Jenike (1964) compressibility and compressibility obtained from Carr (1965) flow properties are not the same parameters measured. Their values will also differ significantly.

Thus, the objective of this present study is to evaluate all the flow properties Carr (1965) and Jenike shear test (1964), for the commercial DDGS samples collected from ethanol plants and also to find if there is any correlation between two set of experiments i.e., Carr and Jenike shear test.

Materials and Methods

Sample Collection

Samples of DDGS were obtained from five commercial ethanol plants across the state of South Dakota, in two collection periods. For each of the properties five replications were performed. The samples were stored in plastic bags under normal room temperature (24 ±1°C) and humidity.

Physical Properties

The soluble content of the commercial DDGS samples were calculated using the technique developed by Ganesan et al. (2006a). The moisture content were determined using AACC standard method (1995), by the use of forced convection laboratory oven (Thelco Precision, Jovan Inc. Wincester, Va.) at 103 °C for 72 hrs. The geometric mean diameter and geometric standard deviation of DDGS particles were calculated using ASAE/ANSI standard S319.3 (2003) and the segregation of the particles were accomplished using a of Rotap Sieve analyzer.

Carr Index Property Measurement

Carr indices tests (ASTM D 6393, 1999) were used to measure the flow properties for the DDGS samples. Hosokawa powder characteristics tester (model PTR, Hosokawa Micron powder systems, NJ) was used to measure the Carr flow properties (Carr, 1965). The carr flow properties includes angle of repose, aerated bulk density, packed bulk density, compressibility, uniformity, angle of fall, angle of spatula, angle of fall, angle of difference, and dispersibility. Powder tester were able to measure both the flowability index which includes angle of repose, compressibility, angle of spatula and uniformity and Floodability index which is the sum of flowability index ,angle of difference, dispersibility and angle of fall.

Jenike Shear Testing Properties

Jenike shear cell techniques were performed to get the instantaneous shear tests for the ten types of DDGS samples obtained. Five commercial ethanol plants and its two corresponding batches makes total ten types of samples .Three level consolidation were performed for these above ten samples. This makes about 30 combinations (10 x 3). Each of samples was replicated thrice thus giving us 90 experimental runs.

Jenike shear cell unit consist of a base, ring, mold, twisting top and cover. The ring was made both of stainless steel or aluminum. For level 3 consolidation, aluminum ring was used and for level 1 and level 2 consolidation stainless steel rings was used. The base, ring and mold were places one over other forming the shear cell. For the rest of other components it is made of stainless steel (Jenike, 1964). DDGS was placed in the shear cell and spread our uniformly while scrapping off excess material from the cell. It consists of three steps. First step is the preconditioning step where the DDGS were preconsolidated by applying about 30 to 60 twists; this twist is determined by trial and error method as described by Jenike (1964). The direction of twists was both in clockwise and anticlockwise directions. The second steps is called the consolidation were the twisting top and mold are being removed and then consolidation weight (W) is being applied to the arrangement. The horizontal shear force was applied on this arrangement. The horizontal shear force was applied at the rate of 2.7 mm/min. This shear force will stop once steady state has been achieved. This second step helps in reproducing flow with the given stress at the steady state conditions (Ganesan et al., 2005b). A strip chart reader attached with this shear cell unit (Model ST-5, Jenike and Johanson Co., Westford, MA) was used to record the steady state force. The third step consists of applying individual shear weight ($\overline{W}_i$) of the DDGS sample inside the cell. This gives the new set of steady state force ($\overline{S}_i$) which was recorded on the same chart recorder. This helps in measuring the shear stress at the failure for the samples. Mohr circles plot were obtained for each failure using AutoCAD v.2005 (Autodesk, INC., San Rafael, CA).

A stainless steel base of dimensions 64 mm inside diameter and depth of 19.05 mm was used in this procedure. The base was filled with DDGS samples uniformly and then covered with stainless steel cover. On top of the cover weight hanger and indicator holder were placed. The indicator holder was a 25 mm travel dial indicator mounted on a stainless steel holder which has a counter bored bottom that fits on the base. For each of the weights placed on the weight hanger there was change in the indicator reading. This indicator reading gives the height measured when there is change in the compressibility of the samples due to increase in weights. The relationship of height (H, mm) and bulk density (γ, kg/cm^3) of the material and which in turn gives the compressibility is given in the equation 4. According to compressibility procedure (Jenike, 1964) log-log plot was used to find the slope of the line which gives the compressibility. However we have used linear plot between bulk density (γ, g/cm^3) and normal load. This was done as we obtained linear relationship between bulk density and normal load. Thus, a log–log plot was replaced by a linear plot in the procedure.

Statistical Procedures

For each of the property a formal statistical data analysis were done using Microsoft Excel v.2003 (Microsoft Corp., Redmond, WA.). Least significant difference test (LSD) at 95 % confidence level was performed on the data points using SAS software (SAS Institute, Carry, NC). LSD test was used to predict the significant difference between the plants and also between the batches for a particular plant. Statistical correlation analysis among the properties was performed to see dependence between the properties at 95% significant level, using the same above SAS software. Correlation coefficient among the all the variables were performed using at 95 % confidence level were performed.

Results and Discussion

Physical Properties

From the selected physical properties as given in table 3, we can clearly see a classification of DDGS based on particle size. The largest particle was obtained from the plant 3 with the average mean diameter of 1.19 mm and the lowest particle size was obtained from plant 2 with an average mean diameter of 0.5 mm. This range of mean diameter was obtained from our previous study (Bhadra et al., 2007). A typical particle size distribution may bring about "shifting". It is phenomena where the smaller particle distribution may be discharged earlier from the hooper than the larger particles. This size segregation that occurs in DDGS may lead to uneven nutrient distribution and may facilitate "bridging" between the particles due to these localized regions (Ileleji et al., 2007). Larger particle do have more flow problem compare to small particle.

The moisture content was to be in range of approximately 4% (db) to 8% (db). This range of moisture content appeared to be half in the ranges found by Rosentrater (2006a).Our results showed the plant which had the highest moisture content (plant 5) had low flowability index (table 4) and plant which had least moisture levels (plant 1) had high relatively high flowability index (table 4). This indicates that moisture as expected did play an important role in flowability properties.

Soluble levels were found to be in the ranges of approximately 11% (db) to 15 % (db). From table 3, plant 3 (batch 2) which had the highest geometric mean diameter showed less solubles content than plant 4 (batch 1), which was found to have highest soluble level of 14.80 % (db). This showed that large diameter does not necessarily mean higher surface coating of the soluble level. This soluble level in DDGS was slightly higher than the values reported by Tjardes and Wright (2002). Soluble which is also known as "syrup" in the industry is higher in fat levels (Buchhiet, 2002; Cruz et al., 2005). A higher soluble level, with higher fats levels would not lead to the conclusion of having higher surface coating which subsequently give rise to larger particle size; as found by our results. Surface nature on Distillers Dried Grain (on which the soluble layers are added) may help in penetrating some of the fat molecules and thus keeping low particle size. Fat molecules are relatively smaller in molecular weight than protein (Das, 1992) which facilitates faster penetration within the DDG (distillers dried grain without solubles). It has also been found out that there was less fat content, when the soluble level was increased to 25 % (db) (Ganesan et al., 2005).

There were significant statistical differences obtained in the moisture and soluble level among the plants and also between the batches. For soluble levels there were no significant difference obtained between the batches in a particular plant but there were difference among the plants. This is because soluble addition on DDG process may differ plantwise but less chance between batches within a single plant. The moisture content on the other hand was found to be different among the plant and also between the batches for a particular plant. Moisture content is a much more vulnerable parameter to control due to environmental factors than soluble levels. This difference indicates inconsistent processing techniques not only among the plants but also in the batches.

Carr Index Properties

The angle of repose was found in the range of approximately 38° to 41°. This is higher than the range of free flowing solids (Rosentrater, 2006). Thus, their might some flow problems related to DDGS. This range of angle of repose was slightly lesser than what was found by Ganesan et al. (2006b). It was reported that there was trend of increasing angle of repose with increase in moisture and soluble levels (Ganesan et al., 2006b). This indicates that with higher moisture and soluble levels there was possible flow problems in DDGS. However, in our study from table 4, we observed highest angle of repose in plant 3 (40.12°) which had lower moisture and soluble content compare to plant 4 and plant 5 (table 3). Angle of repose not only depends on the moisture or soluble content it also greatly influenced by particle shape and size. One reason for plant 3 to have higher angle of repose would be higher particle diameter (table 3) than rest others. According to Carr classification (1965), solids with angle of repose greater than 45° would not flow and between 40° to 45° would have some flow problems (table 1).

There were statistical significant differences observed among the plants. Except for plant 4, there were significant differences observed between the corresponding batches for all the plants.

From table 4 we observe the highest packed bulk densities were obtained from plant 4 with an average of 0.61 g/cm^3 and the lowest ranges of packed bulk densities were obtained from plant 5 with an average of 0.48 g/cm^3 .This result was a very close results of aerated and packed bulk densities obtained by Ganesan et al. (2006b) for 10% moisture and 10% soluble levels. It was found that in plant 4 which had soluble levels of 14.59% (db) had highest packed bulk density of 0.61 g/cm^3. This result was very similar as predicted by Ganesan et al. (2006b), for 15% (db) soluble levels. There were significant differences seen for both type of bulk densities among the ethanol plants and also in their batches. Only for plant 1 there was no significant differences on aerated bulk density (table 3). This leads to vital discussion that DDGS handling and shipping issues becomes more intricate due inconsistent densities.

We obtained compressibility value to be between a range of 3.44 % (db) to 7.56 %(db). The highest compressibility was observed in plant 1 with the overall average value from both the batches was found to be 7.56% (db). Higher the compressibility higher is the tendency of that material to have flow problems. Materials with greater than 25% compressibility were found to less flowable material (Carr, 1965). From table 4 we can also conclude that the compressibility values were quite relatively higher than the values obtained by Ganesan et al. (2006b), for all the types of moisture and solubles conditions used in that particular study. From table 4 we also notice that there were significant differences among the plants. There was difference only between the batches of plant 4 but not in the batches of other plants. One of the reasons of this result could be that compressibility is primarily depended on the particles sizes. Particle sizes vary less between the batches for a particular plant and more among the plants, as it depends on the milling specifications and processing parameters of that plant.

Angle of spatula (average) was found from the range of 54.22° to 63.20° (table 4). These results showed that it was slightly higher than those values found by Ganesan et al. (2006b), for all varying solubles, moisture, and flow agent levels. Materials with angle of spatula of less than 61° are considered to be passable or borderline material (Carr, 1965), in terms of flowability. Less 60° of angle of spatula would have no flow problems; for our samples plant 2 was found to be having higher angle of spatula of 62.42° compare to other plants. There were significant differences observed among the plants and as well in between the batches, for all the values of angle of spatula.

The highest uniformity was found in plant 2 with the value of 2.80 (-). According to Carr classification (1965), uniformity of the materials less than 6 (-) is considered to excellent in flowability.

The flowability index obtained was in the range of 79.55 to 81.60. Higher the flowability index better is the material in terms of flowability. This range of flowability index was slightly higher than it was found in Ganesan et al (2006b). This range of flowability index for our samples shows good flowability in DDGS but sometimes vibrator or agitator is required to increase the flowability. There were significant differences among the plants and as well the batches indicating inconsistent DDGS product, in terms of flowability.

The angle of fall from table 4 was found to be less than 37° (approximately). This is range of values is categorized as “floodable” materials (Carr, 1965). “Floodable” materials mean they flow sporadically and abruptly. This nature in the powders or granular solids is not considered as good criteria for flowability. This range of values was slightly less than the values obtained by Ganesan et al., (2006b) for all combinations of solubles, moisture, and flow agent levels. This was quite logical as our solubles and moisture levels were less than those levels by Ganesan et al., (2006b). Solubles and moisture levels do effect floodability; higher soluble and moisture may lubricate the DDGS to have higher “floodable” character in DDGS.

From table 4 we can say that we got a wide range of dispersibility values .The lowest dispersibility was obtained for plant 2 (9.41%, db) and the highest value was found in plant 3 (44.59%, db). For plant 2 and plant 5 the samples falls under the category of fairly floodable. For plant 3, DDGS was found to be very floodable. Higher the value of dispersibility higher is tendency of that material to flush.

The sum of flow index, angle of fall, angle of difference, and dispersibility gives the floodability index. It gives the characteristics of the material in terms of its ability to “flush”. Floodability index higher than 60 (-) would require rotary seals or other type of preventive measures to stop flushing of DDGS (Carr, 1965). Plant 3 showed the highest floodability index (65.27) and plant 2 (55.35) showed the least floodability index. This range of floodability index was slightly higher than found by Ganesan et al. (2006) for all combinations of soluble, moisture, and flow agents. This indicates that our samples had higher flushing nature which may affect flow and handling properties.

Jenike Shear Testing Properties

From table 5 we see a logical trend in the effective angle of friction (δ, °), with the increase in the pressure from level 3 consolidation to level 1 consolidation which had the highest pressure. We noticed a decrease in the effective angle of friction as we move from level three consolidation to level one consolidation. For level 1 consolidation, the value of effective angle of friction (δ) was found to be in the range of 48.00° (plant 5) to 55.00° (plant 2). Level 2 consolidation had the range of 52.17° (plant 4) to 59.00° (plant 2). Level 3 consolidation had a range of values from 51.50° (plant 4) to 60.17° (plant 5). These ranges of values were found to higher than Ganesan et al. (2007). Higher the value of effective angle of friction higher will be the chances of having flow problems (Jenike, 1964). There were significant differences obtained in the Jenike shear parameters among the plants and as well as between the batches, in a particular plant. This indicates that there will be chances of finding DDGS samples with higher flow problems or lesser flow problems from a particular plant or from different plant.

From table 5 we observe that angle of internal friction (Φ) was found to be in the range of 33.67°(plant 4) to 40.00° (plant 3) for level 1 consolidation, 35.83° (plant 1) to 44.33° (plant 5) for level 2 consolidation, and 31.00° (plant 3) to 52.17° (plant 5) for level 3 consolidation. These ranges of angle of internal friction for each level of consolidation was found to quite similar to those found Ganesan et al. (2007). For our study the highest level of values was found in Plant 5 (8.08%, (db) moisture levels and 11.41%, (db) soluble levels) in level 3 consolidation. This was higher than the highest angle of internal friction found by Ganesan et al. (2007) with 15 % soluble and 10% moisture content. Higher values of internal angle of friction were found to be better in flowability (Duffy and Puri, 1999). Results indicated that DDGS samples would not show any possible flow problems since it had sufficiently high values of angle of internal friction.

For major consolidating stress (σ_1), the highest value was found for plant 4 (28.43 kPa) and the lowest value was obtained for plant 1 (24.53 kPa) (table 5). Highest mean value of major consolidation stress was found to be less than that found by Ganesan et al., (2007). To break the arch to break the maximum stress should be higher than the yield strength, $\sigma_1 > \sigma_c$ thus giving an ease in flowing (Jenike, 1964). Similar kind of relationship was obtained in our DDGS samples, which indicates that there would not be any possible flow problem.

From table 5 we observe that the lowest mean of unconfined yield strength (σ_c) was found in plant 3 (4.88 kPa) and the highest mean was seen in plant 2 (16.74 KPa), for level one consolidation. This indicates that DDGS do have some flow problems, only purely non cohesive solids like sand will have yield strength value of zero (Jenike, 1954). The highest mean value obtained in our results was closely similar to that obtained by Ganesan et al. (2007) for 25 % (db) soluble and 10% (db) moisture levels.

Compressibility (β, cm^{-1}) values of DDGS and the regression equation between bulk density, gamma (kg/cm^3) and the normal load (kg_f/cm^2) is represented in table 6. The highest compressibility was found in plant 2 (0.0219 cm^{-1}). More the compressible the material the more difficult it will during flow process. For powders, the compressibility index (n) generally lies from 0 to 1. Value of the index higher than 0.05 would lead to compressible powders and lower than 0.05 would lead to incompressible solids (Grossman et al., 2004). This compressibility index was calculated from the plot of bulk density and the applied pressure DDGS (figure 1) sample did not show any higher values of compressibility that would lead to flow problems

Flow functions for each DDGS samples were calculated from Jenike shear test results (Jenike, 1954) and it is shown in table 7. There was not a single DDGS sample obtained that showed flow function less 1 which means that there is no flow. At level one consolidation (table 7) we get DDGS samples that showed flow function values for plant 2, plant 5 and plant 4 to be cohesive or highly cohesive while plant 1 ,batch 2 had almost free flow (Jenike, 1964). It was found that plant 5 which showed lowest flowability index from Carr test procedure which means it may have potential flow problems compared to all other samples, (Carr,1965) showed higher flow function index(Jenike, 1954) than plant 2 which indicates that it will show less flow problems than plant 2. Such different results makes it difficult to select and understand what set of test procedure should be the best representation of flowability measurement. Trend in the flow function values does not match for level three and two consolidation.

Property Relationships

Pearson product moment correlation coefficient (Speigel, 1994) was performed for all the properties as stated in table 3, 4, 5, and 6. The correlation coefficient for a particular significant level determines how closely the two properties are related to each other in a linear fashion. Out of 1089 possible combinations only 48 combinations had p values less than α =0.05 (significant correlations) and correlation coefficient (r) greater that 0.500. Out of these above 48 significant combinations, seventeen variable combinations had correlation coefficient (r) from ±0.5 to ± 0.6, twenty one variable combinations had correlation coefficients (r) from ± 0.6 to ± 0.7, seven variable combinations had correlation coefficients (r) from ± 0.7 to ± 0.8, and only three had its coefficients from ±0.8 to± 1.00. Ten variable combinations showing the significant r value from ±0.7 to± 1.00 is given in the table 8. Hausner ratio had higher correlation with compressibility measurement in Carr procedure (Carr, 1965). This seems to quite logical and expected as hausner ratio consists of tapped density and aerated density. Higher amount of tapped density than aerated bulk density indicated higher possibility of the particle to compact. This is due to the reason of inbuilt particle shape and size of DDGS. Floodability index was very highly correlated to the dispersibility property. This is also very reasonable as because dispersibility was the part of floodability index (Carr, 1965). However the results of having more higher correlation of dispersibility with total floodablility index may predict that dispersibility is the key property during floodability characteristics measurement. Our results of correlation procedure among the Carr and Jenike shear test (Jenike, 1964) properties indicates that there were not very strong correlation among each other and one set of experiment can not be replaced by other set. In terms of labor input, skills required, time, and repeatability of the experimental procedure Jenike shear testing properties are more complicated than Carr test procedure. A strong correlation among the two procedures would have been able to select the best possible experimental procedure in terms of time and labor input. Moreover in terms of flowability of DDGS it would have been easier to decide which set of flowability parameters are the best judge for flowability of DDGS.

In some cases there were significant correlations between Carr and Jenike shear test properties. At level three consolidation, angle of friction and effective angle of friction did show a negative correlation with aerated and packed bulk densities. This result is quite logical as higher densities refers to higher compactness of the solid particles and hence less angle of friction between the two particles. Unconfined yield stress did show significant correlation between total floodability and dispersibility. The Jenike shear test properties between two levels had some correlation among each. This quite reasonable as one level of consolidation differs from other level only in terms of load addition and the level procedures remains unchanged. Geometric standard deviation and geometric mean diameter also had quite good amount of correlation with compressibility and hausner ratio. This indicates particle shapes and sizes play an important role in few of flowability parameters. Of all the above Carr and Jenike properties' correlation discussed above although it had a significant p ($p<\alpha$) values but the correlation coefficient (r) was less than ±0.9 and less variable combinations were found to be significant. One of reasons in not being able to get a strong correlation would be significant differences in most of the properties for DDGS samples obtained from various plants. In consistencies in DDGS may lead to difficulty is quantifying flowability studies.

Conclusion

Based on the Carr and Jenike properties one can judge the flowability of DDGS, both of the experimental procedure can be helpful in determining flow problems in solids but it is quite difficult and paradoxical in terms of deciding which set of experimental procedure one should follow. One can predict lower flowability while other can suggest for higher flow tendencies for the same samples for the two types of experimental procedure as described above. Low correlation coefficient among the Carr and Jenike parameters would suggests that one set of experiment can not be totally replaced by other. Operator's choice, experimental design and sample to be tested are needed for deciding which set of parameters one should measure. Jenike shear test procedure and properties mostly depicts the real industrial storage and handling situations but on the other hand, Carr properties are also used widely for pharmaceutical powders. Inconsistencies in DDGS may hinder the possibility of finding the correlation between two experimental procedures. In short, flowability can be justified as a multivariate field where more research is necessary.

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Table 1: Carr (1965) classification of angle of repose.

Angle of repose (°)	Type of flow
<25	Excellent flowability
26-35	Good flowability
36-40	Fair flowability. Some kind of vibration may be required.
41-45	Passable. They belong to the borderline and sometimes there can be flow problems.
46-55	Poor flowability. Agitation or vibration is required.
56-65	Very poor in flowability. Needs vibration more positively.
66-90	Extremely poor in flowability. Special agitation or hoppers are required.

Table 2: Flow function classification in Jenike (1964) shear testing

Flow functions	Classification of flow
F<1	No flow
1<F<2	Highly cohesive
2<F<4	Cohesive
4<F<10	Intermittent flow
10<F	Free flow

Table 3: Physical Properties of DDGS from Commercial ethanol Plants Values in the parenthesis are ± 1 standard deviation. *

Plant	Batch	Geometric mean diameter (d_{gw}, mm)	Geometric standard deviation (S_{gw}, mm)	Moisture content (%, db)	Soluble levels (%, db)
1	1	0.83^{1}	0.48^{1}	4.32^{1}	12.56^{1}
				(0.65)	(3.06)
	2	0.87^{1}	0.55^{1}	4.92^{1}	12.77^{1}
				(1.03)	(2.12)
Overall mean		**0.8^{ab}**	**0.52^{a}**	**4.61^{b}**	**12.56^{ab}**
		(0.03)	**(0.05)**	**(0.87)**	**(3.06)**
2	1	0.79^{1}	0.45^{1}	4.60^{1}	11.03^{1}
				(0.88)	(1.82)
	2	0.21^{2}	0.30^{1}	5.36^{1}	13.73^{1}
				(1.25)	(2.59)
Overall mean		**0.5^{b}**	**0.38^{a}**	**4.98^{b}**	**12.34^{b}**
		(0.41)	**(0.12)**	**(1.10)**	**(2.55)**
3	1	1.00^{1}	0.45^{1}	5.84^{1}	10.58^{1}
				(1.32)	(1.29)
	2	1.38^{2}	0.49^{1}	5.38^{2}	13.38^{1}
				(1.66)	(1.16)
Overall mean		**1.19^{a}**	**0.47^{a}**	**5.61^{b}**	**11.98^{b}**
		(0.27)	**(0.03)**	**(1.44)**	**(1.88)**
4	1	0.80^{1}	0.20^{1}	6.42^{1}	14.80^{1}
				(0.35)	(2.82)
	2	0.81^{1}	0.53^{1}	8.83^{1}	14.32^{1}
				(2.54)	(2.55)
Overall mean		**0.81^{ab}**	**0.37^{a}**	**7.63^{a}**	**14.59^{a}**
		(0.01)	**(0.23)**	**(2.13)**	**(2.55)**
5	1	0.68^{1}	0.47^{1}	7.26^{1}	12.26^{1}
				(0.433)	(1.82)
	2	0.97^{2}	0.54^{1}	8.89^{1}	11.26^{1}
				(3.18)	(1.40)
Overall mean		**0.83^{ab}**	**0.51^{a}**	**8.08^{a}**	**11.41^{b}**
		(0.21)	**(0.05)**	**(2.31)**	**(1.54)**

* Same letters indicate there is no significant difference among the plants.
Same numbers indicate there is no significant difference between the batches in a plant

Table 4: Carr Index Properties of DDGS from Commercial Ethanol Plants. Values in the parenthesis are ± 1 standard deviation.*

	Processing Plants														
	1			2			3			4			5		
	Batch			Batch			Batch			Batch			Batch		
Properties	1	2	Overall mean	1	2	Overall mean	1	2	Overall mean	1	2	Overall mean	1	2	Overall mean
AOR	35.94[2]	40.62[1]	**38.28[b]**	37.76[2]	41.60[1]	**39.68[a]**	39.48[2]	40.76[1]	**40.12[a]**	37.26[1]	38.98[1]	**38.12[b]**	39.82[1]	38.72[2]	**39.27[ab]**
(°)	(1.37)	(0.34)	**(2.64)**	(0.74)	(1.41)	**(2.22)**	(0.64)	(0.85)	**(0.98)**	(1.04)	(1.28)	**(1.43)**	(1.41)	(1.04)	**(1.31)**
ABD	0.49[1]	0.51[1]	**0.50[c]**	0.54[2]	0.59[1]	**0.57[ab]**	0.55[1]	0.54[2]	**0.55[b]**	0.60[1]	0.55[2]	**0.58[a]**	0.47[1]	0.44[2]	**0.46[d]**
(g/cm^3)	(0.01)	(0.01)	**(0.01)**	(0.02)	(0.03)	**(0.04)**	(0.01)	(0.00)	**(0.01)**	(0.01)	(0.02)	**(0.03)**	(0.01)	(0.01)	**(0.48)**
PBD	0.54[2]	0.55[1]	**0.54[c]**	0.56[2]	0.61[1]	**0.59[ab]**	0.58[1]	0.56[2]	**0.57[b]**	0.62[1]	0.59[2]	**0.61[a]**	0.50[1]	0.47[2]	**0.48[d]**
(g/cm^3)	(0.01)	(0.01)	**(0.01)**	(0.00)	(0.03)	**(0.04)**	(0.01)	(0.01)	**(0.01)**	(0.01)	(0.02)	**(0.02)**	(0.01)	(0.00)	**(0.01)**
Hausner Ratio	1.09[1]	1.08[1]	**1.08[b]**	1.04[1]	1.03[1]	**1.04[a]**	1.04[1]	1.04[1]	**1.04[a]**	1.03[1]	1.08[2]	**1.06[a]**	1.05[1]	1.06[1]	**1.05[a]**
(-)	(0.03)	(0.00)	**(0.02)**	(0.04)	(0.01)	**(0.02)**	(0.01)	(0.02)	**(0.01)**	(0.01)	(0.01)	**(0.03)**	(0.01)	(0.01)	**(0.01)**
Compressibility	7.86[1]	7.29[1]	**7.56[a]**	3.60[1]	3.27[1]	**3.44[c]**	3.81[1]	3.91[1]	**3.86[bc]**	2.88[2]	7.46[1]	**5.17[b]**	4.85[1]	5.53[1]	**5.19[b]**
(%)	(2.09)	(0.01)	**(1.43)**	(3.16)	(1.10)	**(2.24)**	(0.71)	(1.43)	**(1.07)**	(1.31)	(0.90)	**(2.64)**	(1.66)	(1.17)	**(1.15)**
AOS (before)	58.02[2]	50.72[1]	**54.37[a]**	64.40[1]	60.44[2]	**62.42[a]**	60.48[2]	64.54[1]	**62.51[a]**	63.40[1]	60.12[2]	**61.76[a]**	60.68[1]	60.80[1]	**60.74[a]**
(°)	(1.53)	(2.90)	**(4.43)**	(1.35)	(2.39)	**(2.78)**	(0.36)	(3.51)	**(3.18)**	(2.76)	(3.79)	**(3.57)**	(3.37)	(1.22)	**(2.39)**
AOS (after)	55.02[2]	58.72[1]	**56.87[a]**	59.74[1]	58.80[1]	**59.30[a]**	64.70[1]	52.12[2]	**58.41[a]**	60.74[1]	55.54[2]	**58.14[a]**	56.58[1]	57.58[1]	**57.08[a]**
(°)	(1.54)	(2.72)	**(2.85)**	(3.99)	(0.89)	**(2.77**	(2.22)	(1.58)	**(6.88)**	(3.37)	(2.71)	**(3.98)**	(4.54)	(2.50)	**(3.50)**
AOS (average)	56.72[1]	51.72[2]	**54.22[c]**	66.73[1]	59.67[2]	**63.20[a]**	62.89[1]	58.30[2]	**60.60[b]**	62.01[1]	57.81[2]	**59.91[b]**	58.77[1]	59.22[1]	**59.00[b]**
(°)	(0.35)	(1.43)	**(2.81)**	(3.04)	(1.47)	**(4.35)**	(0.85)	(2.04)	**(2.38)**	(3.10)	(1.49)	**(3.18)**	(1.83)	(1.66)	**(1.66)**
Uniformity	2.00[1]	2.80[1]	**2.40[b]**	2.80[1]	2.80[1]	**2.80[a]**	2.30[1]	1.20[2]	**1.75[c]**	2.80[1]	2.80[1]	**2.80[a]**	2.00[2]	2.40[1]	**2.20[b]**
(-)	(0.00)	(0.00)	**(0.42)**	(0.00)	(0.00)	**(0.00)**	(0.00)	(0.00)	**(0.58)**	(0.00)	(0.00)	**(0.00)**	(0.00)	(0.00)	**(0.21)**
Total flowability	81.40[1]	81.00[1]	**81.20[a]**	82.40[1]	80.80[2]	**81.60[a]**	80.80[2]	82.10[1]	**81.45[a]**	82.00[1]	79.40[2]	**80.70[ab]**	79.80[1]	79.30[1]	**79.55[b]**
Index(-)	(0.89)	(0.00)	**(0.63)**	(0.96)	(0.84)	**(1.20)**	(0.84)	(1.14)	**(1.17)**	(0.71)	(1.29)	**(1.69)**	(0.76)	(0.45)	**(0.64)**
Angle of fall	33.36[2]	38.26[1]	**35.81[a]**	31.84[2]	35.28[1]	**33.56[b]**	32.04[2]	39.98[1]	**36.01[a]**	31.40[2]	33.94[1]	**32.56[b]**	36.00[1]	34.74[2]	**35.37[a]**
(°)	(0.98)	(0.88)	**(2.73)**	(1.00)	(1.54)	**(2.19)**	(1.26)	(1.16)	**(4.34)**	(1.29)	(0.79)	**(1.59)**	(0.43)	(1.42)	**(1.19)**
Angle of	2.38[1]	2.56[1]	**2.47[c]**	5.92[1]	6.40[1]	**6.16[a]**	7.44[1]	0.88[2]	**4.16[bc]**	5.86[1]	5.04[1]	**5.45[ab]**	4.18[1]	3.98[1]	**4.08[bc]**
difference (°)	(0.76)	(0.70)	**(0.70)**	(0.89)	(1.88)	**(1.41)**	(0.97)	(0.52)	**(3.53)**	(0.89)	(0.67)	**(0.86)**	(1.66)	(1.02)	**(1.30)**
Dispersibility	40.92[1]	37.78[1]	**39.35[a]**	7.22[1]	11.59[1]	**9.41[b]**	51.4[1]	38.04[2]	**44.59[a]**	48.20[1]	24.00[2]	**36.10[a]**	1.39[2]	38.18[1]	**19.79[b]**
(%)	(4.58)	(2.97)	**(4.00)**	(0.65)	(0.86)	**(2.41)**	(2.46)	(3.11)	**(7.39)**	(2.80)	(2.44)	**(12.99)**	(0.35)	(3.89)	**(19.79)**
Flowability index	25.00[1]	25.00[1]	**25.00[a]**	25.00[1]	25.00[1]	**25.00[a]**	25.00[1]	25.00[1]	**25.00[a]**	25.00[1]	25.00[1]	**25.00[a]**	25.00[1]	25.00[1]	**25.00[a]**
(-)	(0.00)	(0.00)	**(0.00)**	(0.00)	(0.00)	**(0.00)**	(0.00)	(0.00)	**(0.00)**	(0.00)	(0.00)	**(0.00)**	(0.00)	(0.00)	**(0.00)**
Total Floodability	63.60[1]	63.4[1]	**63.50[a]**	53.25[2]	57.45[1]	**55.35[b]**	70.20[1]	60.70[1]	**65.27[a]**	70.20[1]	62.10[2]	**66.15[a]**	48.60[2]	64.60[1]	**56.85[b]**
Index (-)	(3.78)	(3.13)	**(3.27)**	(0.64)	(1.84)	**(2.57)**	(0.45)	(2.41)	**(5.27)**	(1.15)	(0.65)	**(4.36)**	(1.52)	(1.52)	**(8.55)**

***** Same letters indicate there is no significant difference among the plants.
Same numbers indicate there is no significant difference between the batches in a plant**.**

Table 5: Jenike Shear Testing Properties of DDGS from Commercial Ethanol Plants. Values in the parenthesis are ± 1 standard deviation.*

Plant	Batch	Effective angle of friction (δ, °)	Angle of internal friction (Φ, °)	Unconfined Yield Strength (σ_c, kPa)	Major Consolidating Stress (σ_1, kPa)
		Level I consolidation			
1	1	52.33^{1}	39.67^{1}	6.86^{1}	31.31^{1}
		(2.52)	(1.53)	(1.73)	(3.62)
	2	45.00^{2}	39.00^{1}	3.23^{2}	17.75^{2}
		(2.00)	(2.00)	(0.30)	(1.04)
Overall mean		**48.67^{bc}**	**39.33^{ab}**	**5.05^{c}**	**24.53^{a}**
		(4.50)	**(1.63)**	**(2.28)**	**(7.80)**
2	1	53.00^{1}	32.67^{2}	18.00^{1}	25.77^{2}
		(1.00)	(2.08)	(1.98)	(0.73)
	2	57.00^{1}	39.00^{1}	15.49^{1}	27.77^{1}
		(2.65)	(1.73)	(2.10)	(0.77)
Overall mean		**55.00^{a}**	**35.83^{ab}**	**16.74^{a}**	**26.77^{a}**
		(2.83)	**(3.87)**	**(2.29)**	**(1.28)**
3	1	51.00^{1}	47.00^{1}	4.78^{1}	26.62^{1}
		(1.00)	(3.61)	(1.37)	(2.90)
	2	49.33^{1}	33.00^{2}	4.98^{1}	22.65^{1}
		(2.08)	(1.73)	(1.34)	(2.71)
Overall mean		**50.17^{b}**	**40.00^{a}**	**4.88^{c}**	**24.64^{a}**
		(1.72)	**(8.07)**	**(1.22)**	**(3.32)**
4	1	42.33^{1}	35.00^{1}	8.21^{1}	28.48^{1}
		(1.15)	(2.65)	(1.15)	(1.09)
	2	47.33^{1}	32.33^{1}	8.69^{1}	28.38^{1}
		(2.52)	(3.06)	(1.99)	(3.31)
Overall mean		**44.83^{c}**	**33.67^{b}**	**8.45^{b}**	**28.43^{a}**
		(3.25)	**(2.94)**	**(1.48)**	**(2.21)**
5	1	43.00^{2}	32.67^{2}	8.69^{1}	28.50^{1}
		(1.73)	(0.58)	(0.54)	(0.70)
	2	53.00^{1}	43.33^{1}	8.61^{1}	26.42^{1}
		(1.00)	(2.89)	(2.40)	(2.50)
Overall mean		**48.00^{bc}**	**38.00^{ab}**	**8.65^{b}**	**27.46^{a}**
		(5.62)	**(6.13)**	**(1.56)**	**(2.00)**
		Level 2 consolidation			
1	1	57.33^{1}	32.67^{2}	2.19^{2}	4.93^{2}
		(2.52)	(4.51)	(0.54)	(0.13)
	2	49.67^{2}	39.00^{1}	3.55^{1}	8.77^{1}
		(2.52)	(3.61)	(0.30)	(0.23)
Overall mean		**53.50^{bc}**	**35.83^{b}**	**2.87^{bc}**	**6.85^{b}**
		(4.76)	**(5.04)**	**(0.84)**	**(2.11)**
2	1	59.33^{1}	46.00^{1}	6.54^{1}	9.51^{1}
		(2.08)	(2.65)	(0.36)	(1.07)
	2	58.67^{1}	38.33^{2}	6.56^{1}	10.40^{1}
		(2.52)	(2.89)	(0.66)	(1.19)
Overall mean		**59^{a}**	**42.17^{a}**	**6.55^{a}**	**9.96^{a}**
		(2.10)	**(4.88)**	**(0.47)**	**(1.12)**
3	1	55.33^{1}	42.67^{1}	1.52^{1}	8.65^{1}
		(1.53)	(0.58)	(0.78)	(2.21)
	2	49.67^{2}	44.00^{1}	1.64^{1}	7.92^{1}
		(0.58)	(1.00)	(0.36)	(1.57)
Overall mean		**52.50^{c}**	**43.33^{a}**	**1.58^{d}**	**8.28^{b}**
		(3.27)	**(1.03)**	**(0.55)**	**(1.76)**
4	1	50.67^{1}	38.00^{1}	2.32^{1}	5.87^{2}
		(1.53)	(3.61)	(0.71)	(0.12)
	2	53.67^{1}	46.00^{1}	1.85^{1}	8.09^{1}
		(2.52)	(1.00)	(1.36)	(2.34)
Overall mean		**52.17^{c}**	**42.00^{a}**	**2.08^{c}**	**6.98^{b}**
		(2.48)	**(4.98)**	**(1.01)**	**(1.92)**

5	1	57.33^{1}	43.67^{1}	3.44^{1}	7.49^{1}
		(2.08)	(2.89)	(0.72)	(0.33)
	2	55.33^{1}	45.00^{1}	4.03^{1}	7.66^{1}
		(2.89)	(2.65)	(0.52)	(0.38)
	Overall mean	**56.33^{b}**	**44.33^{a}**	**3.74^{b}**	**7.57^{b}**
		(2.50)	**(2.58)**	**(0.64)**	**(0.33)**
Level 3 consolidation					
1	1	58.33^{1}	40.67^{1}	0.90^{1}	1.48^{1}
		(1.53)	(4.73)	(0.22)	(0.18)
	2	57.67^{1}	40.67^{1}	1.14^{1}	1.57^{1}
		(2.08)	(4.04)	(0.17)	(0.06)
	Overall mean	**58.0^{a}**	**40.67^{b}**	**1.02^{a}**	**1.53^{a}**
		(1.67)	**(3.93)**	**(0.22)**	**(0.13)**
2	1	57.33^{1}	48.67^{1}	0.71^{1}	1.74^{1}
		(1.53)	(3.21)	(0.20)	(0.20)
	2	59.00^{1}	37.67^{2}	1.19^{1}	2.24^{1}
		(3.61)	(2.52)	(0.29)	(0.46)
	Overall mean	**58.17^{a}**	**43.17^{b}**	**0.95^{ab}**	**1.99^{a}**
		(2.64)	**(6.55)**	**(0.35)**	**(0.42)**
3	1	53.67^{1}	37.00^{1}	1.24^{1}	1.69^{1}
		(1.53)	(1.00)	(0.07)	(0.11)
	2	56.00^{1}	25.00^{2}	0.97^{1}	2.95^{1}
		(2.65)	(2.00)	(0.72)	(1.25)
	Overall mean	**54.83^{b}**	**31.00^{c}**	**1.11^{ab}**	**2.32^{a}**
		(2.32)	**(6.72)**	**(0.48)**	**(1.05)**
4	1	48.33^{2}	40.00^{1}	0.45^{1}	1.86^{1}
		(2.08)	(2.00)	(0.03)	(0.14)
	2	54.67^{1}	42.33^{1}	0.44^{1}	1.83^{1}
		(2.08)	(0.58)	(0.12)	(0.24)
	Overall mean	**51.50^{c}**	**41.17^{b}**	**0.45^{b}**	**1.85^{a}**
		(3.94)	**(1.83)**	**(0.08)**	**(0.18)**
5	1	59.33^{1}	50.00^{1}	0.66^{1}	1.63^{2}
		(1.53)	(3.00)	(0.23)	(0.05)
	2	61.00^{1}	54.33^{1}	0.75^{1}	1.95^{1}
		(1.73)	(3.21)	(0.11)	(0.07)
	Overall mean	**60.17^{a}**	**52.17^{a}**	**0.71^{b}**	**1.79^{a}**
		(1.72)	**(3.66)**	**0.17**	**(0.18)**

* Same letter indicate that there is no significant difference among the plants.
Same numbers indicate there is no significant difference between the batches in a plant.

Table 6. Compressibility of DDGS Samples from Commercial Ethanol Plants. Values in the parenthesis are ± 1 standard deviation.*

Plant	Batch	Regression equation †	Compressibility (β, cm^{-1})
1	1	$y = 0.0125x + 0.5608$, $R^2 = 0.924$	0.0125^{1} (0.0024)
	2	$y = 0.0077x + 0.5627$, $R^2 = 0.9421$	0.0077^{2} (0.0009)
		Overall (β)	0.0100^{b} (0.0031)
2	1	$y = 0.0219x + 0.5293$, $R^2 = 0.9242$	0.0219^{1} (0.0011)
	2	$y = 0.0219x + 0.577$, $R^2 = 0.9124$	0.0219^{1} (0.0018)
		Overall (β)	**0.0219^{a} (0.0014)**
3	1	$y = 0.0029x + 0.5664$, $R^2 = 0.9496$	0.0029^{1} (0.0010)
	2	$y = 0.0135x + 0.5628$, $R^2 = 0.844$	0.0135^{2} (0.0015)
		Overall (β)	**0.0082^{b} (0.0057)**
4	1	$y = 0.0129x + 0.6258$, $R^2 = 0.947$	0.0129^{1} (0.0009)
	2	$y = 0.0093x + 0.5036$, $R^2 = 0.9367$	0.0093^{2} (0.008)
		Overall (β)	**0.0111^{b} (0.0021)**
5	1	$y = 0.0189x + 0.5506$, $R^2 = 0.9793$	0.0189^{1} (0.0022)
	2	$y = 0.0176x + 0.5328$, $R^2 = 0.938$	0.0176^{1} (0.0005)
		Overall (β)	**0.0183^{ab} (0.0017)**

† y represents the bulk density (gamma) (kg/cm^3) and x represents the normal load (kgf/cm^2).
*Same letters indicates there are no significant differences among the plants.
Same numbers indicates there are no significant differences between the batches within the plants.

Table 7: Flow functions (Jenike shear testing) of DDGS samples from commercial Ethanol Plants.

Plant	Batch	Level one consolidation	Level two consolidation	Level three consolidation
1	1	4.56	2.25	1.64
	2	5.35	2.47	1.38
2	1	1.43	1.45	2.45
	2	1.79	1.59	1.88
3	1	5.57	5.69	1.36
	2	4.55	4.83	3.04
4	1	3.47	2.53	4.13
	2	3.27	4.37	4.16
5	1	3.28	2.18	2.47
	2	3.07	1.90	2.60

Table 8: Correlation coefficients for physical, Carr and Jenike shear test properties (α = 0.05, p values < α were found to be significant).

Property relationship	r value	p value
Hausner ratio * Compressibility (Carr)	-0.9648	<0.0001
Compressibility * Geometric mean diameter	-0.7631	0.01
Angle of difference * Angle of fall	-0.7127	<0.0001
Hausner ratios * Geometric standard deviation	-0.7074	0.0221
Geometric standard deviation * Aerated bulk densities	-0.7035	0.0232
Geometric standard deviation * Compressibility (Carr)	0.7104	0.0213
Angle of spatula(before impact) * Angle of spatula (average)	0.7545	<0.0001
Major consolidation stress (level 1) * Major consolidation stress (level 2)	0.7944	<0.0001
Dispersibility *Total floodability Index	0.9269	<0.0001
Aerated bulk Density*Packed bulk density	0.9698	<0.0001

Figure 1. Compressibility of DDGS Samples from the Commercial Ethanol Plants.