Flowability Properties of Commercial Distillers Dried Grains with Solubles (DDGS)

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ABSTRACT

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Distillers dried grains with solubles (DDGS), the 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 characteristics of DDGS samples from five ethanol plants in the north central region of the United States. Carr and Jenike tests were performed and the resulting data were mathematically compared with a previously developed empirical model. The largest particles had an average geometric mean diameter (GMD) of 1.19 mm, while the lowest particle size had an average GMD of 0.5 mm. Soluble solid levels were ≈10.5–14.8% (db). The effective angle of friction (δ) was 43.00–57.00°. Additionally, a few parameters exhibited fairly high linear correlations, including aerated and packed bulk densities (r = 0.97), geometric standard deviation and Carr compressibility (r = 0.71), geometric standard deviation and Hausner ratio (r = –0.70). Overall flowability assessment indicated that the commercial DDGS samples did have the potential for flow problems, although no samples exhibited complete bridging. Quantifying DDGS flowability is a necessary step toward overcoming this logistical challenge facing the fuel ethanol industry.

Distillers dried grain with solubles, commonly known as DDGS, has been extensively used as a source of protein for ruminants and nonruminants for more than two decades. With the exponential growth of the corn-based fuel ethanol industry, it is expected that there will be an increase in supply of, as well as demand for, DDGS during coming years. It is estimated that for every one bushel (56 lb) of corn that is converted to ethanol, ≈17 lb of DDGS are produced, along with 17.6 lbs of ethanol and 18.4 lb of carbon dioxide (Jaques et al 2003). DDGS is a good nutrient source for livestock as it has ≈35% protein, 30% fiber, some traces of nonfermentable starch, and ≈10–12% fat, which accounts for its high energy content. DDGS also has a substantial amount of minerals (calcium, phosphorous, etc.) and some key essential amino acids (methionine, leucine, etc.) (Spiehs et al 2002). This makes DDGS a very good livestock feed. Due to increasing demand, it is becoming increasingly important to ship and handle this product over large distances, generally by railcars and trucks. And DDGS often needs to be stored in large tanks, silos, or storage bins for relatively long time periods.

Storage and handling of DDGS has been troublesome due to poor flowability. In fact, it has been reported that due to the flowability problems, shipping DDGS through railway cars or trucks can be very problematic during unloading (Rosentrater 2006b). Restriction commonly occurs due to the caking phenomenon between particles and thus groups of particles. Due to this caking, also known as bridging, there can be substantial economic loss during shipping of DDGS. Particles tend to stick to each other, which results in unwanted agglomeration and adds cost to DDGS because labor, machinery, and time are required to break these agglomerates (Rock and Schwedes 2005).

Much research has been done with the flowability, handling, and storage characteristics of other granular powders and bulk solids. But there is a great need to understand flowability behavior of DDGS as there is currently very little information available. Understanding flowability properties and their correlations with physical and chemical properties is thus an important area to study to solve flow problems associated with DDGS. Apart from solving the caking problem, it is useful to know the physical and flow characteristics of DDGS for long-term handling, storage, and shipping.

It has also been reported that there can be substantial differences in many physical properties among DDGS samples obtained from commercial plants, and also between batches (collection periods) for a particular plant (Rosentrater 2006; Bhadra et al 2007). Thus, not only would understanding the flowability and physical properties be helpful for solving the flow problem in DDGS, but also elucidating inconsistencies in DDGS samples may be important when dealing with flowability of DDGS in general.

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). Flowability problems are often related to physical properties of granular solids. Flowability is not actually a natural material property of a particular product and, being a multidimensional problem, no single test can determine it. Flowability is a combination of the physical properties of materials, environmental factors, and processing techniques used for production of that material, 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 the flowability of any organic or granular material. Most agricultural and organic materials have a tendency to lose or to gain moisture with changing environmental factors. Moisture content is an important variable that affects cohesive strength and arching of bulk solids (Johanson 1978). Even small changes in moisture can change the frictional properties of bulk solids very significantly (Marinelli and Carson 1992). With an increase in moisture, compressibility increases, causing flowability problems (Moreyra and Peleg 1981; Yan and Barbosa 1997). Moisture can also be coupled with surface properties, and it can change or influence adherence properties between particles and storage tanks (Hollenbach et al 1983). Moisture migration and liquid bridge formation could lead to such

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flowability problems in DDGS. Humidity is strongly related to moisture content of the sample; higher humidity will increase moisture content as DDGS is a hygroscopic material (Ganesan et al 2007a), which may affect its flowability. Humidity increases the angle of repose for starch, sucrose, and sodium chloride powders (Craik and Miller 1958).

Additionally, temperature affects powder flowability. For example, unique temperature changes (especially lower temperatures) may result in phase changes of moisture layers between particles and form ice bridges; hence restricting the flowability of particles (Irani et al 1959; Johanson 1978; Fitzpatrick et al 2004b). Most temperature effects, however, are gradual changes over a wide range of temperatures. Fat plays an important role in flow problems too. High fat content can lead to worse flow conditions 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 thus act as glue between particles. It may also be possible that fat content may itself cause stickiness among the DDGS particles even without changes in temperatures.

Particle size and shape also play vital roles in flowability of powders and granular materials. Particle shapes and size are often adjusted to suit the final requirement and quality for various products. Generally, the smaller the size of the particle, the better the flow, depending on the product. However, a reduction in particle size of powders can make the flowability worse because this increases particle cohesion due to an increase in surface area per unit mass (Fitzpatrick et al 2004a,b). Shear index for general powders, mainly inorganic materials like ceramics, was inversely proportional to volume/surface mean diameter (Farely 1967; Valentin 1968). The finer the particle size, the more contact area between particles, which can lead to greater cohesive forces among the particles, thus causing flowability problems (Marinelli and Carson 1992).

Larger particle sizes can increase compressibility in bulk solids, and lead to flow problems (Yan and Barbosa 1997). Particle shape parameters include roundness, sphericity, and surface roughness. Smooth surfaces with higher roundness ratios generally give better flowability in granular materials than surfaces with rough edges. Rough edges on particles may form a type of lock and key system that interlocks neighboring particles and causes flowability problems. Small particles with higher roughness on surfaces may cause more flow problems than larger particles with smooth edges.

Flowability problems may arise due to combined or synergistic affects of influencing factors such as moisture, humidity, time of storage, fat composition, particle size and shape, compaction pressure distribution, and vibrations during transport. Additionally, the chemical composition such as unfermented or residual starch may also play a role (Bhadra 2007). Variations in the levels of these factors may also lead to flowability problems (Rosentrater 2006b). Flowability of powders and granular solids is commonly determined using procedures develop by Carr (1965) and Jenike (1964).

Even though some work has examined the physical properties of DDGS (Rosentrater 2006; Bhadra et al 2007), little work has examined the flow properties of DDGS. Therefore, the first objective of this study was to evaluate physical and flow properties, following Carr (1965) and Jenike (1964) methodologies for DDGS samples collected from several commercial fuel ethanol plants to quantify flow behavior. The Carr and Jenike procedures are two different approaches that are widely used to evaluate the flowability of bulk solids. However, the Jenike procedure is much more labor-intensive and requires much more skill than Carr testing. Thus, the second objective of this study was to examine possible correlations between the Carr and Jenike test parameters, to determine whether the Carr test could be used in lieu of the Jenike test to predict DDGS flowability.

MATERIALS AND METHODS

Sample Collection

Samples of DDGS were obtained from five commercial fuel ethanol plants across the state of South Dakota through two separate collection times. Even though there were differences in operational settings and parameters, all plants used the traditional dry-grind ethanol production process. The samples were then stored in sealed plastic bags under ambient room conditions (24 ± 1°C). Five commercial ethanol plants, with two independent batches from each, resulted in 10 total separate samples. Five replicates ($n = 5$) were measured for all physical properties and Carr tests on each sample (thus $10 \times 5 = 50$ measurements for each property). There were three levels of consolidation for Jenike testing, and these were determined using three replicates ($n = 3$) each for each sample, for each level of consolidation (thus $10 \times 3 = 30$ measurements for each property for each level of consolidation). Although chemical analysis of the DDGS samples was not the part of this study, this information is important and can be found elsewhere (Bhadra et al 2007).

Physical Properties

The soluble content of DDGS samples were determined using the technique developed by Ganesan et al (2006). The moisture content of each sample was determined using Approved Method 44-19 (AACC International 2000) using a forced convection laboratory oven (Thelco Precision, Jovan, Wincester, VA). The geometric mean diameter and geometric standard deviation of DDGS particles were determined using Standard S319.3 (ASAE/ANSI 2003) using a of Ro-tap sieve analyzer (model RX-29, Tyler Manufacturing, Mentor, OH).

Carr Index Testing

Carr index tests (1965) were used to measure the flow properties of the DDGS samples. A powder characteristics tester (model PTR, Hosokawa Micron Powder Systems, Summit, NJ) was used following the procedures described by Method D6393 (ASTM 1999). The Carr flow properties included 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. These parameters were then used to determine both the flowability index (which incorporated angle of repose, compressibility, angle of spatula, and uniformity) and floodability index (which was the sum of flowability index, angle of difference, dispersibility, and angle of fall).

Angle of repose is defined as the angle formed between the slope of a pile of material with a horizontal plane. Angle of repose of 25–35° generally indicates free-flowing substances. It can be summarized categorically as described in Table I. Bulk density is determined as the mass of granular material that will occupy a specific volume of storage space. Two categories of bulk density include aerated bulk density (or loose bulk density) and packed or (tapped) bulk density. The latter category occurs when an external force or pressure has been applied to the mass of the granular solid and it compresses, displacing the air entrapped between particles. Packed (or tapped) density is an actual representation of the bulk density of a material when it is stored in bins or transported over large distances in a rail car. Hausner ratio is defined as the ratio of tapped bulk density to the aerated (or apparent) bulk density. Values <1.25 typically indicate good flow, whereas values >1.25 generally indicate poor flow (Michael, 2001). The compressibility of a granular solid can thus be calculated as

$$C_c = 100\,(PD - AD)/PD \tag{1}$$

where PD denotes the packed bulk density (kg^3/cm); AD (kg^3/cm) denotes the aerated bulk density for the granular solid, and C_c is the Carr compressibility (%). Angle of spatula is measured by inserting a flat blade into a pile of the powder and then lifting it up. The new angle of repose that the material forms relative to the horizontal plane of the blade gives the measure of the angle of spatula. Uniformity is the ratio obtained between the width of sieve opening that will pass 60% of the sample to the width of sieve opening that will pass only 10% of the sample. Uniformity thus gives a relative measure of the homogeneity of the size and shape of the material. After the evaluation of the above properties (i.e., angle of repose through uniformity, excluding Hausner ratio), values are combined to provide an overall flowability index value for the powder or bulk solid under investigation.

The angle of fall is the new angle of repose that is formed after impaction of the material. The angle of difference is calculated by subtracting the angle of fall from the angle of repose. Dispersibility is measured by discharging a specified amount of material through a fixed column on a watch glass.

The above properties (angle of fall, angle of difference, and dispersibility, in addition to flowability index) accounted for the total floodability index of the bulk solid, which was computed by summing these individual indices. More detailed information on these properties and testing procedures can be found in Carr (1965).

Jenike Shear Testing

Jenike shear testing was performed following the procedures described in Method D6128 (ASTM 2006) to obtain the instantaneous shear behavior for each DDGS sample. The Jenike shear cell unit (model ST-5, Jenike and Johanson, Westford, MA) consisted of a base, ring, mold, twisting top, and cover. The ring was made either of stainless steel or aluminum. For level 3 consolidation, the aluminum ring was used; for level 1 and level 2 consolidation, the stainless steel rings were used. The base, ring, and mold were placed one over another, forming the shear cell. All other components were made of stainless steel. DDGS was placed in the shear cell and spread out uniformly, while scraping off excess material from the cell. The testing procedure included three steps. First, the preconditioning step, where the DDGS sample was preconsolidated by applying 30–60 twists; number of twists were determined by trial and error (Jenike 1964). The direction of twists were both clockwise and counterclockwise directions. Second was the consolidation step, where the twisting top and mold were removed and then a consolidation weight (W) (0.7 kg for level 3 consolidation, 3.0 kg for level 2, 14.5 for level 1) was applied to the arrangement. The horizontal shear force was applied in this arrangement at the rate of 2.7 mm/min. This shear force stopped once steady-state had been achieved. This second step helps in reproducing flow with the given stress at steady-state conditions (Ganesan et al 2008c). A strip chart recorder was attached to the shear cell unit and used to record the steady-state force. Third, was applying individual shear weights ($\overline{W}_i$; 0.3–9.5 kg, depending on the level of consolidation used) to the DDGS sample inside the cell. This provided a new set of steady-state force ($\overline{S}_i$) recorded on the same chart recorder. This step was used to determine the shear stress at failure for the samples. Mohr circles were then plotted for each failure using AutoCAD v.2005 (Autodesk, San Rafael, CA).

TABLE I
Flowability Classification According to Angle of Repose[a]

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. Sometimes there may be flow problems.
46-55	Poor flowability. Agitation or vibration is required.
56–65	Very poor in flowability. Needs vibration.
66–90	Extremely poor in flowability. Special agitation or hoppers are required.

[a] Adapted from Carr (1965).

TABLE II
Flow Function Classification by Shear Testing[a]

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

[a] Jenike (1964).

The angle of internal friction (ϕ in degrees) is the interparticle friction as the bulk solid tends to slide on itself at the onset of flow. Effective angle of internal friction (δ) is measured during flow when the bulk is constantly exposed to pressure. The major pressure acting on a particle element is termed σ_1 while the minor pressure is termed σ_2. The relationship between these two pressures varies very little with changes in either temperature or pressure for most bulk solids (Jenike 1964). The relationship can be expressed as

$$\frac{\sigma_1}{\sigma_2} = \frac{1 + \sin \delta}{1 - \sin \delta} \tag{2}$$

This equation is called the effective yield function; the angle (δ) is called the effective angle of internal friction. It is the measure of interparticle kinematic friction that exists during steady flow. Unconfined yield strength (σ_c) is a measure of the compressive strength (kPa) of a granular solid (Schulze 2006). Major consolidation stress (σ_1) is calculated from the point of intersection between a Mohr circle and the stress axis. Flow function is the ratio of the major consolidation stress (σ_1) to unconfined yield strength (σ_c) of a bulk solid. This can be represented as

$$F = \sigma_1/\sigma_c \tag{3}$$

where F is a dimensionless quantity; general classification categories are listed in Table II.

Jenike compressibility testing was determined using bulk density for various predetermined normal loads as described by Jenike (1964) and following Method D6683 (ASTM 2001) using a stainless steel base with 64 mm i.d. and 19.05 mm depth. The base was uniformly filled with DDGS sample and covered with the stainless steel cover. A weight hanger and indicator holder were placed on top of the cover. The indicator holder was a 25 mm travel dial indicator mounted on a stainless steel holder that had a counterbored bottom. For each of the weights placed on the hanger (0.75–39.75 kg) there was change in the indicator reading that indicated changes in the compressibility of the samples due to weight increase. The relationship between bulk density (γ, kg/m^3), net weight on the material (M, g) and height (H, mm) measured by the compressibility indicator is

$$\gamma = (0.3157\ M)/H \tag{4}$$

The compressibility (β) of the material is calculated graphically from a linear plot of normal load (kN/m^2) versus bulk density (γ, kg/m^3). The slope of the line of this plot directly gives the compressibility of the material. The compressibility testing following Jenike's procedure uses an actual application of force to determine the compressibility of a material. But that determined by the Carr procedure uses only aerated and tapped bulk densities (thus no applied load). Therefore, these compressibilities are actually unique parameters. Jenike (1964) provides a more detailed discussion.

Statistical Analyses

Formal statistical data analyses were completed for each property using Excel v.2003 (Microsoft, Redmond, WA).

SAS software v.8 (SAS Institute, Cary, NC). Analyses included summary statistics and least significant difference testing (LSD) at 95% confidence level ($\alpha = 0.05$) was performed to determine differences between the plants and also between the batches for each particular plant. Correlation analysis among all properties studied was performed to examine relationships between the properties at 95% significance ($\alpha = 0.05$) level.

RESULTS AND DISCUSSION

Physical Properties

The physical properties in Table III reveal a classification of DDGS based on particle size. Overall, the largest particles were obtained from plant 3, with an average geometric mean diameter (GMD) of 1.19 mm; while the lowest particle size was obtained from plant 2, which had an average GMD of 0.5 mm. Particle size distribution may exhibit a shifting in the bulk mass during transport or discharge. It is a phenomenon where the smaller particles may be discharged earlier from the hopper than the larger particles. Size segregation may occur in DDGS, which may lead both to uneven physical properties, as well as nutrient distribution, and may facilitate bridging between the particles due to these localized regions (Ileleji et al 2007).

Sample moisture contents were 4–9% (db). These moisture levels were nearly half of that found by Rosentrater (2006a). Our results showed the plant that had the highest moisture content (plant 5) had a low flowability index (Table IV), while the plant with the least moisture levels (plant 1) had a relatively high flowability index (Table IV). These results indicate that moisture, as expected, did play an important role in flowability behavior.

Soluble levels were 10.5–14.8% (db). As shown in Table III, plant 3 (batch 2), which had the highest GMD, showed a lower soluble content than plant 4 (batch 1), which had the highest soluble level, 14.80% (db). These soluble levels were slightly higher than the values reported by Tjardes and Wright (2002). Solubles, also known as syrup in the industry, are relatively high in fat (Buchheit 2002; Cruz et al 2005). A higher soluble level in the DDGS, which is thus higher in fat levels, would affect the surface coating on DDGS particles and may subsequently give rise to larger agglomerated particle sizes, as observed in our results. The surface nature of the DDGS (onto which the soluble layers are added during drying) may affect how the fat molecules adhere to the surfaces. Fat molecules are relatively smaller in molecular weight than protein (Das 1992); this facilitates faster penetration within the particles during drying.

There were significant statistical differences observed in the moisture content among the plants and also between the batches for a given plant. For soluble levels, however, there were no significant differences between the batches for a particular plant but there were difference among the plants. This was probably due to processing differences, and because the soluble addition process may differ plant-wise but not so much between batches at a single plant. The moisture content, on the other hand, was different among the plants and also between the batches for a particular plant. Moisture content is a much more difficult parameter to control due to environmental factors such as ambient temperature and relative humidity. The noted differences indicate inconsistent processing techniques, not only among the plants, but also in the batches for each plant.

Carr Index Properties

Angle of repose was 35.94–41.60° (Table IV). According to classification of Carr (1965), bulk solids with an angle of repose >45° will generally have very poor flow, but AoR of bulk solids at 40–45° may have some flow problems. More details on the ranges of AoR that create flow problems are described in Table I. Our AoR ranges were higher than those found in previous work with DDGS (Rosentrater 2006a) and are greater than the general range of free flowing solids (Carr 1965), but this range of AoR was slightly lower than that found by Ganesan et al (2008a,b). Thus there may be some flow problems associated with the DDGS samples under investigation. Furthermore, there was a trend of increasing AoR with increases in moisture and soluble levels (Ganesan et al 2008a,b). This indicates that, with higher moisture and soluble levels, there may be possible flow problems in the DDGS. However, in our study (Table IV), we observed highest AoR in plant 3 (40.12°) (average of both batches), which actually had lower moisture and soluble contents compared with plants 4 and 5 (Table III). AoR not only depends on the moisture and soluble content, it is also greatly influenced by particle shape and size. One reason that plant 3 had a higher AoR was the greater particle diameter. There were statistically significant differences observed among the plants. Except for plant 4, there were significant differences observed between the corresponding batches for the other plants.

There were significant differences for both types of bulk densities among the ethanol plants and also in the batches. However, only plant 1 had no significant differences for aerated bulk density (Table III). Table IV shows the highest packed bulk densities were obtained from plant 4, with an average of 0.61 g/cm^3, while

TABLE III
Physical Properties of DDGS from Commercial Ethanol Plants[a]

Plant	Batch	Geometric Mean Diameter (d_{gw}, mm)	Geometric Standard Deviation	Moisture Content (%, db)	Soluble Level (%, db)
1	1	0.83^{1}	0.48^{1}	4.32^{1} (0.65)	12.56^{1} (3.06)
	2	0.87^{1}	0.55^{1}	4.92^{1} (1.03)	12.77^{1} (2.12)
Overall mean		0.80ab (0.03)	0.52a (0.05)	4.61a (0.87)	12.56ab (3.06)
2	1	0.79^{1}	0.45^{1}	4.60^{1} (0.88)	11.03^{1} (1.82)
	2	0.21^{2}	0.30^{1}	5.36^{1} (1.25)	13.73^{1} (2.59)
Overall mean		0.50b (0.41)	0.38a (0.12)	4.98a (1.10)	12.34b (2.55)
3	1	1.00^{1}	0.45^{1}	5.84^{1} (1.32)	10.58^{1} (1.29)
	2	1.38^{2}	0.49^{1}	5.38^{2} (1.66)	13.38^{1} (1.16)
Overall mean		1.19a (0.27)	0.47a (0.03)	5.61a (1.44)	11.98b (1.88)
4	1	0.80^{1}	0.20^{1}	6.42^{1} (0.35)	14.80^{1} (2.82)
	2	0.81^{1}	0.53^{1}	8.83^{1} (2.54)	14.32^{1} (2.55)
Overall mean		0.81ab (0.01)	0.37a (0.23)	7.63a (2.13)	14.59a (2.55)
5	1	0.68^{1}	0.47^{1}	7.26^{1} (0.433)	12.26^{1} (1.82)
	2	0.97^{2}	0.54^{1}	8.89^{1} (3.18)	11.26^{1} (1.40)
Overall mean		0.83ab (0.21)	0.51a (0.05)	8.08a (2.31)	11.41b (1.54)

[a] Values in parentheses are standard deviations. Values for a given dependent variable followed by the same letter are not significantly different ($P < 0.05$) among the plants. Values for a given dependent variable followed by the same superscript number are not significantly different ($P < 0.05$) between the batches in a plant ($P < 0.05$). For each plant (each batch), $n = 5$.

the lowest packed bulk densities were obtained from plant 5, with an average of 0.48 g/cm^3. These results are very close to results of aerated and packed bulk densities from Ganesan et al (2008a) for DDGS with 10% moisture and 10% soluble levels. Plant 4, which had soluble levels of 14.59% (db), also had the highest packed bulk density (0.61 g/cm^3). This result was very similar, as predicted by Ganesan et al (2008a) for 15% (db) soluble levels.

We obtained compressibility values of 2.88–7.86%. The highest compressibility was observed in plant 1, with an overall average value from both batches of 7.56%. The higher the compressibility, the greater the tendency of that material to have flow problems. Materials with compressibility values >25% were less flowable (Carr 1965). These compressibility values were somewhat higher than the values obtained by Ganesan et al (2008a) for all the types of moisture and soluble conditions used in that particular study. Table IV also shows that there were significant differences among the plants. There were differences only between the batches of plant 4, but not between the batches of the other plants. Reasons for this result could be that compressibility is primarily dependent on particles sizes. As shown in Tables III and IV, particle sizes varied less between the batches for a particular plant and more among the plants, as it depends on milling specifications and processing parameters of each plant. More details on variations between batches for each plant can be found in Bhadra et al (2007).

Angle of spatula (average) range was 51.72–66.73° (Table IV). These results were slightly higher than those values from Ganesan et al (2008a) for all soluble and moisture levels. Materials with angle of spatula of <61° are generally considered to be passable or borderline materials (Carr 1965) in terms of flowability; whereas <60°should have no flow problems. For our samples, plant 2 had higher angle of spatula values compared with the other plants. There were significant differences observed among the plants, as well between the batches, for all values of angle of spatula.

The highest uniformity was found in plant 2 with a value of 2.80 (-). According to Carr (1965) classification, uniformity values <6 (-) are generally considered to have excellent flowability.

The total flowability index obtained was 79.30–82.40. The higher the flowability index, the better the material is in terms of flowability. This range of flowability index was slightly higher than the values found by Ganesan et al (2008a). This range of flowability indices for our samples mostly shows good flowability in DDGS, but sometimes a vibrator or bin agitator may be re-

TABLE IV
Carr Index Properties of DDGS from Commercial Ethanol Plants[a]

	Batch 1			Batch 2			Batch 3		
Properties	**1**	**2**	**Overall Mean**	**1**	**2**	**Overall Mean**	**1**	**2**	**Overall Mean**
AoR (°)	35.94^{2} (1.37)	40.62^{1} (0.34)	38.28b (2.64)	37.76^{2} (0.74)	41.60^{1} (1.41)	39.68a (2.22)	39.48^{2} (0.64)	40.76^{1} (0.85)	40.12a (0.98)
ABD (g/cm^3)	0.49^{1} (0.01)	0.51^{1} (0.01)	0.50c (0.01)	0.54^{2} (0.02)	0.59^{1} (0.03)	0.57ab (0.04)	0.55^{1} (0.01)	0.54^{2} (0.00)	0.55b (0.01)
PBD (g/cm^3)	0.54^{2} (0.01)	0.55^{1} (0.01)	0.54c (0.01)	0.56^{2} (0.00)	0.61^{1} (0.03)	0.59ab (0.04)	0.58^{1} (0.01)	0.56^{2} (0.01)	0.57b (0.01)
Hausner Ratio (-)	1.09^{1} (0.03)	1.08^{1} (0.00)	1.08b (0.02)	1.04^{1} (0.04)	1.03^{1} (0.01)	1.04a (0.02)	1.04^{1} (0.01)	1.04^{1} (0.02)	1.04a (0.01)
C$_c$ (%)[b]	7.86^{1} (2.09)	7.29^{1} (0.01)	7.56a (1.43)	3.60^{1} (3.16)	3.27^{1} (1.10)	3.44c (2.24)	3.81^{1} (0.71)	3.91^{1} (1.43)	3.86bc (1.07)
AoS (before) (°)	58.02^{2} (1.53)	50.72^{1} (2.90)	54.37a (4.43)	64.40^{1} (1.35)	60.44^{2} (2.39)	62.42a (2.78)	60.48^{2} (0.36)	64.54^{1} (3.51)	62.51a (3.18)
AoS (after) (°)	55.02^{2} (1.54)	58.72^{1} (2.72)	56.87a (2.85)	59.74^{1} (3.99)	58.80^{1} (0.89)	59.30a (2.77	64.70^{1} (2.22)	52.12^{2} (1.58)	58.41a (6.88)
AoS (average) (°)	56.72^{1} (0.35)	51.72^{2} (1.43)	54.22c (2.81)	66.73^{1} (3.04)	59.67^{2} (1.47)	63.20a (4.35)	62.89^{1} (0.85)	58.30^{2} (2.04)	60.60b (2.38)
Uniformity (-)	2.00^{1} (0.00)	2.80^{1} (0.00)	2.40b (0.42)	2.80^{1} (0.00)	2.80^{1} (0.00)	2.80a (0.00)	2.30^{1} (0.00)	1.20^{2} (0.00)	1.75c (0.58)
Total flowability index(-)	81.40^{1} (0.89)	81.00^{1} (0.00)	81.20a (0.63)	82.40^{1} (0.96)	80.80^{2} (0.84)	81.60a (1.20)	80.80^{2} (0.84)	82.10^{1} (1.14)	81.45a (1.17)
Angle of fall (°)	33.36^{2} (0.98)	38.26^{1} (0.88)	35.81a (2.73)	31.84^{2} (1.00)	35.28^{1} (1.54)	33.56b (2.19)	32.04^{2} (1.26)	39.98^{1} (1.16)	36.01a (4.34)
Angle of difference (°)	2.38^{1} (0.76)	2.56^{1} (0.70)	2.47c (0.70)	5.92^{1} (0.89)	6.40^{1} (1.88)	6.16a (1.41)	7.44^{1} (0.97)	0.88^{2} (0.52)	4.16bc (3.53)
Dispersibility (%)	40.92^{1} (4.58)	37.78^{1} (2.97)	39.35b (4.00)	45.17^{1} (4.50)	55.53^{2} (2.50)	50.35a (3.50)	51.40^{1} (2.46)	38.04^{2} (3.11)	44.59a (7.39)
Flowability index (-)	25.00^{1} (0.00)	25.00^{1} (0.00)	25.00a (0.00)	25.00^{1} (0.00)	25.00^{1} (0.00)	25.00a (0.00)	25.00^{1} (0.00)	25.00^{1} (0.00)	25.00a (0.00)
Total floodability index (-)	63.60^{1} (3.78)	63.4^{1} (3.13)	63.50a (3.27)	53.25^{2} (0.64)	57.45^{1} (1.84)	55.35b (2.57)	70.20^{1} (0.45)	60.70^{1} (2.41)	65.27a (5.27)

[a] Values in parentheses are standard deviations. Values for a given dependent variable followed by the same letter are not significantly different ($P < 0.05$) among the plants. Values for a given dependent variable followed by the same superscript number are not significantly different ($P < 0.05$) between the batches in a plant ($P < 0.05$). For each plant (each batch), $n = 5$.

[b] Compressibility by Carr (1965) test procedure.

TABLE IV (*continued*)
Carr Index Properties of DDGS from Commercial Ethanol Plants[a]

	Batch 4			Batch 5		
Properties	**1**	**2**	**Overall Mean**	**1**	**2**	**Overall Mean**
AoR (°)	37.26^{1} (1.04)	38.98^{1} (1.28)	38.12b (1.43)	39.82^{1} (1.41)	38.72^{2} (1.04)	39.27ab (1.31)
ABD (g/cm^3)	0.60^{1} (0.01)	0.55^{2} (0.02)	0.58a (0.03)	0.47^{1} (0.01)	0.44^{2} (0.01)	0.46d (0.48)
PBD (g/cm^3)	0.62^{1} (0.01)	0.59^{2} (0.02)	0.61a (0.02)	0.50^{1} (0.01)	0.47^{2} (0.00)	0.48d (0.01)
Hausner ratio (-)	1.03^{1} (0.01)	1.08^{2} (0.01)	1.06a (0.03)	1.05^{1} (0.01)	1.06^{1} (0.01)	1.05a (0.01)
C$_c$ (%)[b]	2.88^{2} (1.31)	7.46^{1} (0.90)	5.17b (2.64)	4.85^{1} (1.66)	5.53^{1} (1.17)	5.19b (1.15)
AoS (before) (°)	63.40^{1} (2.76)	60.12^{2} (3.79)	61.76a (3.57)	60.68^{1} (3.37)	60.80^{1} (1.22)	60.74a (2.39)
AoS (after) (°)	60.74^{1} (3.37)	55.54^{2} (2.71)	58.14a (3.98)	56.58^{1} (4.54)	57.58^{1} (2.50)	57.08a (3.50)
AoS (average) (°)	62.01^{1} (3.10)	57.81^{2} (1.49)	59.91b (3.18)	58.77^{1} (1.83)	59.22^{1} (1.66)	59.00b (1.66)
Uniformity (-)	2.80^{1} (0.00)	2.80^{1} (0.00)	2.80a (0.00)	2.00^{2} (0.00)	2.40^{1} (0.00)	2.20b (0.21)
Total flowability index(-)	82.00^{1} (0.71)	79.40^{2} (1.29)	80.70ab (1.69)	79.80^{1} (0.76)	79.30^{1} (0.45)	79.55b (0.64)
Angle of fall (°)	31.40^{2} (1.29)	33.94^{1} (0.79)	32.56b (1.59)	36.00^{1} (0.43)	34.74^{2} (1.42)	35.37a (1.19)
Angle of difference (°)	5.86^{1} (0.89)	5.04^{1} (0.67)	5.45ab (0.86)	4.18^{1} (1.66)	3.98^{1} (1.02)	4.08bc (1.30)
Dispersibility (%)	48.20^{1} (2.80)	36.40^{2} (3.15)	42.30ab (2.50)	42.80^{2} (2.00)	38.18^{1} (3.89)	40.24b (15.79)
Flowability index (-)	25.00^{1} (0.00)	25.00^{1} (0.00)	25.00a (0.00)	25.00^{1} (0.00)	25.00^{1} (0.00)	25.00a (0.00)
Total floodability index (-)	70.20^{1} (1.15)	62.10^{2} (0.65)	66.15a (4.36)	48.60^{2} (1.52)	64.60^{1} (1.52)	56.85b (8.55)

[a] Values in parentheses are standard deviations. Values for a given dependent variable followed by the same letter are not significantly different ($P < 0.05$) among the plants. Values for a given dependent variable followed by the same superscript number are not significantly different ($P < 0.05$) between the batches in a plant ($P < 0.05$). For each plant (each batch), $n = 5$.

[b] Compressibility by Carr (1965) test procedure.

quired to increase the flowability. There were significant differences among plants, as well the batches, indicating inconsistent DDGS products in terms of flowability.

The angle of fall for the samples in this study was <37° (approximately). This lies in a range of values categorized as floodable materials (Carr 1965). Floodable means materials will flow sporadically and abruptly. This nature in powders or granular solids is not considered good for flowability. This range of values was slightly less than the values obtained by Ganesan et al (2008a) for all combinations of solubles and moisture levels. This was quite logical, as our solubles and moisture levels were less than those levels used by Ganesan et al (2008a). Solubles and moisture levels do effect floodability; higher soluble and moisture may, in fact, act to lubricate the DDGS and thus have a higher floodable character in DDGS.

Table IV shows a wide range of dispersibility values .The lowest dispersibility was obtained for plant 2 (7.22%), while the highest value was found in plant 3 (51.4%). For plants 2 and 5, the samples fell under the category of fairly floodable. For plant 3, on the other hand, DDGS was very floodable. Typically, the higher the value of dispersibility, the greater the tendency of that material to flush.

The sum of flow index, angle of fall, angle of difference, and dispersibility gives the floodability index, which characterizes the nature of the material in terms of its ability to flush. A floodability index value >60 (-) would require rotary seals or some other type of preventive measures to stop flushing of DDGS (Carr 1965). Plant 3 showed the highest floodability index (65.27), while plant 2 (55.35) showed the lowest floodability index.

This range of floodability index was slightly higher than found by Ganesan et al (2008a) for all combinations of soluble and moisture contents, which indicate that our samples had a higher flushing nature, which may, in fact, affect flow and handling properties.

TABLE V
Jenike Shear Testing Properties of DDGS from Commercial Ethanol Plants[a]

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 1 consolidation					
1	1	52.33^{1} (2.52)	39.67^{1} (1.53)	6.86^{1} (1.73)	31.31^{1} (3.62)
	2	45.00^{2} (2.00)	39.00^{1} (2.00)	3.23^{2} (0.30)	17.75^{2} (1.04)
Overall mean		48.67bc (4.50)	39.33ab (1.63)	5.05c (2.28)	24.53a (7.80)
2	1	53.00^{1} (1.00)	32.67^{2} (2.08)	18.00^{1} (1.98)	25.77^{2} (0.73)
	2	57.00^{1} (2.65)	39.00^{1} (1.73)	15.49^{1} (2.10)	27.77^{1} (0.77)
Overall mean		55.00a (2.83)	35.83ab (3.87)	16.74a (2.29)	26.77a (1.28)
3	1	51.00^{1} (1.00)	47.00^{1} (3.61)	4.78^{1} (1.37)	26.62^{1} (2.90)
	2	49.33^{1} (2.08)	33.00^{2} (1.73)	4.98^{1} (1.34)	22.65^{1} (2.71)
Overall mean		50.17b (1.72)	40.00a (8.07)	4.88c (1.22)	24.64a (3.32)
4	1	42.33^{1} (1.15)	35.00^{1} (2.65)	8.21^{1} (1.15)	28.48^{1} (1.09)
	2	47.33^{1} (2.52)	32.33^{1} (3.06)	8.69^{1} (1.99)	28.38^{1} (3.31)
Overall mean		44.83c (3.25)	33.67b (2.94)	8.45b (1.48)	28.43a (2.21)
5	1	43.00^{2} (1.73)	32.67^{2} (0.58)	8.69^{1} (0.54)	28.50^{1} (0.70)
	2	53.00^{1} (1.00)	43.33^{1} (2.89)	8.61^{1} (2.40)	26.42^{1} (2.50)
Overall mean		48.00bc (5.62)	38.00ab (6.13)	8.65b (1.56)	27.46a (2.00)
Level 2 consolidation					
1	1	57.33^{1} (2.52)	32.67^{2} (4.51)	2.19^{2} (0.54)	4.93^{2} (0.13)
	2	49.67^{2} (2.52)	39.00^{1} (3.61)	3.55^{1} (0.30)	8.77^{1} (0.23)
Overall mean		53.50bc (4.76)	35.83b (5.04)	2.87bc (0.84)	6.85b (2.11)
2	1	59.33^{1} (2.08)	46.00^{1} (2.65)	6.54^{1} (0.36)	9.51^{1} (1.07)
	2	58.67^{1} (2.52)	38.33^{2} (2.89)	6.56^{1} (0.66)	10.40^{1} (1.19)
Overall mean		59a (2.10)	42.17a (4.88)	6.55a (0.47)	9.96a (1.12)
3	1	55.33^{1} (1.53)	42.67^{1} (0.58)	1.52^{1} (0.78)	8.65^{1} (2.21)
	2	49.67^{2} (0.58)	44.00^{1} (1.00)	1.64^{1} (0.36)	7.92^{1} (1.57)
Overall mean		52.50c (3.27)	43.33a (1.03)	1.58d (0.55)	8.28b (1.76)
4	1	50.67^{1} (1.53)	38.00^{1} (3.61)	2.32^{1} (0.71)	5.87^{2} (0.12)
	2	53.67^{1} (2.52)	46.00^{1} (1.00)	1.85^{1} (1.36)	8.09^{1} (2.34)
Overall mean		52.17c (2.48)	42.00a (4.98)	2.08c (1.01)	6.98b (1.92)
5	1	57.33^{1} (2.08)	43.67^{1} (2.89)	3.44^{1} (0.72)	7.49^{1} (0.33)
	2	55.33^{1} (2.89)	45.00^{1} (2.65)	4.03^{1} (0.52)	7.66^{1} (0.38)
Overall mean		56.33b (2.50)	44.33a (2.58)	3.74b (0.64)	7.57b (0.33)
Level 3 consolidation					
1	1	58.33^{1} (1.53)	40.67^{1} (4.73)	0.90^{1} (0.22)	1.48^{1} (0.18)
	2	57.67^{1} (2.08)	40.67^{1} (4.04)	1.14^{1} (0.17)	1.57^{1} (0.06)
Overall mean		58.0a (1.67)	40.67b (3.93)	1.02a (0.22)	1.53a (0.13)
2	1	57.33^{1} (1.53)	48.67^{1} (3.21)	0.71^{1} (0.20)	1.74^{1} (0.20)
	2	59.00^{1} (3.61)	37.67^{2} (2.52)	1.19^{1} (0.29)	2.24^{1} (0.46)
Overall mean		58.17a (2.64)	43.17b (6.55)	0.95ab (0.35)	1.99a (0.42)
3	1	53.67^{1} (1.53)	37.00^{1} (1.00)	1.24^{1} (0.07)	1.69^{1} (0.11)
	2	56.00^{1} (2.65)	25.00^{2} (2.00)	0.97^{1} (0.72)	2.95^{1} (1.25)
Overall mean		54.83b (2.32)	31.00c (6.72)	1.11ab (0.48)	2.32a (1.05)
4	1	48.33^{2} (2.08)	40.00^{1} (2.00)	0.45^{1} (0.03)	1.86^{1} (0.14)
	2	54.67^{1} (2.08)	42.33^{1} (0.58)	0.44^{1} (0.12)	1.83^{1} (0.24)
Overall mean		51.50c (3.94)	41.17b (1.83)	0.45b (0.08)	1.85a (0.18)
5	1	59.33^{1} (1.53)	50.00^{1} (3.00)	0.66^{1} (0.23)	1.63^{2} (0.05)
	2	61.00^{1} (1.73)	54.33^{1} (3.21)	0.75^{1} (0.11)	1.95^{1} (0.07)
Overall mean		60.17a (1.72)	52.17a (3.66)	0.71b (0.17)	1.79a (0.18)

[a] Values in parentheses are standard deviations. Values for a given dependent variable followed by the same letter are not significantly different ($P < 0.05$) among the plants. Values for a given dependent variable followed by the same superscript number are not significantly different ($P < 0.05$) between the batches in a plant ($P < 0.05$). For each plant (each batch), $n = 5$.

As shown in Table V, we observed a clear trend in the effective angle of friction (δ, °) with an increase in the pressure from level 3 consolidation to level 1 consolidation (highest pressure). For level 1 consolidation, the effective angle of friction (δ) was in the range of 43.00° (plant 5) to 57.00° (plant 2). Level 2 consolidation range was 50.67° (plant 4) to 59.33° (plant 2). Level 3 consolidation range was 48.33° (plant 4) to 61.00° (plant 5).

These ranges of values were somewhat higher than those of Ganesan et al (2008c). Typically, the higher the values of effective angle of friction, the greater the chances of having flow problems (Jenike 1964). Additionally, there were significant differences obtained in the Jenike shear parameters among the plants, as well as between the batches of particular plants. Increased variability further indicated an increased chance of finding DDGS samples with higher flow problems.

From Table V, we note that angle of internal friction (Φ) was 32.33°(plant 4) to 47.00° (plant 3) for level 1 consolidation; from 32.67° (plant 1) to 45.00° (plant 5) for level 2 consolidation; and from 25.00° (plant 3) to 54.33° (plant 5) for level 3 consolidation. These ranges of angle of internal friction for each level of consolidation were quite similar to those found Ganesan et al (2008c). For this study, the highest values were found in plant 5 (8.08%, db moisture content and 11.41%, db soluble levels) for level 3 consolidation. This was higher than the highest angle of internal friction found by Ganesan et al (2008c) that occurred at 15% soluble and 10% moisture content.

For major consolidating stress (σ_1), the highest value was found for plant 4 (28.48 kPa), while the lowest value was obtained for plant 1 (17.75 kPa) (Table V). The highest mean value of major consolidation stress was less than that found by Ganesan et al (2008c). To break an arch, the maximum stress must be higher than the yield strength in the granular solid ($\sigma_1 > \sigma_c$) (Jenike 1964). A similar kind of relationship was observed in our DDGS samples, which indicates that there may not be any flow problems with our samples.

We also observed that for level one consolidation, the lowest mean unconfined yield strength (σ_c) was found in plant 3 (4.78 kPa), while the highest mean value was found in plant 2 (18.00 kPa) (Table V). This indicates that our DDGS samples may have some flow difficulties, as only purely noncohesive solids (like sand) will have yield strength values of zero (Jenike 1954). The highest mean value obtained in our results was very similar to that obtained by Ganesan et al (2008c) for 25% (db) soluble and 10% (db) moisture levels.

The compressibility for each sample was calculated from the plot of bulk density and the applied pressure (Fig. 1). A summary of compressibility (β, cm^{-1}) values for our DDGS samples, and the resulting linear regression equations between bulk density (γ, kg/m^3) and normal load (kN/m^2) are provided in Table VI. The highest compressibility was found in plant 2 (22.30 cm^{-1}). Often, the more the compressible the material, the more difficult it will flow.

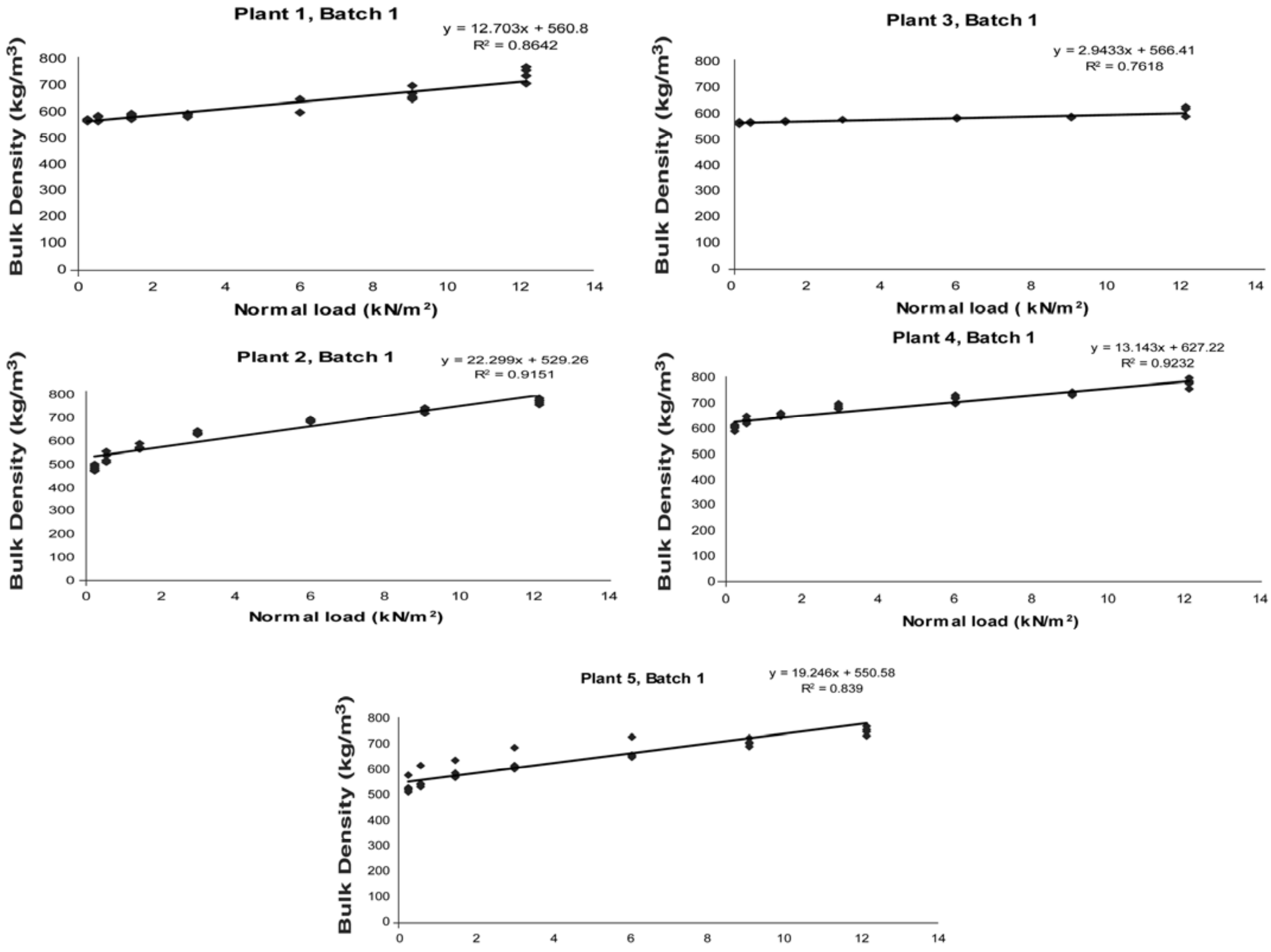

Fig. 1. Compressibility of DDGS from commercial ethanol plants (*n* = 5 for each plant in batch 1).

Flow functions for each DDGS sample were then calculated from Jenike (1954) shear test results (Table VII). There was not a single DDGS sample that showed a flow function <1.0 (which would mean no flow). At level one consolidation, flow function values for plant 2, plant 5, and plant 4 indicated that the DDGS was cohesive or highly cohesive, while plant 1, batch 2 had almost free flow (Jenike 1964). It should be noted that plant 5 showed the lowest flowability index from the Carr test procedure; which means it may indeed have potential flow problems compared with all other samples. It should also be noted that trends in the flow function values across all consolidation levels varied among plants, and batches within a given plant, which reinforces the point that variability in DDGS may have a strong role in flowability problems.

Property Relationships

Pearson product moment correlation analysis (Speigel 1994) was performed for all the properties in the study (3, 4, 5, and 6). The correlation coefficient determines how closely the two properties are related to each other in a linear fashion. Out of 1,089 possible combinations, only 48 of these had significant correlations ($P < 0.05$) and had correlation coefficient (r) values >0.5 (in absolute value). Out of these 48, 17 variable combinations had an $r = 0.5–0.6$, 21 variable combinations had correlation coefficients of 0.6–0.7, seven combinations had $r = 0.7–0.8$ and only three had $r = 0.8–1.0$. The 10 combinations with $r = 0.7–1.0$ are given in Table VIII and an examination of them provides several insights. Hausner ratio had a high correlation with Carr compressibility (C_c), which was anticipated because Hausner ratio consists of tapped density and aerated density, which are measurements that are also used to calculate C_c. The higher the tapped density value compared with aerated bulk density indicates a higher propensity for the particles to compact, which in turn is a function of the DDGS particle shapes and sizes. Floodability index was very highly correlated to the dispersibility. This is also very reasonable because dispersibility was part of the calculation that determined floodability index (Carr 1965). However, the results of having a higher correlation of dispersibility with total floodability index may predict that dispersibility is the key property to consider when examining the overall DDGS flowability.

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 indicate higher compactness of the particles and, hence, a lower angle of friction between the particles. Unconfined yield stress did show significant correlations between total floodability and dispersibility. Major consolidation stress between various consolidation levels did have some correlation as well. This was quite reasonable, as one level of consolidation differs from other levels only in terms of load addition, but the testing procedures are the same. Geometric standard

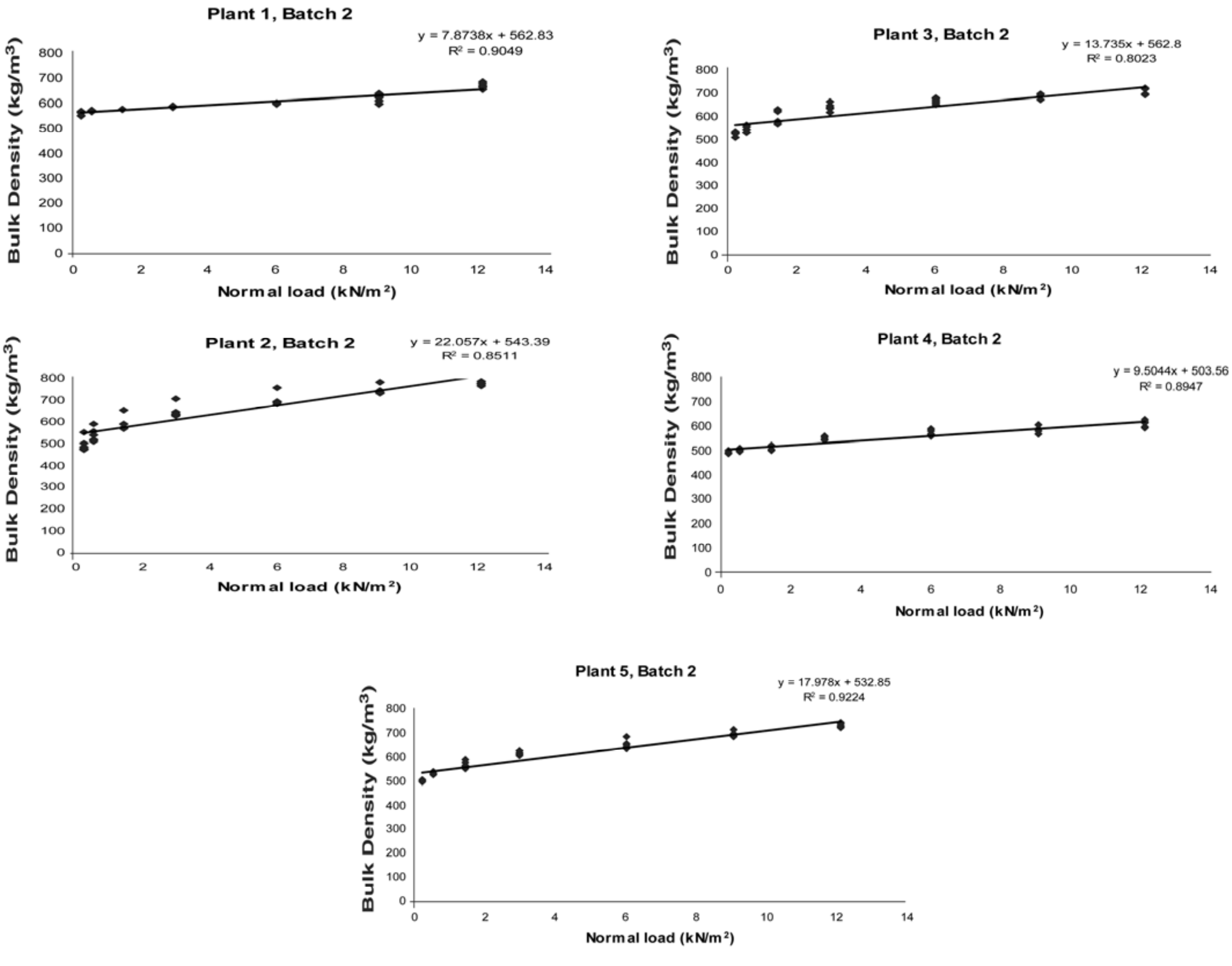

Fig. 1. ***(continued)*** Compressibility of DDGS from commercial ethanol plants ($n = 5$ for each plant in batch 2).

TABLE VI
Jenike Compressibility of DDGS Samples from Commercial Ethanol Plants[a,b]

Plant	Batch	Regression Equation	Compressibility (β, cm^{-1})
1	1	$y = 12.703\,x + 560.80$, $R^2 = 0.8642$	12.70^1 (0.02)
	2	$y = 7.8738\,x + 562.83$, $R^2 = 0.9049$	7.87^2 (0.09)
	Overall (β)		10.29b (0.05)
2	1	$y = 22.299\,x + 529.26$, $R^2 = 0.9151$	22.30^1 (0.01)
	2	$y = 22.057\,x + 543.39$, $R^2 = 0.8511$	22.06^1 (0.02)
	Overall (β)		22.18a (0.02)
3	1	$y = 2.9433\,x + 566.41$, $R^2 = 0.7618$	2.94^1 (0.01)
	2	$y = 13.735\,x + 562.8$, $R^2 = 0.8023$	13.73^2 (0.02)
	Overall (β)		8.34b (0.06)
4	1	$y = 13.143\,x + 627.22$, $R^2 = 0.9232$	13.14^1 (0.0009)
	2	$y = 9.504\,x + 503.66$, $R^2 = 0.8947$	9.50^2 (0.08)
	Overall (β)		11.32b (0.02)
5	1	$y = 17.978\,x + 532.85$, $R^2 = 0.9224$	17.98^1 (0.02)
	2	$y = 19.246\,x + 550.58$, $R^2 = 0.839$	19.25^1 (0.05)
	Overall (β)		18.62ab (0.02)

[a] Values in parentheses are standard deviations. Values for compressibility followed by the same letter are not significantly different ($P < 0.05$) among the plants. Values for compressibility followed by the same superscript number are not significantly different ($P < 0.05$) between the batches in a plant ($P < 0.05$). For each plant (each batch), $n = 5$.

[b] y, Bulk density (γ) (kg/m^3); x, normal load (kN/m^2).

TABLE VII
Jenike Flow Functions (F) for DDGS Samples from Commercial Ethanol Plants[a]

		Consolidation		
Plant	Batch	Level 1	Level 2	Level 3
1	1	4.56^2	2.25^2	1.64^1
	2	5.35^1	2.47^1	1.38^2
	Overall mean	4.96b (0.56)	2.36c (0.16)	1.51d (0.18)
2	1	1.43^2	1.45^1	2.45^1
	2	1.79^1	1.59^1	1.88^2
	Overall mean	1.61e (0.25)	1.52e (0.10)	2.17c (0.40)
3	1	5.57^1	5.69^1	1.36^2
	2	4.55^2	4.83^2	3.04^1
	Overall mean	5.06a (0.72)	5.26a (0.61)	2.20c (1.19)
4	1	3.47^1	2.53^2	4.13^1
	2	3.27^1	4.37^1	4.16^1
	Overall mean	3.37cd (0.14)	3.45b (1.30)	4.15a (0.02)
5	1	3.28^1	2.18^1	2.47^1
	2	3.07^2	1.90^2	2.60^1
	Overall mean	3.18d (0.15)	2.04d (0.20)	2.54b (0.09)

[a] Values in parentheses are standard deviations. Values for a given consolidation level followed by the same letter are not significantly different ($P < 0.05$) among the plants. Values for a given consolidation level followed by the same superscript number are not significantly different ($P < 0.05$) between the batches in a plant ($P < 0.05$). For each plant (each batch), $n = 5$.

TABLE VIII
Significant Pearson Linear Correlation Coefficients (r) Between Physical, Carr, and Jenike Shear Test Properties[a]

Property Relationship	r Value	P Value
Hausner ratio × C_c	–0.9648	<0.0001
β × geometric mean diameter	–0.7631	0.01
Angle of difference × angle of fall	–0.7127	<0.0001
Hausner ratio × geometric standard deviation	–0.7074	0.0221
Geometric standard deviation × aerated bulk density	–0.7035	0.0232
Geometric standard deviation × C_c	0.7104	0.0213
Angle of spatula (before impact) × angle of spatula (avg)	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

[a] β is Jenike compressibility; C_c is Carr compressibility; ($\alpha = 0.05$).

deviation and GSD also had good correlation with compressibility (Jenike) and Hausner ratio. These indicate that particle shapes and sizes do play an important role in determining flowability parameters. Overall, correlation results indicate that there were not very strong correlations among many of the properties, and thus one set of experiments (Jenike vs. Carr testing) cannot really take the place of the other set when examining flowability behavior. In terms of labor input, skills required, time, and repeatability of the experimental procedure, Jenike shear testing is more complicated than the Carr testing procedure. A strong correlation among the two procedures would help to indentify the best possible experimental procedure to assess DDGS flowability.

Overall Flowability Assessment and Implications

Ganesan et al (2007b) developed an empirical predictive model for DDGS flowability based on both Jenike and Carr test data simultaneously and used it as a flowability indicator. The relationship that best described the data can be functionally written as

$$(C_c/\text{dispersibility})(\delta/\Phi) = f\,(\text{PBD/ABD}) \qquad (5)$$

where C_c represents Carr compressibility, δ represents effective angle of friction, and Φ represents angle of internal friction. Lower values of PBD/ABD typically indicate good flow in DDGS (Ganesan et al 2007b). Data obtained for our commercial samples were fitted using this relationship (Fig. 2), which yielded an $R^2 = 0.8368$ for a nonlinear curve. However, we found a higher R^2 (0.8823) using a linear relationship. The range of PBD/ABD was higher in our data compared with Ganesan et al (2007b) and actually falls in a bad or potentially problematic flow region. Thus the overall flowability assessment indicates that some of our DDGS samples may have the potential for flow problems but unfortunately the flowability analysis is not conclusive.

Our results indicate that follow-up studies are required to further validate our model as a prediction tool to evaluate potential DDGS flowability problems. Additionally, research should be pursued that examines the effects of particle size, shape, surface coating of CDS, composition, and the simultaneous influence on flowability. Moreover, studies using commercial DDGS samples obtained both with and without flow problems could help provide a better understanding of the specific origin of these problems in DDGS.

CONCLUSIONS

Samples of DDGS from commercial fuel ethanol plants were analyzed for physical and flowability properties. None of the samples studied exhibited completely poor flow behavior, although many did show a propensity for potential problems. Flowability of DDGS was judged based on both Carr and Jenike analyses. Both approaches are useful in determining flow problems in granular solids but it is paradoxical in terms of deciding which set of experimental procedures is optimal for flowability assessment. One can predict lower flowability, while the other may suggest higher flow tendencies for the same samples. Moreover, low correlation coefficients among the Carr and Jenike pa-

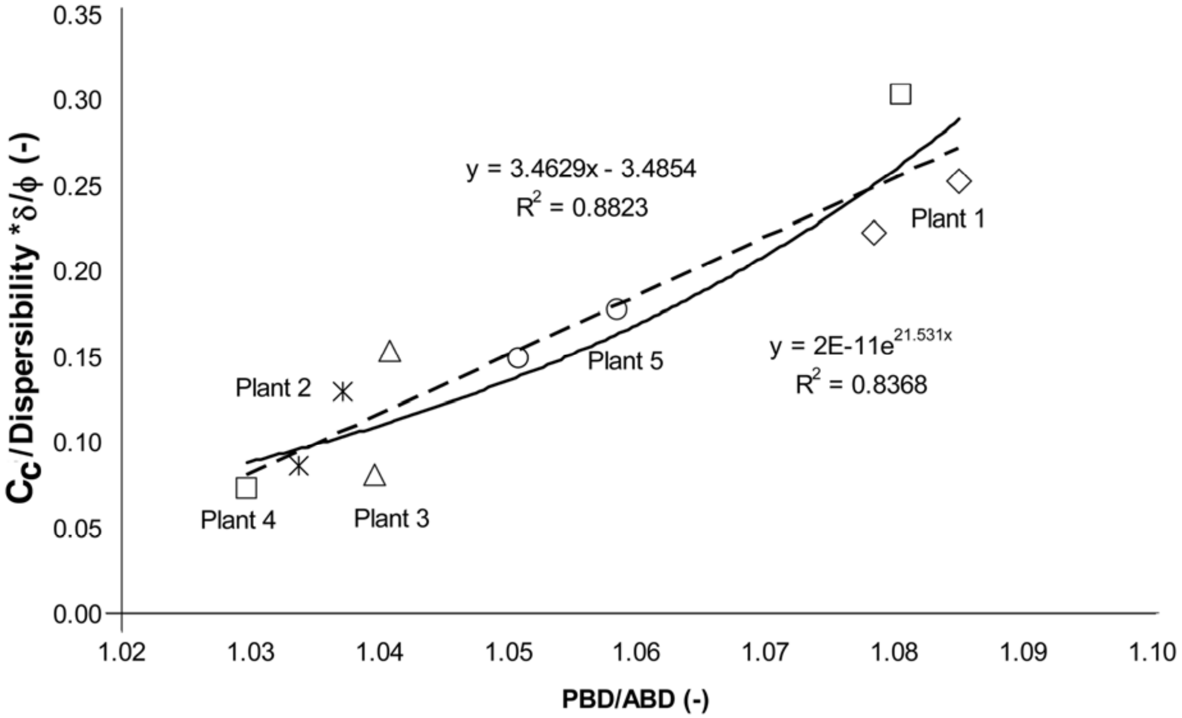

Fig. 2. Flowability indicator level, following the relationships developed by Ganesan et al (2007a).

rameters suggests that one set of experiments can not be totally replaced by the other. Operator choice, experimental design, and sample to be tested are needed for deciding which set of parameters one should measure to quantify flowability. The Jenike shear test procedure depicts real industrial storage and handling situations, but on the other hand, Carr properties are used widely for pharmaceutical powders and are much less time-consuming to measure. Added to this, inconsistencies in DDGS between samples and among plants may hinder the possibility of finding adequate correlations between two experimental procedures. In short, flowability is a multivariate field where more research is necessary to totally understand the mechanisms at play in DDGS.

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