June, 2007

Flow Properties Of DDGS with Varying Soluble and Moisture Contents Using Jenike Shear Testing

Vykundeshwari Ganesan, *South Dakota State University*
Kasiviswanathan Muthukumarappan, *South Dakota State University*
Kurt A. Rosentrater, *United States Department of Agriculture*

An ASABE Meeting Presentation

Paper Number: 076063

Flow Properties Of DDGS with Varying Soluble and Moisture Contents Using Jenike Shear Testing

V. Ganesan, Graduate Research Assistant

South Dakota State University, Department of Agricultural and Biosystems Engineering, Brookings 57007, SD. vyku.ganesan@sdstate.edu

K. Muthukumarappan, Professor

South Dakota State University, Department of Agricultural and Biosystems Engineering, Brookings 57007, SD. muthukum@sdstate.edu

Kurt A. Rosentrater, Scientist

NCARL, USDA-ARS, Brookings 57006, SD. krosentr@ngirl.ars.usda.gov

Written for presentation at the
2007 ASABE Annual International Meeting
Sponsored by ASABE
Minneapolis Convention Center
Minneapolis, Minnesota
17 - 20 June 2007

Abstract. *Distillers dried grains with solubles (DDGS) are an excellent source of energy, minerals, and bypass protein for ruminants and are used in monogastric rations as well. With the remarkable growth of the US fuel ethanol industry in the past decade, large quantities of distillers grains are now being produced. Flow of DDGS is often restricted by caking and bridging during its storage and transportation. In our previous works, the Carr powder tester was used to measure various flow properties of DDGS. The objective of this study was to measure the flow properties (cohesion, effective angle of friction, internal angle of friction, yield locus, flow function, major consolidating stress, and unconfined yield strength) of DDGS using the Jenike shear tester. This work investigated the influence of four levels of solubles (10, 15, 20, and 25% db) and five levels of moisture content (10, 15, 20, 25, and 30% db) on the resulting flow properties of DDGS. With an increase in soluble levels, the flow function curves of DDGS shift in an anticlockwise direction towards the shear stress (σ_c) axis. Depending on the soluble level, above certain moisture contents, the moisture actually began acting as a lubricant, easing the flow of the DDGS. Also, with higher solubles and moisture levels, the* *compressibility of DDGS was found to increase. Overall, the DDGS was classified as a cohesive material, and it is likely to produce cohesive arching problems.*

Keywords. *Compressibility, DDGS, Flow function, Flow index, Jenike shear test, Major consolidation stress, Mohr circle, Unconfined yield strength.*

Introduction

Distillers dried grain with solubles (DDGS) is one of the coproducts obtained from the yeast fermentation of corn for the production of ethanol. DDGS usually contains about 86 to 93% (db) dry matter, 26 to 34% (db) crude protein, and 3 to 13% (db) fat (Tjardes and Wright, 2002; Rosentrater and Muthukumarappan, 2006). DDGS is an excellent source of bypass protein and is used to improve the palatability and nutrient balance of animal feed rations. Significant quantities of distillers grains are now being produced, due to the increased demand for ethanol as a fuel additive. By 2008-2009, distillers grains are projected to displace more than 1 billion bu. of corn for feed per year (NCGA, 2006). It has been reported that DDGS can have flowability issues (AURI and MCGA, 2005) and also the transportation cost can be very high if it has to be transported out of the Corn Belt states. Moreover, during transport DDGS can become hardened, which can lead to damage to the railcars while unloading. These issues impede the expansion of the DDGS market. In addition to that, marketing of distillers grain products is hampered by variability in their physical and chemical properties, both within a single plant over time as well as between the plants. Quantification of physical and chemical properties is important, because DDGS storage and flow behavior depends to a large extent on these properties, as well as environmental conditions. Some of the properties which affect flowability are particle size, cohesion, particle interaction, ability to recover from compaction, vibration during transportation, temperature, and relative humidity. The flowability of DDGS, and its resulting flow behavior under various pressures, temperatures, and humidities are important in handling operations such as storage in silos or hoppers, and transportation through railcars and trucks. It is necessary to determine and quantify the factors which are responsible for the flowability problems associated with DDGS, and find a solution to address this issue.

The handling, storage, and flow of any particulate material (such as DDGS) is important in industries associated with agricultural, food, chemical, ceramic, pharmaceutical and metallurgical bulk solids and powder processing. Flow is defined as the relative movement of a bulk of particles among neighboring particles, or along a container wall surface (Peleg, 1977). Flow characteristics are important in bulk material handling and processing, since the ease of conveying, blending, and packaging depends on them. Reliable flow is necessary to optimize designs and maximize profits. To ensure steady and reliable flow, it is crucial to accurately characterize the flow behavior of bulk materials (Kamath et al, 1994). Caking and stickiness are common problems that almost every industry associated with granular solids and powders encounters. It is very important that bulk solids do not cake, either partially or totally, even after an extended storage time. If flowability problems arise, then machinery, manpower, and time are needed to break these unwanted agglomerates thus adding costs to the customer (Röck and Schwedes, 2005).

Previously, the authors used the Carr Powder tester to study various flow properties of DDGS. We found that increased addition of solubles and moisture negatively affects DDGS flow (Ganesan et al., 2005). The Carr Indices are only one set of flowability parameters, however. Jenike (1964) was the first to apply soil mechanics techniques to measure the flow properties of powders. He developed a shear cell suitable for industrial powders. Jenike (1964) found that a powder may gain strength and develop flow problems when it is exposed to compressive stress over time. This behavior purely depends on the physical properties of that powder and the external conditions (e.g., temperature, humidity, compression, etc,). Some researchers have used the Jenike shear tester to measure the flow properties of food powders, cement, and other granular materials (Schrämli, 1967; Peleg and Mannheim, 1973; Kamath et al, 1994; Teunou and Fitzpatrick, 2000; Fitzpatrick et al, 2004a, 2004b; Iqbal and Fitzpatrick, 2006). The Jenike shear cell technique has been preferred more than other shear test methods, such as the triaxial method, because of its several advantages (Kamath et al., 1993). AURI and MCGA (2005), conducted a preliminary investigation of the flow characteristics of five different DDGS (Control 1, Control 2, De-oiled, reduced syrup and pelleted) samples using the Jenike shear test. Otherwise, there are no published reports available on flow properties of DDGS measured using Jenike shear cell technique. Hence the objective of this study was to investigate the effect of four levels of solubles (10, 15, 20, and 25% db) and five levels of moisture content (10, 15, 20, 25, and 30% db) on the flow properties of DDGS using the Jenike shear cell technique.

Materials and Methods

Sample Collection and Preparation

Samples of Condensed Distillers Solubles (CDS) and Distillers Dried Grains (DDG) were obtained from a commercial ethanol plant (Dakota Ethanol LLC, Wentworth, SD). The procured samples were stored in sealed plastic buckets (the DDG at room temperature, and the CDS at 4 ± 1^{o}C) until needed. The soluble content of both the DDG and the CDS were determined, and then DDGS samples with four different soluble levels (10, 15, 20, and 25% db) were prepared using the methodology developed by Ganesan et al. (2006). The moisture contents of the DDG and CDS were determined using Method 44-19 (AACC, 1995). The prepared DDGS samples were then dried to five specific moisture content levels (10, 15, 20, 25, and 30% db) using a hot air oven at 100^{o}C. The time taken for drying the samples was between 15 to 50 minutes.

Consolidation Testing

Instantaneous shear tests were performed on the DDGS samples (4 soluble levels x 5 moisture contents) using the Jenike shear cell techniques (Jenike, 1964). Three levels of consolidation were measured on the 20 DDGS samples, which resulted in a total of 60 treatment combinations (a 4 × 5 × 3 factorial design) for the study, which was implemented using a Completely Randomized Design. Each treatment was measured in triplicate for all the flow property analysis, which resulted in a total of 180 experimental runs. Statistical analyses were done using Proc GLM of SAS software (SAS Institute, Cary, NC, USA) with a Type I error rate (α) of 0.05 to test for Least Significant Differences between the treatments.

The Jenike shear cell unit is comprised of a base, ring, mold ring, twisting top, and cover. The inside diameter of the base, ring, and mold ring used for this test was 95 mm. The base, mold ring, and twisting top were constructed of stainless steel, while the cover and ring were both stainless steel and aluminum. The aluminum components were used for low pressure tests (Level 3 consolidation), while the stainless steel was used for high pressure tests (Level 1 and Level 2 consolidation). The testing procedure delineated by Jenike (1964) was followed for this study. The base, ring, and mold ring were placed one over another, and the offset of the ring was set to 3 mm (Figure 1). DDGS was placed in the shear cell, layer after layer, spreading it uniformly without over-packing. Excess material was scraped off and the twisting top was placed over the specimen. The weight hanger was then placed over the twisting top, and appropriate weights were added to the hanger depending on the test. The selection of weights was done on the basis of the bulk density of the DDGS samples, following the procedure outlined by Jenike (1964), because bin pressures are proportional to the bulk density of the material. The specimen was then pre-consolidated by applying a number of 60^o twists, with both clockwise and anti-clockwise rotations. The number of twists required for pre-consolidation was determined by a trial and error method as described by Jenike (1964). The weight hanger, twisting top, and mold ring were carefully removed from the specimen and the excess material was scraped off without disturbing the ring after twisting. The cover was then placed over the specimen, with the bracket lined up with the stem and the loading pin contacting the ring (Figure 2). Consolidation weights (W) were placed on the weight hanger, and a horizontal shear force was applied to the specimen. The automated stem moved at the rate of 2.7 mm/min. The horizontal shear force was stopped once steady state had been reached. The steady state force (S) was recorded using a strip chart reader attached to the shear cell unit (Model ST-5, Jenike and Johanson Co.,Westford, MA). Individual shear weights ($\overline{W}_i$) were then placed on the hanger (shear weights were always less than the consolidation weight), and again the same procedure was repeated, and the resulting steady state force ($\overline{S}_i$) was recorded. The entire procedure was repeated, using the same consolidation weight but different shear weights, to obtain one yield locus. For this study, 3 levels of consolidation (Table 1) were performed on each DDGS samples. Five different shear weights were used for each level of consolidation to achieve three well spaced points on the flow function curve. Triplicates were measured for each test.

As the steady state values of ($\overline{S}_i$) were somewhat scattered, prorating was used for interpolation. This was accomplished by:

$$(\overline{S}_i)_{Prorated} = (\overline{S}_i)_{tested} * \left(\frac{S_{selected}}{S_{tested}} \right) \quad (1)$$

where $S_{selected}$ is the average value of S obtained for the test, S_{tested} and $\overline{S}_{i\,tested}$ are the values of S and $\overline{S}_i$ obtained for the corresponding $\overline{W}_i$. The prorated results were used to obtain the yield locus (YL) for each test. Mohr circles of failure were drawn for each replication using AutoCAD v.2005 (Autodesk, Inc., San Rafael, CA). A typical plot is shown in figure 3. The values of unconfined yield strength (σ_c), major consolidation stress (σ_1), angle of internal friction (ϕ), and effective angle of friction (δ) were obtained from these Mohr circle plots.

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

The yield strength which a granular solid develops as it flows in a channel is an important criterion for determining the flowability of that bulk solid. Yield locus (YL) is a plot of failure shear stress vs. normal stress for a given consolidating stress (Fitzpatrick et al, 2004a). For free flowing solids (e.g. gravel, dry sand etc.,), the Mohr stress circles exhibits a straight envelope which passes through the origin. This envelope is called the effective yield locus (EYL). Both YL and EYL are dimensionless quantities.

Unconfined Yield Strength, UYS, (σ_c)

Unconfined yield strength (σ_c) is the compressive strength of the bulk solid (Pa) (Schulze, 2006). For example, the stresses acting on an exposed surface are zero, the surface is the principal plane, and the major pressure within the solid is tangential to this surface. When this pressure causes yield, it is referred to as unconfined yield pressure. Unconfined yield strength is a very important factor concerned with arching of bulk solids in silos (Jenike, 1964).

Major Consolidation Stress, MCS, (σ_1)

A Mohr circle is the circle which passes through the steady state point (V, S) and is tangent to the YL (Fig 3) (Jenike, 1964).V is the normal load and S is the shear force applied during the shear test. The point of intersection of the Mohr circle with the normal stress axis determines the value of the major consolidating stress (Pa).

Angle of Internal Friction (ϕ)

The angle of internal friction (deg) is a measure of the inter-particle friction as a bulk solid starts to slide on itself at the onset of flow (Jenike, 1964). An increase in pressure generally increases the value of ϕ, but not always.

Effective Angle of Internal Friction (δ)

The effective angle of internal friction, measured in degrees, is the angle developed between EYL and normal load (V) (Jenike, 1964). The normal load is the load applied to the material vertically by adding the weights in the weight hanger. The effective angle of internal friction is thus the measure of interparticle kinematic friction which exists during steady flow. It generally varies between 30^o and 70^o for various bulk solids. Fine and dry solids tend to have low values of δ, while coarse and wet solids tend to have large values of δ. Effective angle of internal friction generally decreases with increasing pressure particularly at low pressures (Jenike 1964).

Flow Function (F)

The relationship between unconfined yield strength (σ_c) and major consolidation stress (σ_1) is called the flow function of the material (Eqn 2):

$$F = \frac{\sigma_1}{\sigma_c} \qquad (2)$$

Flow function is a dimensional quantity. Jenike (1964) classified the flowability of solids according to the flow function value (Table 2). All the properties discussed are influenced not only by the physical nature of the particles themselves, but also by temperature, time of storage at rest, moisture, and chemical compositions.

Compressibility Testing

A stainless steel base with an inside diameter of 64 mm and a depth of 19.05 mm was used for compressibility tests. The base was placed over the Jenike tester's shear disc, and DDGS was filled in to the base uniformly without over-packing. Then the cover, weight hanger, and indicator holder were placed over the specimen, cover, and base, respectively. The indicator holder was a 25mm travel dial indicator mounted on a stainless steel holder which has a counter-bored bottom that fits over the base. Once the indicator hand was stabilized, the reading was recorded. Weights (Table 3) were placed on the weight hanger and the readings were noted for each weight. After that, the indicator holder, weights, weight hanger, and cover were removed from the specimen. The material attached to the cover itself was brushed back in to the base, and the base with the material was weighed. To determine the bulk density (γ), for various loads (Eqn 3) the base weight was deducted and the net weight of the material was recorded.

$$\gamma = \frac{0.3157\,\mathrm{M}}{\mathrm{H}} \tag{3}$$

where γ is bulk density of material (g/cm^3), M is the net weight of the material (g), and H is the height measured by the indicator (mm). The compressibility (β) was then determined from a semi-log plot of the normal load vs. the resulting bulk density (γ). The slope of the line was the compressibility.

Results and Discussion

Instantaneous shear tests of DDGS samples with four soluble levels (10, 15, 20, and 25% db) and five moisture contents (10, 15, 20, 25, and 30% db) were determined. The flow properties for Level 3 consolidation for all the DDGS samples could not be obtained though, as the consolidation pressure given was too small (Table 1). The higher the pressure, the greater the consolidation, and thus the strength of the DDGS. Because of this, YL of many samples passed through the negative Y (shear stress) axis and thus the Mohr circle used to obtain the unconfined yield strength could not be drawn. So, the statistical analyses on the collected data exclude the Level 3 consolidation data. Table 4 and 5 provide the results obtained from the instantaneous shear tests.

Unconfined Yield Strength, UYS, (σ_c)

Results show that there are significant differences between the treatments, but none of the flow properties showed any trends between the treatments. The higher the consolidation, the larger the yield strength of a bulk material it can be (Jenike, 1964). Cohesive materials often exhibit unconfined yield strength when subjected to consolidation. Free flowing or non cohesive materials practically show an unconfined yield strength value of 0, even at higher consolidations. The highest mean unconfined yield strength was obtained for DDGS with 25% solubles/10% moisture content at Level 1 consolidation (15.12 kPa) and lesser value was obtained for DDGS with 10% soluble/15% moisture at Level 2 consolidation (0.18 kPa) treatment combination. This result indicates that the DDGS is a cohesive material and thus it is likely to give arching problems.

Major Consolidation Stress, MCS, (σ_1)

The highest mean major consolidation stress value was obtained for DDGS with 20% solubles/10% moisture content (34.95 kPa) as well as for 10% solubles/15% moisture content (34.79 kPa) at Level 1 consolidation. The lowest stress was observed for DDGS with 10% solubles/30% moisture content (1.76 kPa). The maximum stress has to prevail over the yield strength ($\sigma_1 > \sigma_c$) for the arch to break and hence for easing the bulk material flow (Jenike, 1964). In our experiments, the MCS values of DDGS were way higher than UYS values and therefore this result implies that DDGS should not have any flow problem.

Angle of Internal Friction (ϕ)

According to Jenike (1964), the higher the angle of internal friction, the higher the bulk materials' flow will be. Duffy and Puri (1999) observed that soybeans with ϕ of 47.5^o exhibited a better flow compared to cottonseeds (8.7^o) and shelled corn (8.3^o) at 11.1% (db) moisture content. The highest mean angle of internal friction value (46^o) was obtained for DDGS with 15% soluble/10% moisture content combination at consolidation Level 2. The least values of ϕ were obtained for DDGS with 20% soluble/20% moisture content at consolidation Level 1 (18.33^o); 20% soluble/25% moisture content at Level 1 consolidation (18^o); and 25% soluble/25% moisture content at Level 1 consolidation (17.67^o) treatment combinations. In our experiments, half of the treatment combinations had ϕ greater than 30^o. This behavior was not systematic and did not appear to be due to specific levels of solubles or moisture contents or consolidations. These results suggest that DDGS should not have any sever flow problems.

Effective Angle of Internal Friction (δ)

The effective angle of internal friction (δ) did not show any trends between the treatments. The DDGS with 20% soluble/10% moisture content at Level 2 consolidation (53.33^o); and 25% soluble/10% moisture content at Level 2 consolidation (53^o) had the highest mean effective angle of internal friction. The lowest mean values of δ were obtained for 20% soluble/25% moisture content at Level 1 consolidation(29^o); and 20% soluble/30% moisture content at Level 1 consolidation(28.67^o). This shows that the results were agreeing with the discussion that δ decreases with increasing pressures. The values of δ were higher compared to ϕ values of all treatment combinations. According to Jenike (1964), δ is equal to ϕ, so ($\delta/\phi=1$) for non cohesive materials such as dry sand. As a result, the higher the δ of a material, the higher its probability to have flow problem and vice versa.

Flow Function (F)

The flow functions determined for twenty different DDGS samples are presented in Figure 4. In these flow function figures, the lines lying towards the bottom of graph represents easy flow, while more difficult flow is represented as the flow function moves upwards in an anticlockwise direction. The flow function curves moved towards the shear stress axis as the soluble level increased from 10% to 25%. This indicates that DDGS with 25% soluble was the one with most strength, the greatest ability to support obstructions to flow, and hence the least free-flowing one. On the other hand, DDGS with 10% solubles was a comparatively free-flowing material with the flow function curve towards the normal stress ($\sigma 1$) axis. No trend could be predicted in the flow function curves with an increase in moisture content levels however. Table 5 shows the flow index values and flowability classification for DDGS with various soluble and moisture content combinations. All the DDGS, except two treatment combinations (10 and 15% soluble with 10% moisture content), were classified as cohesive. The flow index values (Table 5) for DDGS with 10 and 15% solubles decreased with increase in moisture content (10 to 20%); at 25 and 30% moisture content the flow index started increasing. But for DDGS with 20% solubles, the flow index values increased with increase in moisture content. However, the values were not significantly different from each other.

The same trend has been followed by DDGS with 25% solubles, except at 25% moisture content. The flow was likely to be more difficult with increased soluble levels rather than moisture content levels (Figure 4). Increases in moisture content will impede the flow of DDGS, however, above certain moisture content, the moisture might act as a lubricant and partially improved the flow. But the classification of DDGS remains the same, "cohesive nature", for all DDGS with higher soluble and moisture content levels.

Compressibility Testing

Figure 5 and Table 5 show the plot of consolidating pressure vs. bulk density of the 20 DDGS samples. The slope of the line gives the compressibility of DDGS. In general, the compressibility values of DDGS were found to increase with increases in soluble level and moisture content, which indicates that DDGS is likely to have flow difficulty. Over a period of time, the DDGS with higher soluble and moisture contents might be prone to caking/bridging problems.

Conclusions

Flow properties of twenty different DDGS samples were measured using a Jenike shear tester. Overall, the study showed that soluble level and moisture content had significant effects on the flow properties of DDGS. But, unconfined yield strength, major consolidation stress, angle of internal friction, and effective angle of internal friction did not show any specific trends with increases in soluble levels or moisture contents. The unconfined yield strength varied from 0.05 to 15.96 kPa, major consolidation stress varied from 1.21 to 36.64 kPa, angle of internal friction varied from 12^{o} to 54^{o}, and effective angle of internal friction varied from 25^{o} to 58^{o}. The flow function curves moved upward in an anticlockwise direction with an increase in soluble level. The flow index values decreased with increasing moisture content (10 to 20%), but increased for 25 and 30% moisture content. This indicates that, above certain a moisture content, moisture may act as a lubricant and ease the flow of DDGS. Only two DDGS (10% and 15% solubles with 10% moisture content) were categorized as "intermittent flow", the rest of the DDGS samples were classified as cohesive in nature. The compressibility of DDGS was also affected by increases in soluble level and moisture content. The compressibility values increased with an increase in soluble and moisture content. The highest compressibility value (0.0024 cm^{-1}) was obtained for DDGS with 25% solubles and 30% moisture content. DDGS with higher soluble and moisture content can be classified as cohesive and more compressible. Thus it is likely to give more cohesive, arching problems. Future studies should investigate the effect of storage time on the flow properties of DDGS, and include soluble levels and moisture contents as primary factors, as consolidation may also have an impact on DDGS flowability.

Acknowledgements

The authors would like to thank the Dakota Ethanol Plant (Wentworth, SD) which contributed samples for the study, the South Dakota Corn Utilization Council (SDCUC), the South Dakota Agricultural Experimental Station (AES), and the USDA-ARS for financial support.

References

AACC 44-19. 1995. Moisture – Air oven method, drying at 135°C. *AACC Approved Methods* (9th ed.). St. Paul, MN, USA.

AURI and MCGA. 2005. *Methods to improve the flowability and pelleting of distillers dried grains with solubles (DDGS).* Prepared by AURI for MCGA. Available online at http://www.auri.org/research/Flowability_summary_10_17_05.pdf. Accessed 26 February 2007.

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

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

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

Ganesan, V., K. A. Rosentrater, and K. Muthukumarappan. 2005. Effect of moisture content and soluble levels on the physical and chemical properties of DDGS. *ASAE Paper No. 056110*. St. Joseph, MI: ASAE.

Ganesan, V., K. A. Rosentrater, and K. Muthukumarappan. 2006. Methodology to determine soluble content in dry grind ethanol coproduct streams. *Applied Engineering in Agriculture* 22(6):899-903.

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

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

Kamath, S., V. M. Puri, H. B. Manbeck, and R. Hogg. 1993. Flow properties of powders using four testers-measurement, comparison and assessment. *Powder Technology* 76(3): 277-289.

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

NCGA. 2006. How much ethanol can come from corn?. *National Corn Growers Association*. Available online at http://www.ncga.com/ethanol/pdfs/2006/HowMuchEthanolCan%20ComeFromCorn.v.2.pdf. Accessed 26 February 2007.

Peleg, M., and C. H. Mannheim. 1973. Effect of conditioners on the flow properties of powdered sucrose. *Powder Technology* 7(1): 45-50.

Peleg, M. 1977. Flowability of food powders and methods for its evaluation-A review. *Journal of Food Process Engineering* 1: 303-328.

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

Rosentrater, K.A., and K. Muthukumarappan. 2006. Corn Ethanol Coproducts: Generation, Properties, and Future Prospects. *International Sugar Journal.* 108(1295): 648-657.

Schrämli, W. 1967. On the measurement of the flow properties of cement. *Powder Technology* 1(4): 221-227.

Schulze, D. 2006. Storage of powders and bulk solids in silos. Dietmar Schulze.com. Available online at http://www.dietmar-schulze.de/storagepr.html. Accessed 12 March 2007.

Teunou, E., and J. J. Fitzpatrick. 2000. Effect of storage time and consolidation on food powder flowability. *Journal of Food Engineering* 43 (2): 97-101.

Tjardes, K., and C. Wright. 2002. Feeding corn distiller's co-products to beef cattle. Extension Extra - SDSU Extension Cooperative Service. Available online at http://agbiopubs.sdstate.edu/articles/ExEx2036.pdf . Accessed 20 December 2006.

Disclaimer

Mention of a trade name, propriety product or specific equipment does not constitute a guarantee or warranty by the United States Department of Agriculture and does not imply approval of a product to the exclusion of others that may be suitable.

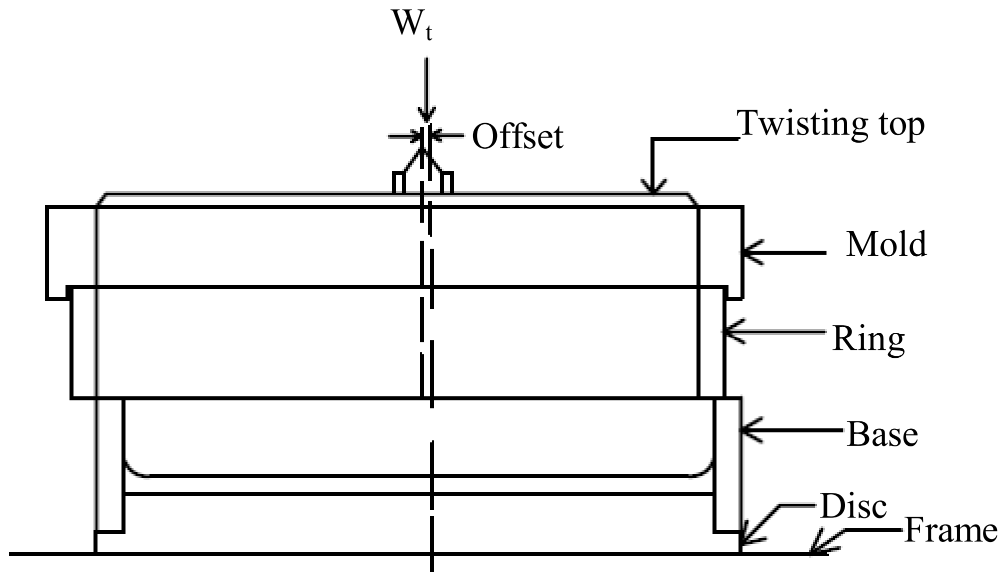

Figure 1. Pre-consolidation of Jenike Shear cell.

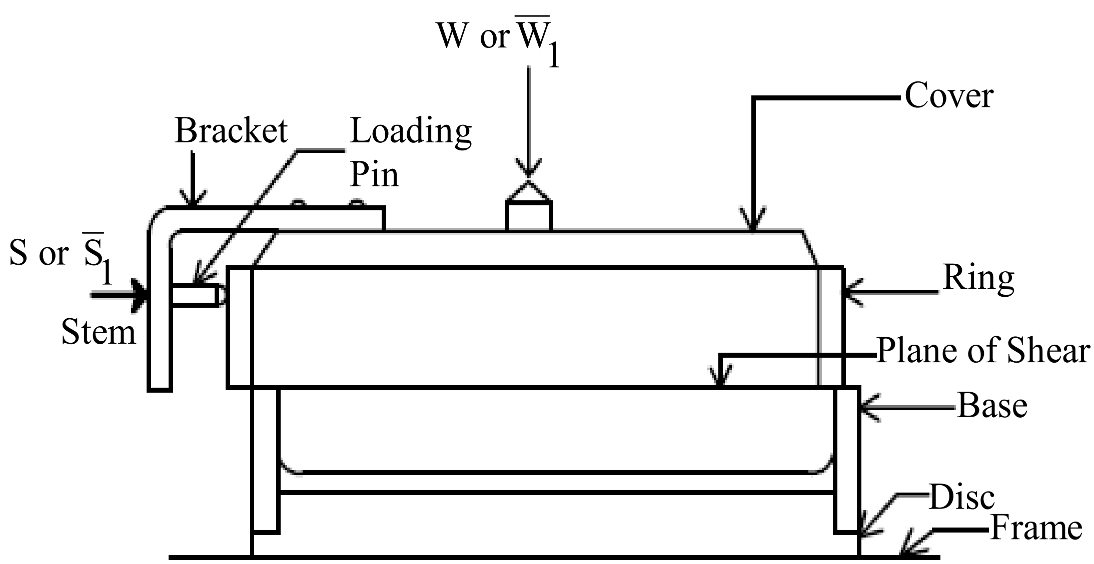

Figure 2. Consolidation and shear of Jenike Shear cell.

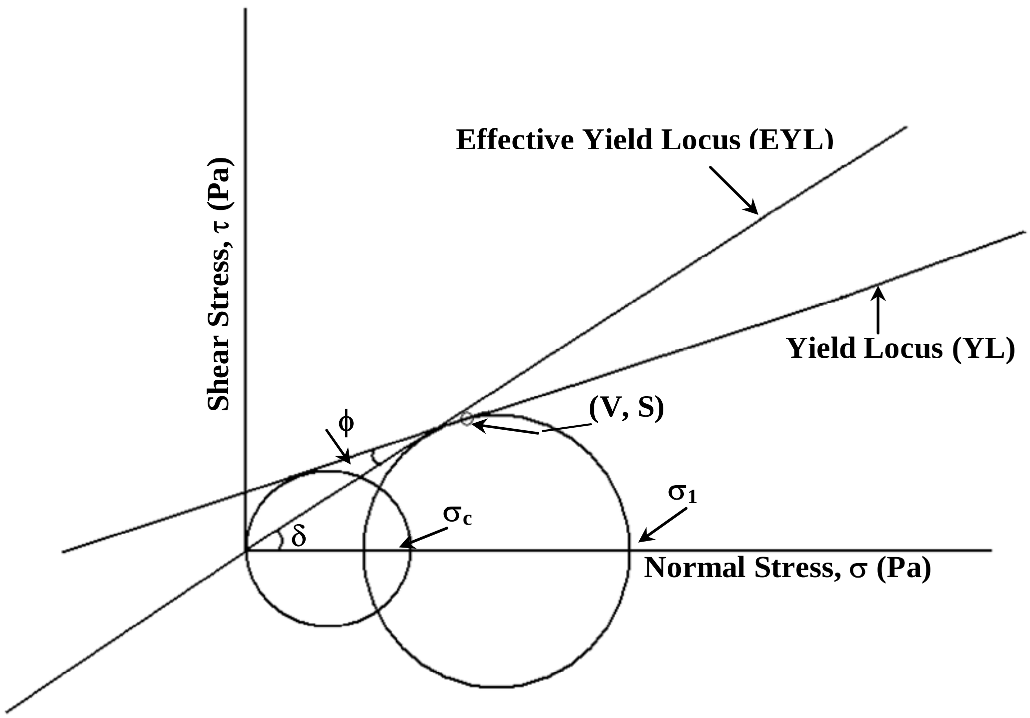

Figure 3. Typical plot of Mohr circles, used to analyze Jenike shear cell experimental results.

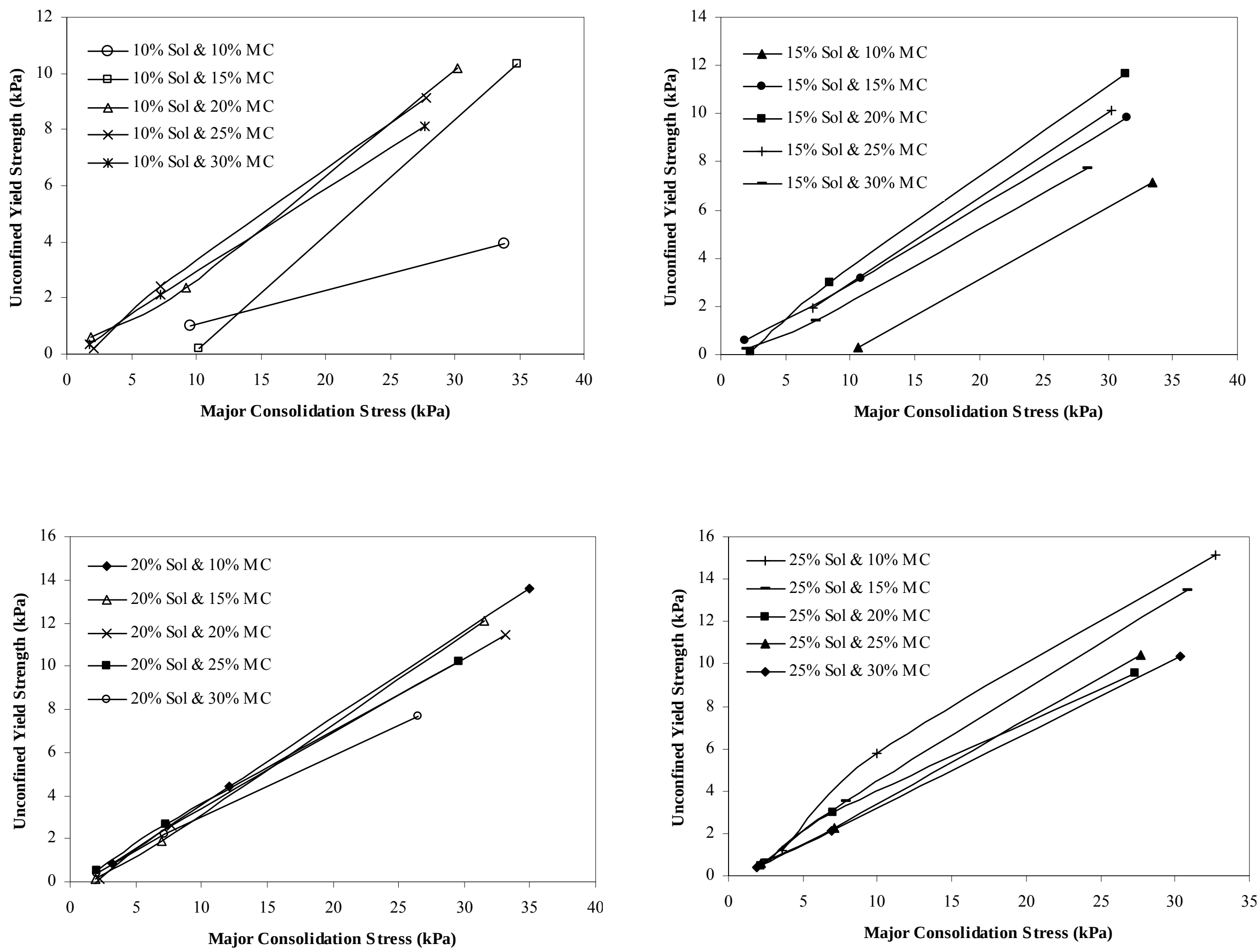

Figure 4. Flow functions of DDGS with 10, 15, 20, and 25% (db) solubles at moisture contents of 10, 15, 20, 25, and 30% (db).

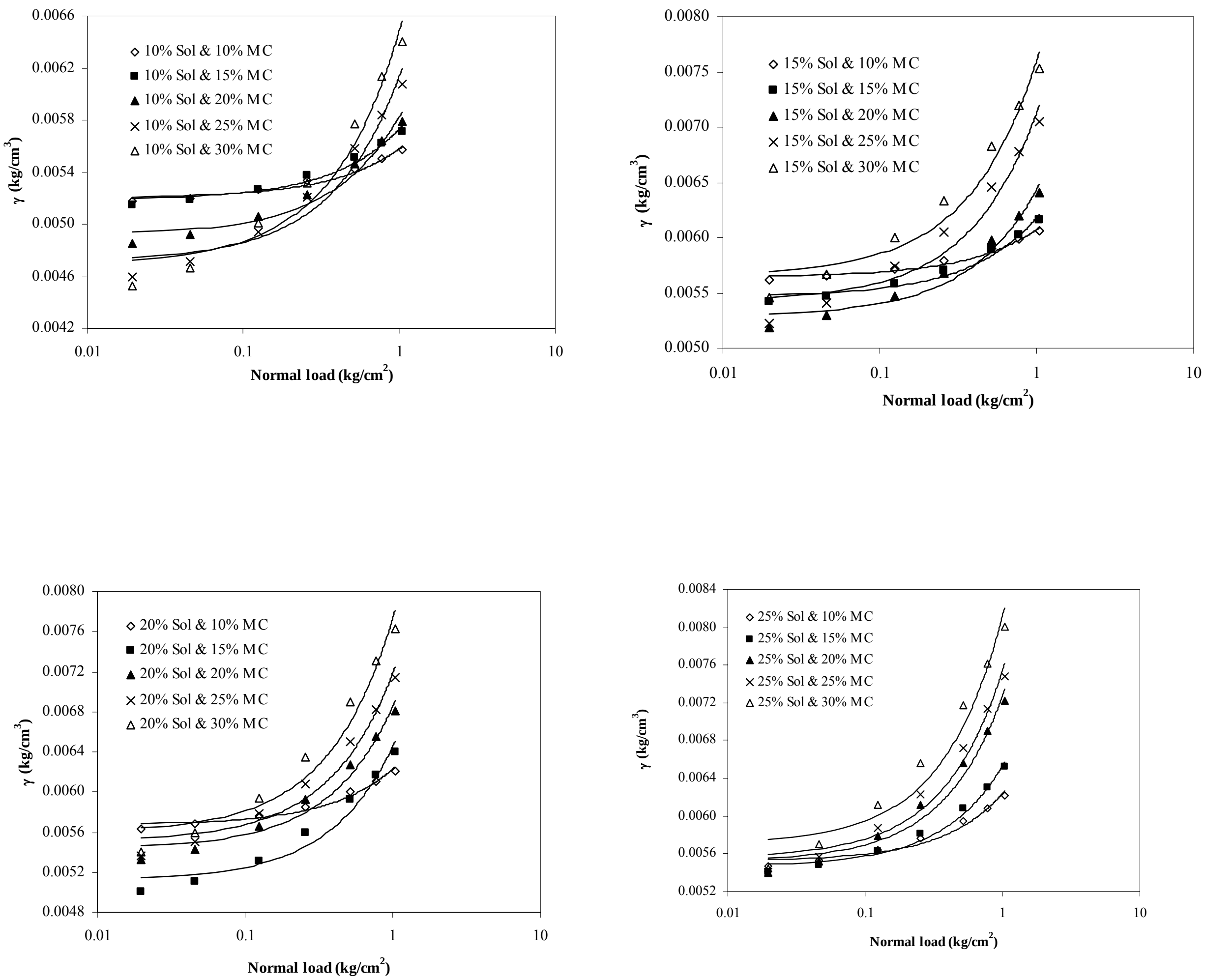

Figure 5. Compressibility of DDGS with soluble levels of 10, 15, 20, and 25% (db) at moisture contents of 10, 15, 20, 25, and 30% (db).

Table 1. Weights used for instantaneous shear tests.

Bulk Density (g/cm^3)	Consolidation Level	Cell†	W (kg)	$\overline{W}_1$ (kg)	$\overline{W}_2$ (kg)	$\overline{W}_3$ (kg)	$\overline{W}_4$ (kg)	$\overline{W}_5$ (kg)
0.3 - 0.8	1	95 mm SS	14.5	9.5	7.5	6.5	5.5	4.5
0.3 - 0.8	2	95 mm SS	3.0	2.0	1.7	1.35	1.1	0.85
0.3 - 1.6	3	95 mm Alum	0.7	0.3	0.25	0.2	0.15	0.1

† SS – Stainless Steel; Alum – Aluminum

Table 2. Jenike's classification of powder flowability by flow function.

Flow Function (F)	Classification
F<1	No flow
1<F<2	Highly cohesive
2<F<4	Cohesive
4<F<10	Intermittent flow
10<F	Free flow

Table 3. Weights used for compressibility tests.

No.	Wt (including hanger) (kg)
1	0.75
2	1.75
3	4.75
4	9.75
5	19.75
6	29.75
7	39.75

Table 4. Treatment combination effects due to soluble content, moisture content, and consolidation level on the resulting flow properties of DDGS. Values in the table are mean values and (standard deviations).‡

		Soluble (% db)											
		10			15			20			25		
	MC	Consolidation Level											
Properties	(% db)	1	2	3†	1	2	3†	1	2	3†	1	2	3†
Unconfined Yield	10	3.91^{j-l}	1.00^{no}	-	7.14^{hi}	0.28^{o}	0.27	13.57^{ab}	4.43^{jk}	0.84	15.12^{a}	5.78^{ij}	0.71
Strength		(0.47)	(0.82)	-	(1.90)	(0.22)	-	(1.19)	(1.48)	-	(1.13)	(1.15)	-
(σ_c)	15	10.36^{c-f}	0.18^{o}	0.05	9.83^{d-g}	3.18^{k-n}	0.59	12.13^{bc}	1.88^{l-o}	0.15	13.50^{ab}	3.51^{k-m}	0.70
(kPa)		(1.45)	(0.11)		(2.31)	(0.62)		(0.46)	(0.21)	-	(2.11)	(1.12)	-
	20	10.19^{c-f}	2.36^{k-o}	0.59	11.68^{b-d}	3.01^{k-n}	0.12	11.48^{b-d}	2.62^{k-n}	0.13	9.59^{d-g}	2.99^{k-n}	0.47
		(2.39)	(1.75)		(1.71)	(0.34)	-	(1.23)	(1.04)	-	(1.29)	(0.29)	-
	25	9.12^{e-h}	2.40^{k-o}	0.19	10.15^{c-f}	1.94^{l-o}	-	10.22^{c-f}	2.70^{k-n}	0.54	10.43^{c-e}	2.25^{k-o}	0.57
		(1.84)	(0.79)		(0.48)	(0.93)	-	(0.88)	(0.31)	-	(0.48)	(0.36)	-
	30	8.14^{f-h}	2.13^{l-o}	0.35	7.71^{g-i}	1.42^{m-o}	0.21	7.67^{g-i}	2.21^{k-o}	0.39	10.37^{c-f}	2.13^{l-o}	0.39
		(0.44)	(0.67)		(4.66)	(0.77)	-	(2.53)	(0.33)	-	(0.47)	(0.58)	-
Major Consolidating	10	33.82^{ab}	9.55^{k-m}	-	33.44^{ab}	10.59^{jk}	1.65	34.95^{a}	12.16^{j}	3.18	32.68^{bc}	9.95^{kl}	3.58
Stress		(1.36)	(0.22)	-	(0.89)	(0.32)	-	(1.42)	(1.32)	-	(2.37)	(1.12)	-
(σ_1)	15	34.79^{a}	10.24^{kl}	2.41	31.49^{cd}	10.85^{jk}	1.91	31.49^{cd}	7.02^{n}	1.91	30.80^{de}	7.85^{mn}	2.57
(kPa)		(2.61)	(0.90)		(2.43)	(0.78)	-	(3.06)	(0.17)	-	(1.44)	(0.17)	-
	20	30.26^{de}	9.23^{k-m}	1.91	31.29^{c-e}	8.44^{l-n}	2.33	33.15^{a-c}	7.74^{mn}	2.30	27.28^{hi}	6.98^{n}	2.14
		(1.56)	(0.19)		(0.59)	(0.26)	-	(2.66)	(0.30)	-	(0.75)	(0.17)	-
	25	27.81^{g-i}	7.31^{n}	2.11	30.21^{d-f}	7.15^{n}	-	29.60^{e-g}	7.30^{n}	2.08	27.65^{hi}	7.08^{n}	2.16
		(0.41)	(0.17)		(0.88)	(0.17)	-	(2.28)	(0.21)	-	(0.52)	(0.11)	-
	30	27.65^{hi}	7.26^{n}	1.76	28.37^{f-h}	7.32^{n}	1.94	26.49^{i}	7.17^{n}	2.08	30.35^{de}	6.93^{n}	1.91
		(0.60)	(0.20)		(0.48)	(0.08)	-	(1.24)	(0.13)		(0.34)	(0.24)	-
Effective angle of	10	38.00^{j-l}	40.00^{g-j}	-	41.33^{e-j}	46.33^{bc}	38.00	44.33^{c-f}	53.33^{a}	51.50	41.00^{f-j}	53.00^{a}	58.00
Friction (δ)		(2.65)	(0.00)	-	(2.08)	(0.58)	-	(2.31)	(2.31)	-	(4.00)	(7.00)	-
(deg)	15	41.33^{e-j}	45.00^{c-e}	46.00	36.00^{k-n}	50.67^{a}	43.00	31.67^{p-s}	43.00^{c-g}	43.67	37.67^{j-m}	51.33^{a}	54.33
		(1.15)	(1.00)	-	(4.00)	(1.53)	-	(3.51)	(1.00)	-	(3.79)	(0.58)	-
	20	36.00^{k-n}	50.00^{ab}	44.00	34.33^{l-p}	45.33^{cd}	45.50	30.00^{rs}	41.00^{f-j}	43.00	30.67^{p-s}	42.33^{d-h}	42.67
		(3.61)	(1.00)	-	(1.53)	(2.31)	-	(2.64)	(2.00)	-	(3.21)	(1.15)	-
	25	31.00^{p-s}	42.33^{d-h}	43.00	32.00^{o-s}	42.00^{d-i}	-	29.00^{s}	40.33^{g-j}	37.00	30.33^{q-s}	38.67^{h-k}	43.00
		(2.65)	(0.58)	-	(2.00)	(1.00)	-	(2.65)	(1.53)	-	(1.15)	(0.58)	-
	30	29.33^{rs}	34.00^{m-q}	36.00	31.67^{p-s}	39.00^{h-k}	37.00	28.67^{s}	38.33^{i-k}	35.00	33.00^{n-r}	35.67^{k-o}	31.33
		(1.15)	(1.00)		(3.06)	(1.00)	-	(3.21)	(0.58)	-	(1.00)	(2.31)	-
Angle of Internal	10	35.33^{c-e}	37.67^{b-d}	-	35.67^{c-e}	46.00^{a}	34.00	33.67^{c-f}	44.67^{ab}	45.00	26.33^{g-m}	35.00^{c-e}	54.00
Friction (ϕ)		(2.89)	(2.08)	-	(3.21)	(0.00)	-	(3.05)	(1.15)	-	(6.03)	(10.15)	-
(deg)	15	33.33^{c-g}	44.33^{ab}	45.00	27.00^{f-k}	44.00^{ab}	35.00	19.33^{mn}	36.00^{c-e}	41.67	23.33^{i-n}	38.67^{bc}	48.00
		(0.58)	(1.15)	-	(6.00)	(4.36)		(3.21)	(1.00)	-	(6.66)	(6.81)	-
	20	25.67^{h-m}	44.00^{ab}	36.00	22.33^{j-n}	35.67^{c-e}	44.50	18.33^{n}	31.00^{d-h}	42.00	19.33^{mn}	29.33^{e-j}	37.00
		(7.09)	(4.58)	-	(4.04)	(3.06)	-	(3.05)	(7.00)	-	(4.73)	(3.06)	-
	25	20.33^{k-n}	33.00^{c-g}	41.00	21.67^{k-n}	34.67^{c-e}	-	18.00^{n}	29.67^{e-i}	29.00	17.67^{n}	30.00^{e-i}	36.33
		(4.93)	(4.00)	-	(2.08)	(4.04)	-	(3.00)	(1.53)	-	(1.53)	(1.73)	-
	30	20.00^{k-n}	25.67^{h-m}	35.00	23.33^{i-n}	33.67^{c-f}	34.33	19.67^{l-n}	29.67^{e-i}	30.50	22.33^{j-n}	26.67^{f-l}	26.00
		(1.73)	(3.79)		(8.74)	(3.79)	-	(6.81)	(1.15)	-	(1.53)	(5.13)	-

‡Values followed by the same letter within the same property are not significantly different ($P<0.05$).

†The force applied was less at Level 3 consolidation, and flow properties could not be obtained for all the treatment combinations.

Table 5. Flow index, flowability classification, and compressibility values of DDGS due to soluble level and moisture content.

Soluble Level (% db)	MC (% db)	Flow Index	Classification	Compressibility β (cm^{-1})
10	10	8.64	Intermittent flow	0.0004
	15	3.36	Cohesive	0.0005
	20	2.97	Cohesive	0.0009
	25	3.05	Cohesive	0.0014
	30	3.40	Cohesive	0.0018
15	10	4.68	Intermittent flow	0.0004
	15	3.20	Cohesive	0.0007
	20	2.68	Cohesive	0.0012
	25	2.98	Cohesive	0.0017
	30	3.68	Cohesive	0.0019
20	10	2.57	Cohesive	0.0006
	15	2.60	Cohesive	0.0013
	20	2.89	Cohesive	0.0014
	25	2.90	Cohesive	0.0017
	30	3.46	Cohesive	0.0021
25	10	2.16	Cohesive	0.0007
	15	2.28	Cohesive	0.0011
	20	2.84	Cohesive	0.0018
	25	2.65	Cohesive	0.0020
	30	2.93	Cohesive	0.0024