Assessment of the flow properties of crushed grain products depending on the granulometric condition

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Abstract: Several methods were developed to assess the flowability of bulk material. Jenike introduced flowability values to assess the flowability of bulk material like mineral raw material under given loads. A method developed by Carr uses several granulometric parameters to describe the flow properties without influence on the load. The aim of the own study was to evaluate the recommendations of Jenike and Carr regarding to their application onto crushed grain. Therefore measurements with grainy and powdery grain products were carried out to determine flow properties regarding Jenike and Carr. Additionally unloading tests with a level model silo were performed to find out the influence of the outlet diameter. The evaluations of the flow properties according to Jenike and Carr deliver partially different textual evaluations. The flowability to Jenike and the flow index according to Carr drop abruptly in the range Q_3(0.2 mm) = 5% ... 20%. This shows that the flow properties are mainly influenced by their share of cohesive fines. A classification of the flow properties according to Jenike is more realistic for crushed grain.

Keywords: crushed grain, flow properties, Jenike shear cell, Carr index

Citation: Fürll, C., and T. Hoffmann. 2015. Assessment of the flow properties of crushed grain products on the granulometric condition. Agric Eng Int: CIGR Journal, 17(4):359-368.

1 Introduction

The bases of calculation for silo designs conducive to flow and for measuring technology to determine flow properties have been described in relevant literature for about 50 years now (Schwedes, 1968; Schwedes, 1980). Up to now, several test devices and methods were developed for the assessment of parameters attributed to the flowability (Schwedes, 2003; Schulze, 2008). The parameters of interest depend on the given problems.

Key parameters obtained by measuring the flow properties with shear testing equipment and used for designing silos are the internal friction, the uniaxial strength of the material, the wall friction, the stress-dependent bulk or storage density and the flowability. Measuring equipment used worldwide includes the translation shear cell according to Jenike (Schwedes, 1968) and the ring shear tester according to Walker (1966), or in an essentially more modern design according to Schulze (1994). The flow properties are still chiefly assessed according to a classification by Jenike (Schwedes, 1968) on the basis of the flowability ff_c, which is calculated from the division of consolidation stress σ_1 and uniaxial compressive strength σ_c:

$$ff_c = \frac{\sigma_1}{\sigma_c} \quad (1)$$

However, the influence of density on the flow properties is not taken into account. Probably for this reason Jenike remarks in a publication of 1975 (Jenike, 1975) that his original recommendation was too simple. He therefore suggests using the smallest width of a rectangular unloading outlet to assess the flowability. In this way the material density is also taken into account.

If samples to be compared differ strongly in their bulk density, Schulze (2008) proposes the calculation of an adjusted value for the flowability ff_ρ with

Received date: 2015-07-30 Accepted date: 2015-09-29

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consideration of the bulk density ρ_b and the density of water ρ_w = 1000 kg/m^3 (liquid water at 0 ℃, one bar):

$$ff_\rho = ff_c \cdot \frac{\rho_b}{\rho_w} \qquad (2)$$

The flowability ff_ρ is not physically based, but Equation (2) gives a non-dimensional value which is called the "density-weighed flowability".

The density influence is taken into account when assessing the flow properties according to a proposal by Peschl (1989) and Shear-Test GmbH (ShearTest, 2015). This defines a relative flowability FLR, calculated in accordance with the following equations:

$$FLR = \frac{(\sigma_1 - \sigma_2)}{\sigma_c} \qquad (3)$$

Where, σ_1 and σ_2 are the major principal stresses of the Mohr cycle which is tangent on the end point of the yield locus, and σ_c is the uniaxial compressive strength. The density influence is included in the function of the relative flowability FLA:

$$FLA = FLR \cdot \frac{\rho}{\rho_w} \qquad (4)$$

Where, ρ/ρ_w is the ratio of the bulk density of the material examined to the density of water.

In examinations of mineral raw materials, for instance by Kurz and Münz (1975), Münz (1976) and Höhne and Schünemann (1980), connections between particle size and the parameters of various particle size functions and the flow properties were determined. They were also ascertained for crushed grain products (Fürll, 1978; Fürll, 2007) and various agricultural model products (Fürll, 1978; Fürll, 1979). Cohesionless properties are only available for crushed grain as of particle sizes from 200 to 300 μm (Fürll, 2006; Fürll, 2007). This agrees with the results of Nothdurft (1977), who states from experiences with a wide range of agricultural bulk materials that as of particle sizes x > 250 μm, the bulk materials are generally cohesionless. Ogniwek (1979) derives from test results with nine different product samples, including wheat, wheat flour and crushed soy, that substances are cohesive already as of a mass component Q_3(200 μm) ≥ 3%. This was also confirmed by our own test results (Fürll, 2006; Fürll, 2007).

Results obtained by Höhne and Schünemann (1980) document that the flow properties are a function of density. They ascertained that with mineral raw materials, particle sizes of x > 5 μm already possess cohesionless properties.

The granulometric condition sizes are also included directly and indirectly in the evaluation of flow properties by Carr (1965). He awards points for the angle of repose, spatula angle, coefficient of compressibility and the "cohesion according to Carr" or the coefficient of uniformity of the particle size distribution of a material. The flowability is classified according to a given scale from 0 (absolutely not flowing) to 100 (absolutely free flowing). The advantage of this method lies in the generally easy determinability of the parameters. A disadvantage is that the measurements are carried out without influence on the load and that the result obtained does not represent any possibility of calculating container geometries.

Altogether it must be ascertained that the influence of the particle density is not taken into account on assessing the flow properties. This leads to misinterpretations, above all when assessing the flow properties from results of shear tests with the aid of the flowability according to Jenike ffc and the classification he recommended.

Several results about the flow behaviour of mineral materials or materials from the pharmaceutical industry were published. But only few publications deal with agricultural materials like whole wheat grains (Chang, 1988), distillers dried grains with solubles (Ganesan et al., 2008), cereal powders and non-starch powders (Stasiak and Molenda, 2008), starch of maize, wheat and potatoes (Stasiak et al., 2013), or shredded grain products (Fürll and Hoffmann, 2013).

The aim of the own investigation was to determine the flow properties of grainy and powdery grain products in accordance with the early recommendations of Jenike and using the methods according to Carr. The results and their practical relevance are then to be checked by experimental investigations. A correction of the recommendations provided in literature to date is then to be derived from the results, taking the influence of the material density into account. In addition, the study examines whether there is any connection between the flowability ff_c and the geometry of the unloading outlet.

2 Materials and methods

2.1 Flowability according to Jenike

The flowability according to Jenike ff_c is calculated from the ratio of the principle stress σ_1 (consolidation stress) of the Mohr's circle which is tangent to the end point of a yield locus to the uniaxial compressive strength σ_c which is the maximum principle stress of the Mohr's circle which touches on the yield locus and which second principle stress is zero (Equation (1)).

According to its value, the flow properties of a bulk good are classified on the basis of an original recommendation by Jenike:

$ff_c < 2$	very cohesive, non-flowing
$2 < ff_c < 4$	cohesive
$4 < ff_c < 10$	easily flowing
$10 < ff_c$	free flowing

As Jenike later suggested using the minimal necessary outlet width as dimension for the flowability (Jenike, 1975), it is interesting whether there is a connection between outlet diameter d_A and flowability ff_c. If $\sigma_{c\ krit.}$ is replaced by σ_1/ff_c in the equation for calculating the outlet widths (Equation (5)), it becomes apparent that d_A is inversely proportional to ff_c (Equation (6)).

$$b, d_A = H(\Theta) \cdot \frac{\sigma_{c\ krit}}{\rho_b \cdot g} \quad (5)$$

$$b, d_A = H(\Theta) \cdot \frac{\sigma_1}{ff_c \cdot \rho_b \cdot g} \quad (6)$$

b	gap width, m
d_A	outlet diameter, m
$H(\Theta)$	function that takes the geometrical form of the outlet into account, -
$\sigma_{c\ krit.}$	critical uniaxial compressive strength, N/m ²
ρ_b	bulk density during storage, kg/m ³
g	acceleration due to gravity, m/s ²

In this equation the principle stress σ_1 can be assumed to be virtually constant, while all ff_c-values have been obtained as mean value from the experimentally determined yield loci.

Furthermore, the influence of density becomes clear from Equation (6).

2.2 Flow index according to Carr

Carr (1965) determines the flow index ff_{cc} according to a given evaluation scale from the measured values of angle of repose, spatula angle, compressibility and cohesion or coefficient of uniformity. By the method of Carr the values for the four criteria mentioned are determined by separate tests and are assigned to a list of score points. Each value can lie between 0 points (bad) and 25 points (excellent). The flow index according to Carr ff_{cc} is the sum of alle four score points and can reach in the best case 100 points. The experimental method is specified in a work instruction (ASTM D6393).

To determine the angle of repose the material is poured by a vibrating funnel on a round plate. The angle of repose is measured.

Due to determine the angle spatula, a spatula is lifted from the bottom of a container with the material and the slope angle of the material on the spatula is measured.

The compressibility C is calculated from the packed bulk density P and the loose bulk density L:

$$C = \frac{P - L}{P} \cdot 100\,\% \quad (7)$$

The material residue remaining after test screening on three screens is used to determine the cohesion K according to Carr. First of all 2 g is weighed out as sample mass. The cohesion is obtained in % from the residual mass on the upper screen m_{RoS}, the middle screen m_{RmS} and the lower screen m_{RuS}:

$$K = \frac{100}{2}\left(m_{RoS} + m_{RmS}\cdot\frac{3}{5} + m_{RuS}\cdot\frac{1}{5}\right) \quad (8)$$

It is measured if the determination method allows this. If this is not possible, the coefficient of uniformity U from the screen analysis is used:

$$U = \frac{x_{60;3}}{x_{10;3}} \quad (9)$$

Each value is determined from three repeat tests so that the flow index ff_{cc} according to Carr of a bulk material sample results from 15 individual experiment tests.

2.3 Test material

A standard commercial dry compound feed with a barley component of 72% and a rye component of 20% is used as test material. In order to be able to determine the influences of the granulometric parameters particle size and particle size distribution, the samples are made up in accordance with the bi-parametric and tri-parametric logarithmic normal distribution (LND). The granulometric condition of pig finishing feed is varied for the bi-parametric logarithmic normal distribution by systematically altering the central value $x_{50;3}$ and the standard deviation σ_ζ. For the material systems with tri-parametric logarithmic normal distribution, the standard deviation is σ_ζ^* constant $\sigma_\zeta^* = 0.9$. This corresponds to the real value in practice. The granulometric condition is varied by systematically changing the central value $x^*_{50;3}$ and the maximum particle size x_{max}. At constant standard deviation σ_ζ^*, the central value $x^*_{50;3}$ and the maximum particle size x_{max} determine both the half value and the width of the particle size distribution function.

2.4 Performance of the experiments

Shear strength measurements are carried out to determine the flow properties according to Jenike. The ring shear tester and the translation shear tester according to Jenike can be considered measuring equipment here. As the ring shear tester is more suitable for compressible organic substances than the translation shear tester due to the infinite shear path, it was used in this case.

The following parameters are determined from a yield locus family and the wall yield locus: angle of internal friction φ_i, effective angle of friction φ_e, stationary angle of friction φ_{St}, uniaxial compressive strength σ_c, cohesion τ_c (shear strength at normal stress $\sigma_N = 0$), wall friction angle φ_x and adhesion τ_{cx} (wall shear strength at the normal stress $\sigma_N = 0$).

The experimental unloading tests were carried out with a level model silo. The dimensions height x width are 100 x 50 cm. The hopper angle θ can be varied infinitely. The gap width of the unloading outlet can also be varied infinitely up to 100 mm.

3 Results and discussion

3.1 Flowability according to Jenike

Given the same values of the flowability ff_c, higher values for the unloading outlet are obtained with lower densities (Schulze, 2012). If we use σ_1 = 3 kPA in Equation (5) for the consolidation stress and ρ_L = 700 kg/m^3 for the bulk density (grain products), ρ_L = 1500 kg/m^3 (mineral raw materials) and ρ_L = 2500 kg/m^3 (iron ores) and for H(θ) = 2 (simplified), then for $d_A = f(ff_c)$ we obtain the following family of curves with the density as parameter (Figure 1):

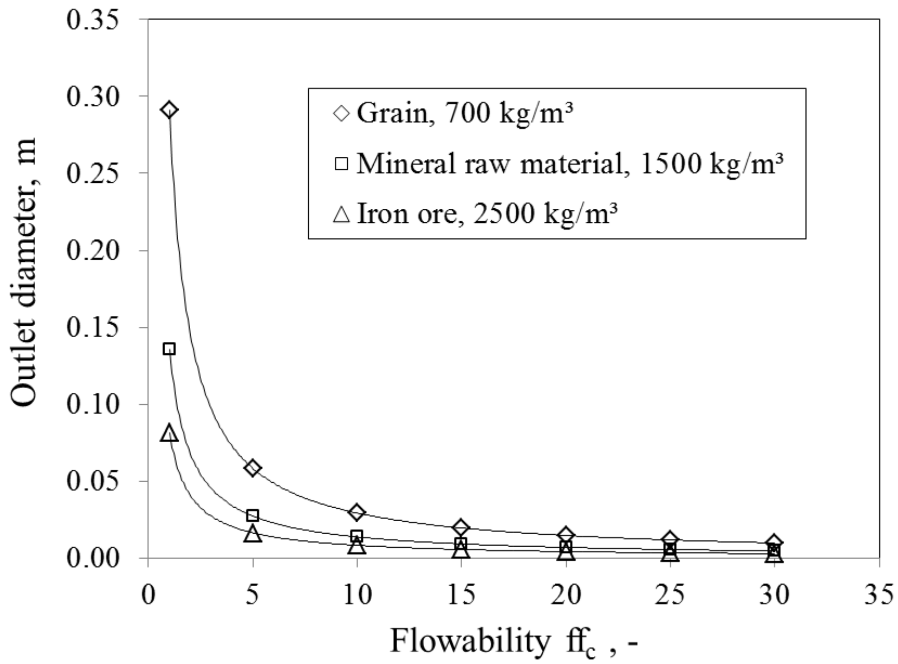

Figure 1 Connection between the outlet diameter d_A and flowability ff_c in accordance with the dimensioning equation for unloading outlets at a consolidation stress σ_1 = 3 kPa

Jenike thus subsequently recognised that the flowability is also a function of the density.

The smaller the particle size $x_{50,3}$, the lower the flowability according to Jenike (Figure 2). For particel sizes x < 0.2 mm the flowability reaches very low values of $ff_c < 10$.

This is evident from examinations with uniform grain ($0.08 < \sigma_\zeta < 0.22$) and coincides with the results of measurements conducted in parallel on the tensile strength of the angle of repose, spatula angle and compressibility (Fürll and Hoffmann, 2013).

In material systems with a particle size distribution according to the bi-parametric LND, the influence of the standard deviation on the flow function in the range examined is inversely proportional. The central value $x_{50;3}$ influences the flow properties according to the third power (Figure 3).

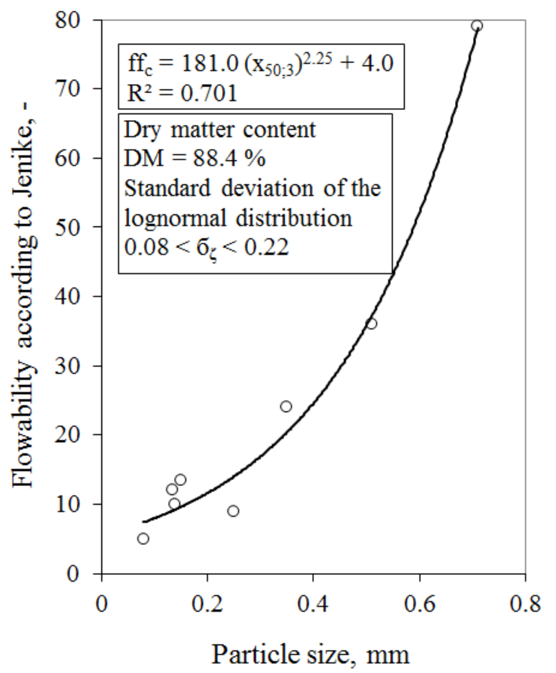

Figure 2 Flowability ff_c according to Jenike as a function of the particle size $x_{50,3}$ of grain – dry compound feed

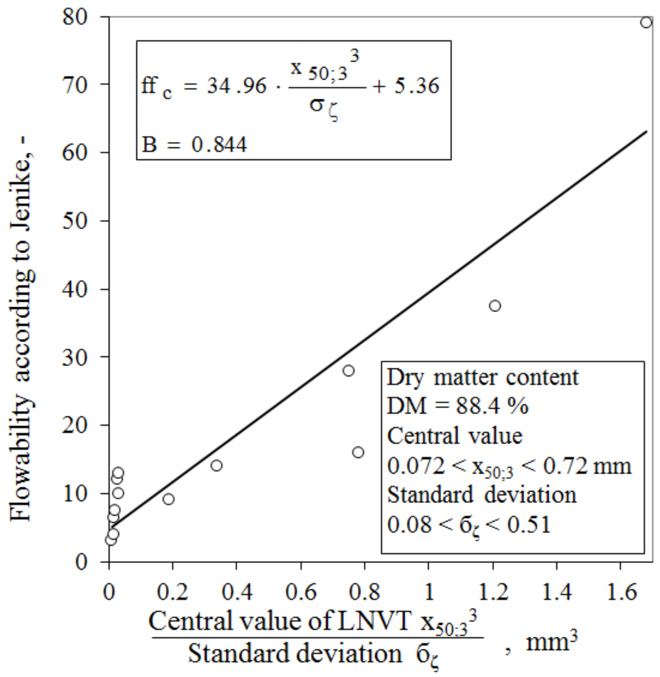

Figure 3 Flowability ff_c according to Jenike as a function of the ratio central value $x_{50;3}$/standard deviation σ_ζ of the bi-parametric LND

The share of cohesive fines results in a sudden drop in the range Q_3(0.2 mm) = 5% to 20%, for both material systems with a particle size distribution in accordance with the bi-parametric LND and systems in accordance with the tri-parametric LND (Figure 4).

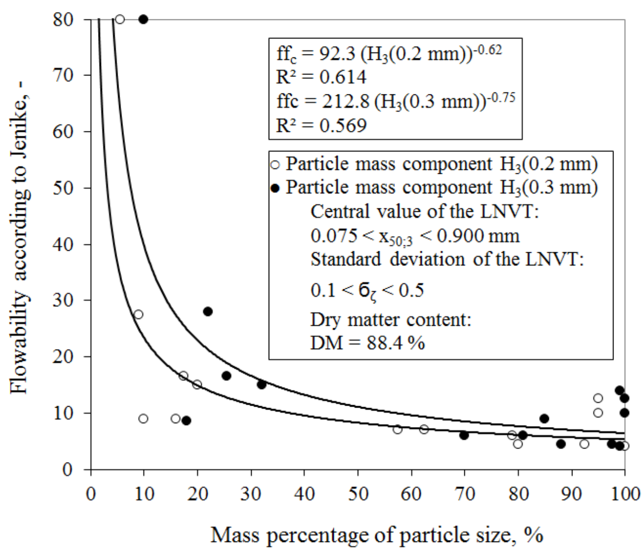

Figure 4 Flowability ff_c according to Jenike for grain – dry compound feed as a function of the mass percentage of particle size $Q_3(x)$ of the cohesive fines for particle size distributions in accordance with the bi-parametric LND

3.2 Flow index according to Carr

For the grain/dry compound feed examined, in principle the same trends apply for the flow index according to Carr ff_{cc} as a function of the granulometric condition as for the results of the flow function according to Jenike ff_c. Material systems with a particle size distribution according to the bi-parametric LND display a dependence of the flow index ff_{cc} on the ratio $x_{50;3}/\sigma_\zeta$ (Figure 5).

The course of the flow index according to Carr as a function of the cohesive fines share $Q_3(x_{FG})$ brings about a sudden drop in the values in the range of Q_3(0.2 mm) = 50% to 20%, as in the flow function according to Jenike ff_c.

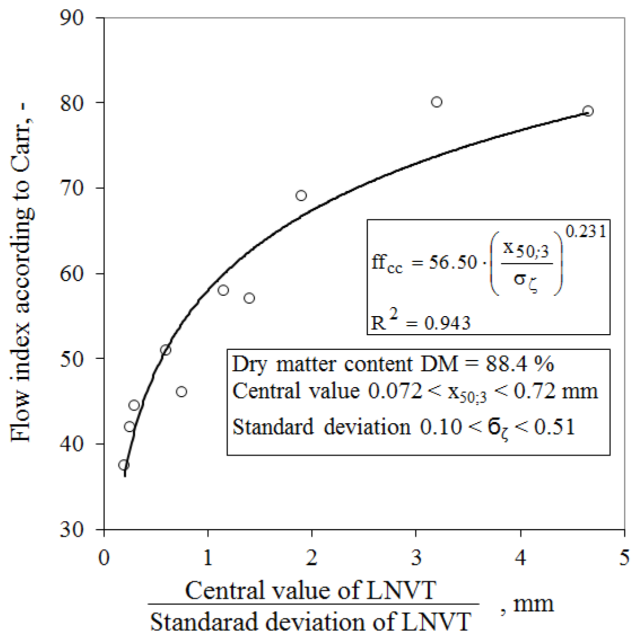

Figure 5 Flow index ff_{cc} according to Carr of grain/dry compound feed as a function of the ratio central value $x_{50;3}$ / standard deviation σ_ζ for particle size distributions in accordance with the bi-parametric logarithmic normal distribution (LND)

The verbal textual assessment of the flow properties results in a few differences between the classifications by Carr and Jenike (Table 1). In the area that Jenike estimates as "easily flowing", Carr states "not good" or even "poor".

3.3 Outflow from a model container

The examinations to determine the minimum gap width b as a function of the hopper inclination for disturbance-free outflow were carried out with uniform grain material systems and with material systems with a particle size distribution according to the tri-parametric logarithmic normal distribution. At the minimum gap width for cohesionless materials stated by Kvapil (1959), uniform grain substance systems only flow undisturbed as of a particle size x > 1.2 mm and a hopper inclination angle Θ = 15° (Figure 6). At a linear connection between the minimum gap width and particle size, completely cohesionless behaviour only exists as of a particle size x > 0.8 mm. For particle sizes x < 0.2 mm, the minimum gap widths are rise abruptly. This corresponds to a flowability value ff_c according to Jenike of $ff_c < 10.0$.

Material systems with a real particle size distribution, expressed by the Sauter diameter $d_{St,}$ require a larger minimum gap width b than uniform grain material systems in the range $d_{St} > 0.5$ mm to be

Table 1 Assessment of the flow properties of grain/dry compound feed with dual parameter particle size distribution according to Carr and Jenike

Sample No.	Central value $x_{50;3}$ mm	Standard deviation σ_ζ -	Flow index ff_{cc} acc. to Carr-	Assessment of flowability ff_{cc} acc. to Carr	Flowability ff_c acc. to Jenike -	Assessment of flowability ff_c acc. to Jenike
1	0.550	0.49	58.25	not good	14.6	free flowing
2	0.540	0.28	69.00	normal	28.1	free flowing
3	0.510	0.11	79.00	good	37.5	free flowing
4	0.165	0.51	44.75	not good	6.2	easily flowing
5	0.165	0.30	51.00	not good	6.6	easily flowing
6	0.154	0.11	57.50	not good	14.0	free flowing
7	0.075	0.49	37.50	poor	4.4	easily flowing
8	0.076	0.29	42.00	not good	4.6	easily flowing
9	0.072	0.10	46.00	not good	4.1	easily flowing
10	0.720	0.22	80.00	completely good	79.7	free flowing
11	0.720	0.22	80.00	completely good	39.2	free flowing

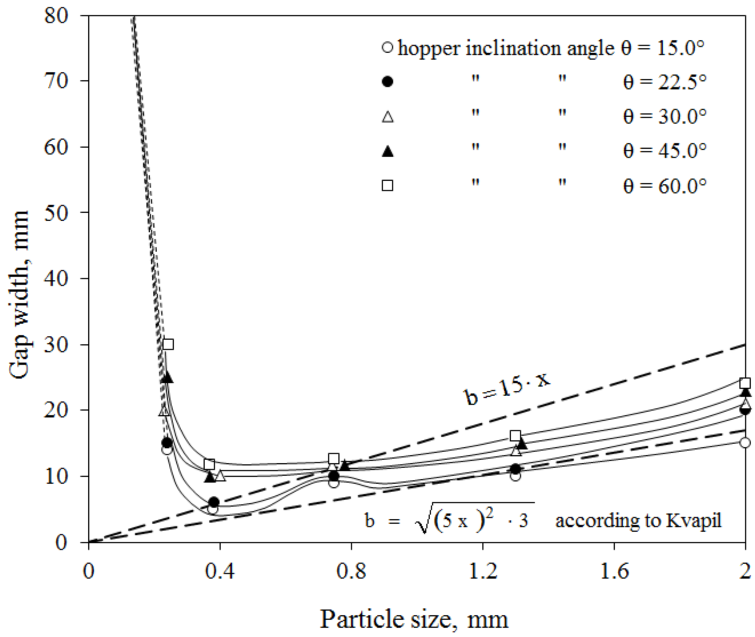

Figure 6 Minimum gap width b for disturbance-free outflow of pig finishing feed from a level laboratory container as a function of the parameters particle size x of uniform grain material systems and the hopper inclination angle

considered as cohesionless.

Hopper inclination angles θ ≤ 45° show a similar relation between Sauter diameter d_{St} and minimum gap width and can be combined (Figure 7). They lead to mass flow. Greater angles θ ≥ 60° result in core flow.

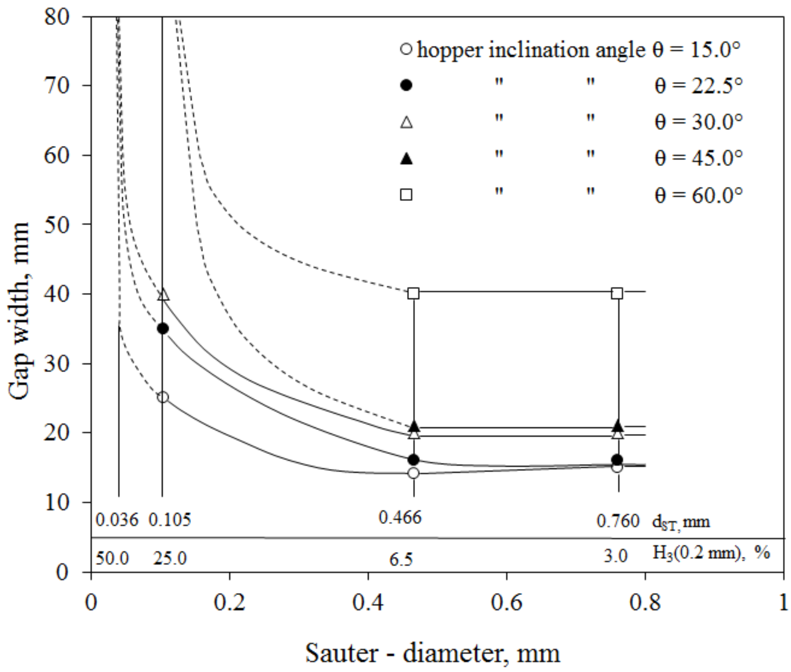

Figure 7 Minimum gap width b for disturbance-free outflow of pig finishing feed from a level laboratory container as a function of the Sauter diameter d_{St} and the cohesive share of fines Q_3(0.2mm) as well as the hopper inclination angle θ as parameters

A Sauter diameter d_{St} = 0.5 mm requires in the case of mass flow (θ ≤ 45°) a minimum gab width of 20 mm. For the practical application of mass flow, a slightly greater gab width of 25 mm should be selected. Therefore the minimum gab width b (25 mm) is 50 times greater than d_{ST} (0.5 mm). For core flow a Sauter diameter d_{St} = 0.5 mm demands a gab width greater 40 mm. Considering a safety margin, b > 50 mm should be chosen. Therefore, the following relations can be drawn up for the minimum gap width from the test results for disturbance-free outflow:

$b > 50\ d_{St}$ for mass flow

$b > 100\ d_{St}$ for core flow

It is not possible to state the minimum gap width as a function of the Sauter diameter in the cohesive range. It is apparent from the experiments and on the basis of the flowability according to Jenike and the flow index according to Carr that even slight components of cohesive fines Q_3(0.2 mm) > 7.0% substantially reduce the flow properties, above all for outflow in the core flow (Figure 7).

3.4 Comparison of the results

It becomes clear from the results of the experimental studies that the textual evaluation of the flow properties produces some differences between the classification by Carr and the original recommendation by Jenike (Table 1). According to the experiments conducted to determine the minimum gap width, it can be appraised that the assessment according to Carr is more realistic for crushed grain products.

Despite this assessment, the method by Carr is more suitable for verbal assessments of the flowability (Schwedes, 2003; Ganesan et al., 2008). In contrast, the shear test according to Jenike delivers physical based material parameters. These parameters are the basis for dimensioning the silo outlets.

Up to the time of publishing his classification, Jenike probably only conducted examinations with mineral raw materials that on average possess a three to four times higher bulk density than grain products. As the storage density according to Jenike is used inversely proportionately to calculate the outlet geometry, the differences can be explained (Equation (4)).

That is why the following classification is suggested on the basis of our own examinations of crushed grain products for these substances:

$ff_c < 6$	very cohesive, non-flowing
$6 < ff_c < 30$	cohesive
$30 < ff_c < 50$	easily flowing
$50 < ff_c$	free flowing

A hyperbolic curve is obtained from the ff_c-values for the flowability determined from shear tests and the calculated outlet diameters (Figure 8). This function curve coincides approximately with the values calculated in accordance with Figure 1.

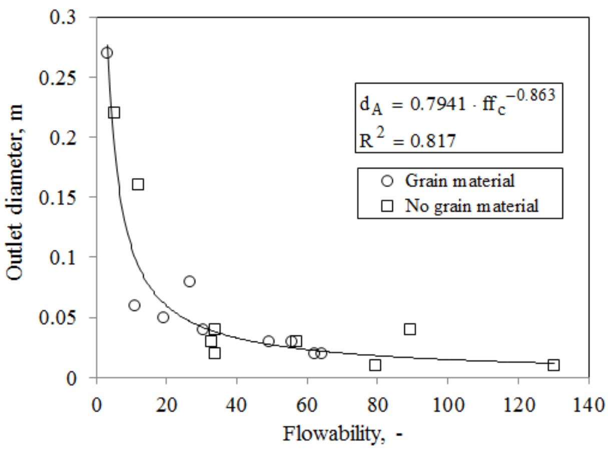

Figure 8 Connection between the flowability ff_c and the calculated diameter d_A of the unloading outlet from experiments with crushed grain

4 Conclusions

At particle size distributions according to the bi-parametric LND, the ratio of central value $x_{50;3}$ / standard deviation σ_ζ influences the flowability ff_c according to Jenike and the flow index ff_{cc} according to Carr inversely proportionately according to statistically secured connections. The flow properties of particle size distributions according to the tri-parametric LND at constant transformed standard deviation σ_ζ^* are above all a function of the transformed central value $x^*_{50:3}$. The causes lie in the outstanding influence of the cohesive fines $Q_3(x_{FG})$. The flowability ff_c according to Jenike and the flow index ff_{cc} according to Carr drop abruptly in the range of $Q_3(x_{FG})$ = 5% to $Q_3(x_{FG})$ = 25%. This connection also becomes clear from the results of experimental unloading tests and confirms that the flow properties are determined above all by their share of cohesive fines. For grain/dry compound feed, the boundary particle size below which the cohesive properties increase progressively is x_{FG} = 0.2 mm.

In the textual evaluation of the flow properties roughly the same tendencies are obtained using the methods according to Jenike and Carr, but partially very different textual evaluations result. This is attributable to the fact that in his original classification Jenike did not take the material density into account. He corrected this later with the recommendation that the outlet widths be used as measure for the flowability. On the basis of the examinations conducted a more realistic classification is suggested for evaluating the flow properties of crushed grain products with the help of the flowability ff_c according to Jenike.

However, it is better to use the required opening width as a value for characterising the flowability, as proposed by Jenike (1975).

References

ASTM D6393: Standard Test Method for Bulk Solids Characterization by Carr Indices. American Society for Testing and Materials (ASTM), ASTM International, www.astm.org. (Accessed on Aug 12, 2015)

Carr, R. L. 1965. Evaluating flow properties of solids. *Chemical Engineering*, 72(2): 163-168.

Chang, C. S., and H. H. Converse. 1988. Flow rates of wheat and sorghum through horizontal orifices. *Transaction of the ASAE*, 31(1): 300-304.

Fürll, C. 2007. Influence of the granulometric condition on the flow properties of crushed grain products. *Bulk Solids& Powder – Science &Technology*, 2(1): 55–62.

Fürll, C. 2006. Beurteilung der Fließeigenschaften von Getreideschrot mit Hilfe einfach bestimmbarer Schüttgutkenngrößen. *Mühle + Mischfutter*, 143(1): 17–22.

Fürll, C. 1978. Einfluss des Abriebanteils von kompaktiertem Trockenfutter auf die Gestaltung von Lagerbehältern. *Agrartechnik*, 28(5): 200-203.

Fürll, C. 1979. Einfluss des Feinkornanteils auf das Ausfließen von pelletiertem Futter aus Behältern. *Freiberger Forschungsheft*, A 634, 127-141.

Fürll, C., and T. Hoffmann. 2013. The influence of the granulometric condition on the flow characteristics of shredded grain products in their dependence on the duration of storage. *Powder Technology*, 235: 307-311.

Ganesan, V., K. A. Rosentrater, and K. Muthukumarappan. 2008. Flowability and handling characteristics of bulk solids and powders – a review with implications for DDGS. *Biosystems Engineering*, 1010: 425-435.

Höhne, D., and U. Schünemann. 1980. Untersuchungen zum Einfluss der Korngrößenverteilungsparameter auf die Fließfähigkeit feinkörniger Schüttgüter. *European Symposium ParticleTechnology*, Amsterdam, Vol. B: 968-980.

Jenike, A. W. 1975. A measure of flowability for powders and other bulk solids. *Powder Technology*, 11: 89-90.

Kurz, H. P., and G. Münz. 1975. The influence of particle size distribution on the flow properties of limestone powders. *Powder Technology*, 11(1): 37-40.

Kvapil, R. 1959. *Schüttgutbewegung in Bunkern*. VEB Verlag Technik, Berlin, 83 p.

Münz, G. 1976. *Entwicklung eines Ringschergerätes zur Messung der Fließeigenschaften von Schüttgütern und Bestimmung des Einflusses der Teilchengrößenverteilung auf die Fließeigenschaften kohäsiver Kalksteinpulver*. PhD-thesis, Universität Karlsruhe.

Nothdurft, H. 1977. Lagern von Sojaschrot. *Kraftfutter*, 60(5): 189-193.

Ogniwek, D. 1979. Die innere Reibung von Schüttgütern – Untersuchungen von Materialeigenschaften verschiedener Silolagerstoffe. *Fortschrittberichte der VDI-Zeitschriften*, Reihe 3, Nr. 50, VDI-Verlag, Düsseldorf.

Peschl, I. A. S. Z. 1989. Quality control of powders for industrial application. *Powder handling & processing*, 1(4): 357-363.

Schulze, D. 1994. Entwicklung und Anwendung eines neuartigen Ringschergerätes. *Aufbereitungstechnik*, 35(10): 524-535.

Schulze, D. 2008. *Powders and bulk solids*. Springer-Verlag Berlin Heidelberg, p. 47.

Schwedes, J. 1968. *Fließverhalten von Schüttgütern in Bunkern*. Verlag Chemie, Weinheim/ Bergstraße.

Schwedes, J. 1980. Vergleichende Betrachtungen zum Einsatz von Schergeräten zur Messung von Schüttguteigenschaften. *Freiberger Forschungshefte*, A 634: 35-51.

Schwedes, J. 2003. Review on tester for measuring flow properties of bulk solids. *Granular Matter*, 5(1): 1-43.

ShearTest. 2015. Measurement of physical properties of bulk materials. homepage of the company Shear-Test GmbH. http://www.shear-test.de/de/lit-grundlagen.php (Accessed on Feb 25, 2015).

Schulze, D. 2012. Personal communication. Sept. 2012.

Stasiak, M., and M. Molenda. 2004. Direct shear testing of flowability of food powders. *Research in Agricultural Engineering*, 50(1): 6-10.

Stasiak, M., M. Molenda, I. Opalinski, and W. Blaszczak. 2013. Mechanical properties of native maize, wheat and potato starches. *Czech Journal of Food Sciences*, 31(4): 347-354.

Walker, D. M. 1966. An approximate theory for pressures and arching in hoppers. *Chemical Engineering Science*, 21(11): 975-997.