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FLOW PROPERTIES FOR SILO DESIGN - A REVIEW

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ABSTRACT

Silos are essential structures to maintain the quality of products such as grains, seeds and other agricole products used by industries, agricultural, and mineral sectors. The correct dimensioning and design of a silo project depends on determining the physical and mechanical properties of the products to be stored, since the type of flow as well as the intensity and distribution of stresses in the structure depend on these. There-fore, product characterization should be one of the first steps taken when designing or modifying a loading and unloading system. The characterization of the product to be stored consists of determining its physical properties, such as: consolidated specific weight, internal friction angle, effective internal friction angle, friction angle of the product with the wall, flow function, granulometry, and moisture and product content, which must be carried out under the most severe conditions that can occur in the silo. The Jenike Shear Test device is suitable equipment to measure these properties, making it possible to determine the stresses that the product will be subjected to during storage and in the flow conditions predicted to happen in the silo. There-fore, this review aimed to approach the physical and flow properties of stored products, enabling the development of safe, robust and reliable projects, in such a way that operations such as unloading, transilage, dosing, and packaging of products can be maximized. The importance of each property is noted, as it intrinsically affects the behavior of the product during storage, handling and processing.

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INTRODUCTION

Silos are storage structures widely used in the industry and agricultural sector aiming at stock conservation, supply of the manufacturing process and efficient use of space, both for granular and powdery materials (YU *et al*., 2017; ZHANG *et al*., 2018). However, they are complex structures to design since they often present operational problems since there are different types of products that can be stored (DORNELAS *et al*., 2021), these impasses occur mostly in systems in which the structures are designed without knowledge of the relevant characteristics of the flow of the product to be stored. In order to obtain an economic, safe and durable structure, the determination of the relevant properties of the product to be stored constitutes the first step in the design of silos, which are fundamental for understanding the flow and calculating the pressures that will occur during the loading, storage and unloading operations (ALONSO-MIRAVALLES *et al*., 2020). During product loading, problems such as compaction and segregation may occur and, in the unloading operation, there is the possibility of formation of stable vaults over the discharge orifice, causing serious flow problems (obstructions) and structural problems in the installation (PAULA, 2020). Common problems include clogging, segregation, clogged or partially limited discharge orifice, sudden and uncontrollable flow and sticking of product to silo walls, which causes loss of usable storage area and can lead to deterioration of stored material (WESTOVER *et al*. al., 2015). In this way, it is essential that the properties of the flow of stored products can be reliably determined and reach the actual conditions of expected operations. Currently, there are several types of equipment to obtain the flow properties of stored materials (MASCARENHAS *et al*., 2017), in which shear cells are the most used devices worldwide (JIN *et al*., 2018; MACRI *et al*., 2020) highlighting the "Jenike Shear Cell" or Jenike shear cell as one of the most accepted methods to determine the flow properties of cohesive or non-cohesive products (MEIRA *et al*., 2019) and recommended by most international standards (GUO *et al*., 2019). al., 2018; MALLICK *et al*., 2018). With this equipment, the voltage to which the product will be subjected during air-storage can be determined, as well as the flow conditions predicted to occur in the silo and obtaining the following parameters for the flow design: consolidated specific weight (γ), internal friction angle (ϕ_i), effective internal friction angle (ϕ_e), friction angle of the product with the wall (ϕ_w) and flow function (FF) (JIN *et al*., 2018; FURLL & HOFFMANN, 2015; STASIAK *et al*. al., 2015; CALDERÓN *et al*., 2017; MALAGALAGE *et al*., 2018). In addition to these, it is extremely important to determine the granulometry (d_{max} and d_{min}) and moisture content (w) of the product. Because silos are structures designed to store a diverse range of bulk solids and these, in turn, vary greatly in their properties, making a silo designed to properly store one material inefficient and dangerous to store another. Knowledge of the physical and mechanical properties of agricultural products is of fundamental importance for the rational and safe dimensioning and design of the silos, as the pressures that develop are directly related to these. Thus, the objective of this review was to present a comprehensive explanation of the heterogeneity of the main parameters of stored products that must be evaluated in the structural design of silos.

METHODOLOGY

The present study is a narrative review about the flow properties for designing vertical silos. The review covered scientific articles, monographs, theses and dissertations published and available in the following databases: Capes (Coordination for the Improvement of Higher Education Personnel), Scielo (Scientific Electronic Library Online) and Googleacadêmico. Studies that did not present the abstract, and did not address the subject under study, were discarded, as well as opinionated articles that were not supported by research data or that did not have the support of a systematic data collection.

REVIEW

Consolidated specific weight (γ): Property defined as weight per unit of volume, being affected by the degree of compaction of the product resulting from its humidity, overpressures that occur in the silo, storage time, rate and mode of loading and drop height of the product (FURLL & HOFFMANN, 2015). The specific weight has no direct relationship with the flow prediction, however, its determination is essential because it is an important parameter for calculating the pressures acting on silo walls and hoppers (JAGER *et al*., 2015) in addition to the estimation of the silo capacity (STASIAK *et al*., 2015). A common assumption is that the specific gravity is constant within a silo. However, solids are porous materials, mainly grains, so the specific weight of the product varies with the pressure it is subjected to (and therefore with the depth of the product in the silo) (CHENG *et al*., 2017).

Low specific gravity powdery products have the advantage of flowing with less resistance to compaction in the hopper section, however, they have the disadvantage of inertia at rest and a high air resistance. In contrast, a high specific gravity powder may compact for greater strength in the hopper section, but will have a low inertia at rest. It is known that granular products do not have high compressibility, therefore, they do not develop much resistance in the silo discharge orifice. The specific weight can be obtained by weighing the Jenike shear cell with the dry product, after the shear test, subtracting the cell's own weight, dividing the result by the cell volume, and multiplying by the acceleration of gravity ($g = 9.81$ m s-^{2}). For the design limit state, (GOMES & CALIL JÚNIOR, 2005) propose the range for the specific weight as $0.75 \leq \gamma \leq 1.20$. Major foreign standards such as European EN 1991-4:2006; ISO 11697:2012 and the Australian AS 3774:1996, provide, through tables, characteristic values of this physical property (lower and upper limits or only an average estimate) for certain agricultural and industrial products, according to Table 1. However, these values vary between the norms, recommending, whenever possible, to carry out tests in the laboratory to characterize the product to be stored.

Table 1. Characteristic values of specific weight (kN m-3) recommended by the standards for some products

Product	Standards				
	Australian AS3774/199		European EN 1991-4/200		European ISO 11697/1
	γ	$\gamma S_{uperior}$	$\gamma_{inferior}$	$\gamma S_{uperior}$	γ_{medium}
Sugar	8	10	8	9,5	10
Barley	7	8,5	7	8	8,5
Cement	13	16	13	16	16
Corn	7	8,5	7	8	8,5
Soy	7	8	7	8	8,5
Wheat	7,5	9	7,5	9	8,5
Flour	6,5	7,5	6,5	7,0	7,5

Granulometry: Granulometry characterizes one of the properties that directly influences the flow pattern, determining the type of flow (JAGER *et al*., 2015) Products classified as granular are generally free-flowing, whereas fine-grained products commonly have less fluidity due to cohesion (SILIVERU *et al*., 2017). MELLMANN *et al*., 2013 studied the effect of the shape and granulometry of different granular producers (wheat, barley, oats and corn) on the flow properties, with two granulometric ranges evaluated, from 0.315 to 0.5 mm and 0.5 to 0.8 mm. The authors found an increase in fluidity for the largest granulometric range (0.5 to 08 mm), due to the fact that they present non-cohesive properties. In terms of shape, the results revealed that the fluidity of the crushed grains decreased the more the shape of the particles moved away from the spherical shape. LIU *et al*.,2015 evaluated the effect of granulometry on the fluidity of powdered coal. The authors observed during the experiment a progressive transition from mass flow to mixed flow and complete obstruction as the particle size decreased. Coal whose particles had a diameter greater than 100 μm obtained mass flow, variation between 40 and 100 μm presented unstable flow, and the formation of a cohesive arc was obtained for the product whose diameter was less than 40 μm. The determination of flow properties for sawdust and wood chips with different moisture contents showed that the increase in the moisture content of both materials results in an increase in the consolidated specific weight and a reduction in fluidity (STASIAK *et al*., 2015). A similar behavior was observed by SILIVERU *et al*., 2017 when analyzing three granulometric ranges of wheat flour (75-106, 45-75 and <45 μm). Based on the average size distribution of wheat particles, the authors concluded that there is a significant contribution in increasing cohesion and reducing product fluidity for granulometry of <45 μm. For this characteristic property of storable products, there is a proposal for classifying solid products according to the dimensions of the diameter of the particles in terms of cohesion and flow (Table 2) (CALIL JÚNIOR, 1984).

Table 2. Grain size classification of solid products (CALIL JÚNIOR, 1984)

Particle diameter (mm)	Classification
D > 0,42	Granular
0,42 ≤ D ≤ 0,149	Cohesive powders
0,149 < D ≤ 0,079	Fine cohesive powders
D < 0,079	Extra-fine cohesive powders

When the product has varied granulometry, the product fluidity is governed by the smaller particles, while the larger particles have a greater tendency to cluster close to the discharge orifice, which can cause product compaction, with the formation of a mechanical arc.

Moisture content (w): The determination of moisture is fundamental, constituting a property that directly affects the density, durability and ability to flow of the product (RIPP *et al*., 2015) The increase in moisture associated with storage time makes fluidity difficult, increasing the possibility occurrence of flow obstructions, especially for powdery products (MITRA *et al*., 2017). As the moisture content increases, the flow of the stored product decreases, reaching a maximum value around 80 to 90% saturation. Above these moisture contents, viscous properties are presented by the solid product, making it impossible to carry out shear tests (CALIL JÚNIOR, 1990). However, some researchers consider that moisture, up to certain levels, improves the flow of powdery products, as it can act as a lubricant, facilitating the flow, or acting by preventing the formation of electrostatic charges between the particles, consequently, reducing cohesion and internal friction, thus preventing flow interruption (MITRA *et al*., 2017). COSTA *et al*., 2014 determined the mechanical and flow properties of granular products (rice grains and crushed corn) with moisture contents of 10, 12 and 14% and of powdery product (cassava flour) with moisture contents of 10 and 12%. The authors found that the angle of internal friction (φi) and effective angle of internal friction (φe) for all products studied increased as a function of the increase in moisture content. MITRA *et al*., 2017 analyzed the flow properties of powdered milk product (basundi) at different moisture contents (3, 6 and 9%). The results showed that the flow properties of the product were largely affected by the moisture content, indicating an increase in cohesion with higher moisture contents (6 and 9%), requiring a steeper hopper design to obtain mass flow. For NASCIMENTO, 1996, under high levels of humidity and adverse atmospheric conditions, the grains can undergo fermentation, acquiring resistance and ceasing to be free-flowing. Soybean flour contains oil, presents union of its particles under conditions of high temperature and moisture content, forming a mass of difficult flow. For safe storage, grains must have between 13 and 14% moisture on a wet basis (b.u.) (SOUZA *et al*., 2015). The Australian standard AS 3774 provides for an increase in pressure on the walls of the silo when there is expansion of the stored product due to the absorption of moisture, describing the changes that occur in the horizontal pressure and friction force on the walls, being valid when the variation of the content humidity exceeds 1% after storage of the product. In contrast, the American standard ANSI/ASAE EP433, 1988 reports that the moisture content during storage can increase by 4% or more, providing increased lateral pressures under static conditions; and that a 4% increase in moisture content provides six times greater lateral pressure, and for a 10% increase in product moisture after storage, the pressure increases by a factor of 10. Due to the potential for high loads, it is recommended that silos be designed, located and handled in such a way as to avoid an increase in moisture content of more than 1-2% during storage.

Angle of repose (ϕr): The angle of repose can be defined as the maximum angle of the slope formed by the product in relation to the horizontal (WOJICIK *et al*., 2019; LI *et al*., 2020), and can be used as an indication of product fluidity (RACKL *et al*., 2017; JIN *et al*., 2018). In practical terms, the angle of repose is widely used in the design of silos and hoppers to determine the storage capacity (AL-HASHEMI & AL-AMOU-DI, 2018). However, numerous factors, such as internal friction angle, particle size and shape, density, moisture content, segregation, roughness of the base on which the material is deposited, speed and height of spillage (according to the equipment used to determine), material morphology, and addition of solvents can affect the angle of repose (RACKL *et al*., 2017; AL-HASHEMI & AL-AMOUDI, 2018). The main methods for determining the angle of repose require very simple settings, however, as the angle depends on many internal material properties, as well as external factors such as pre-consolidation or measurement technique, there is no consensus on how its value must be determined and the few national and international standards and guidelines are inconsistent (RACKL *et al*., 2017). Several methods can be used to determine the angle of repose of solid particles, the most commonly used for physical measurement (Figure 1): fixed funnel method; box with one side removable and hollow cylinder method (RACKL *et al*., 2017; AL-HASHEMI & AL-AMOUDI, 2018) tipping box method, rotating cylinder/drum method, tipping cylinder method; and can also be obtained by numerical methods, such as the discrete or distinct element method (DEM), electrical capacitance tomography (ECT) and photogrammetric method (WOJCIK *et al*., 2019; LI *et al*., 2020).

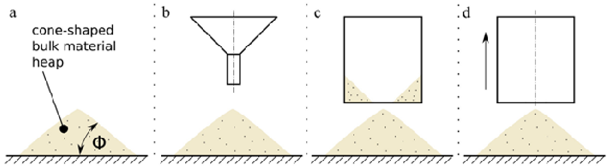

Figure 1. Visualization of angle of repose definition, Φ, (a) and three methods to generate suitable stacks for angle of repose measurements. b: Fixed funnel method, c: Box with one side removable, configuration to measure angle of repose (bottom part) and drained angle of repose (top part), d: hollow cylinder method (RACKL et al., 2017)

Given the diversity of methods for determining this property, researchers claim that the method should be selected based on pre-defined objectives and for a specific material and application (AL-HASHEMI & AL-AMOUDI, 2018). Conducting a comparison between different methods can be challenging because each method is targeted for a specific application. The funnel method is widely used in silo designs, for powdery and granular materials (AL-HASHEMI & AL-AMOUDI, 2018).

Internal friction angle (ϕi) and Effective internal friction angle (ϕe): Both properties are obtained directly from the slip locus, by laboratory testing (Jenike's shearing machine, for example) or by means of tables provided by the main foreign standards for silo design, with lower and upper limits of the angles of certain products. For materials not listed in the standard, or for accurate calculations, testing is recommended. To determine the ϕi and ϕe through shear tests, it is necessary to know the Mohr-Coulomb envelopes (Figure 2). All stress circles tangential to the slip locus represent the stress states in which the product starts to flow (KOYNOV *et al*., 2015) and the axis of normal stresses. When the analyzed material is not free-flowing, the aforementioned line does not pass through the origin, with cohesion (C) being the coordinate at which this line cuts the origin.

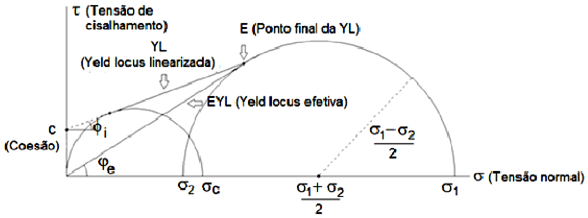

Figure 2. Graphic representation of the Mohr-Coulomb envelopes, internal friction angle, effective internal friction angle and product cohesion (MASCARENHAS et al., 2017)

The line passing through the origin and tangent to the largest Mohr semicircle, that is, the circle representing the state of steady flow, is called the effective locus of slip and the angle formed between this line and the axis of normal stresses, effective internal friction angle (ϕe) (Figure 2) (RIPP *et al*., 2015; KOYNOV *et al*., 2015). Factors such as ambient temperature, product moisture content and storage period can significantly influence test results. Therefore, the tests must be conducted as close as possible to the conditions expected for the storage of the product (CHEN *et al*., 2018). The internal friction angle refers to the internal conditions of the product in the storage condition, that is, the friction existing between the particles, and the effective internal friction angle is used to estimate the flow conditions. With this parameter, the maximum angle of inclination of the hopper wall in relation to the vertical is determined to obtain the desired flow pattern (STASIAK *et al*., 2015). It is verified, therefore, that the flow parameters, such as the internal friction angle and effective internal friction angle, were presented by Jenike not only to demonstrate the flow behavior, but also to provide a theoretical basis for the design of the silo. This makes the design of the structure and equipment for handling and transporting materials more accurate and suitable for real situations (CHEN *et al*., 2018).

Internal friction angle of the product with the wall (ϕw): Special attention should be paid to the friction angle of the product with the wall, both for the determination of the geometric characteristics of silos, as well as hoppers (minimum angle) and dimensions of the discharge hole, representing the adhesion effort between the stored product and the surface of the wall material (JAGER *et al*., 2015). It is essential to know this parameter for the elaboration of structural and stability projects of silos in which safe and consistent discharges must be guaranteed (JAGER *et al*., 2015; IQBAL & FITZPATRICK, 2006). The friction angle of the product with the silo wall can be determined by testing with the Jenike apparatus. To obtain it, the base of the shear cell is changed by a base of the material that will be analyzed, thus enabling the evaluation of the most varied wall materials (smooth, rough steel, acrylic, concrete, etc.) and consequently, determination of the material that will provide more advantages for the product flow (Figure 3).

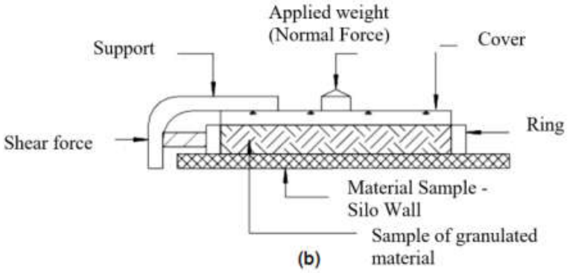

Figure 3. Determination of the friction of the product with the wall in the Jenike cell (MASCARENHAS et al., 2015).

As the wall friction depends on the applied normal stress, the normal stress is varied incrementally during the test. In this way, the values of the wall friction angle can be determined at various normal stresses (JAGER *et al*., 2015; SOGAARD *et al*., 2014). The relationship between the shear stress and the stress normal to the wall will form a straight line that will define the sliding locus with the wall. Its inclination will indicate the friction angle of the product with the silo wall material (Figure 4).

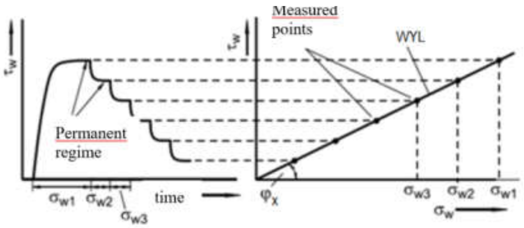

Figure 4. Determination of the friction angle with the wall (MASCARENHAS et al., 2017)

The composition, moisture content and particle size distribution of the products will influence their wall friction characteristics. Smaller particles tend to increase the friction with the wall, as there is greater contact surface area between the particles and the wall surface (IQBAL & FITZPATRICK, 2006). Corroborating what was found by RIPP *et al*., 2015 when analyzing granular (wheat seeds) and powdery (wheat flour) products. Regardless of the wall material, the authors found that the angles of friction with the wall were greater for flour than for seeds, influencing the angle of the hopper.

SILVA *et al*., 2011 analyzed coffee with different moisture contents and stated that the increase in product friction with the wall as a function of water content is possibly due to the fact that products with higher moisture contents generate greater adhesion and cohesion forces between the grains and also between the product and the between the angle of friction of the product with the wall and the particle size. Within the coarse particle range (>100 µm), the wall friction angle for pulverized coals was relatively low and independent of particle size. On the other hand, for fine particles, the angle of friction with the wall increased exponentially with the decrease in particle size, indicating that the friction between the wall and the product will constitute the main effect on the behavior of the flow of pulverized coal. JAGER *et al*., 2015 observed in their studies that the wall friction angle increased with decreasing consolidation stress.

At low values of consolidation stress, the material particles did not undergo appreciable deformation and their surface roughness remained relatively intact, resulting in greater friction with the material on the hopper wall. At higher values of consolidation stress, the particles began to deform into flatter and smoother bodies, resulting in less friction with the material on the hopper wall. For this reason, the ratio of friction/adhesion forces to bonding stress becomes greater with decreasing bonding stress, because friction and adhesion forces do not decrease proportionally to applied stress.

Flow Function (FF): The flow function (FF) characterizes the ability of the product to flow by gravity (flowability measure) (GUO *et al*., 2018) being represented by a straight line generated in the graph with coordinates of main consolidation stresses and unconfined slip stresses of the product in which the slope defines the degree of flowability of the material (Figure 5).

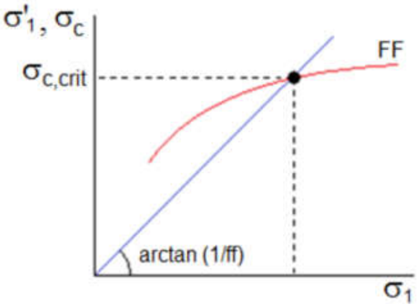

Figure 5. Determination of the Product Flow Function (FF) (MASCARENHAS et al., 2017)

Curves close to the horizontal axis represent free-flowing products and, following a counterclockwise direction, the tendency is for the product to present greater resistance to flow (MASCARENHAS *et al*., 2017), that is, the flowability of the product is configured if as inversely proportional to the angle that the line FF makes with the horizontal. This slope is strongly influenced by storage time (MASCARENHAS *et al*., 2017; NASCIMENTO, 1996), making it necessary to determine the flow function with time (Figure 6).

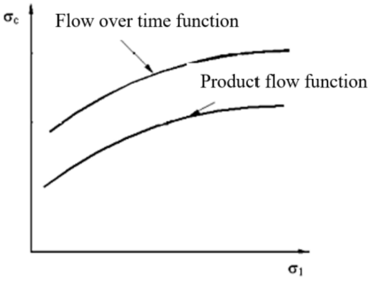

Figure 6. Product flow function and flow function with time (PALMA, 2005).

Each stored product has its own flow function and flow function over time, and the determination of these relationships is important in the design of a silo, in order to prevent flow problems. The greater the consolidation of the product that is stored, the greater its consolidation tension, density and unconfined rupture tension. Free-stress practically null, even for conditions of great consolidations. On the other hand, most cohesive products show unconfined tensile strength when consolidated. The FF values (Table 3) were classified by Jenike, 1976 from their limit. According to Jenike's classification of fluidity, a higher FF value means easier flow. When the FF is in the range of 4-10, particles flow easily. When the FF is in the range of 2-4, fluidity is reduced, due to cohesive properties (GUO *et al*., 2018).

Table 3. Classification of the Product Flow Function according to Jenike, 1976

Flow Function	Classification
FF < 2	Very cohesive products – no flow
2 < FF < 4	Cohesive products
4 < FF < 10	Low cohesive products - easy flow
10 < FF	Free flowing products

CONCLUSION

It is concluded that the knowledge of the physical and mechanical properties of agricultural products is of fundamental importance for the dimensioning and the rational and safe design of the silos, since the type of flow and the pressures that develop are directly related to these. After approaching the main properties, the importance of determination was denoted, in such a way that the tests with the products for design purposes must identify the worst conditions that can happen during the operational life of the silo, since the tests for the characterization of products used in research and presented in foreign normative codes are as representative as possible of real conditions. Thus, a careful determination is necessary aiming at an adequate dimensioning of them for the storage and unloading of this material so that problems such as clogging, segregation, among others do not occur.

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