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RESEARCH ARTICLE OPEN ACCESS

ANALYSIS OF PRESSURES IN A STORAGE SILO OF BEAN CULTIVARS WITH DIFFERENT TYPES OF STEEL

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ABSTRACT

The Brazilian agricultural production exceeds the storage capacity, with that the construction of silo becomes essential, being the loads exerted by the product stored in the structure, the main factor for disasters in silos. In view of this, the present work aims to determine the pressures exerted by bean cultivars, according to EUROCODE 1. The experiment was conducted at the Laboratory of Rural Constructions and Ambience - LACRA of the Federal University of Campina Grande, in the municipality of Campina Grande- PB, analyzing the different types of beans: carioquinha (*Phaseolus vulgaris L.*), black (*Phaseolus vulgaris L.*) and macassar (*Vigna unguiculata*). The physical and flow characteristics of the products were measured, and two types of steel were used, being smooth steel and rough steel, to determine the pressure exerted by these cultivars in the storage silo. It was concluded that the products are classified as coarse grains, with free flow, the pressures exerted by the product are consistent with the norms established in the Eurocode 1 standard.

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INTRODUCTION

The storage capacity in Brazil is limited, not following the country's agricultural production, causing economic losses for producers, thus, the construction of vertical silos appears as an alternative to solve this problem (Bandeira et al., 2020). Grain production grows sharply annually due to increased crop productivity, grain production in Brazil according to the National Supply Company, it is estimated for the 2020/21 crop a total of 268.7 million tons, an increase of 11 million tons compared to the 2019/20 harvest (CONAB, 2021). Beans (Phaseolus vulgaris L.) are an important source of protein, fiber, iron, carbohydrates, minerals and vitamins for millions of people in both developing and developed countries (Lin et al., 2008). It is estimated that there are 55 species of the genus Phaseolus (Carneiro, 2005). This genus comprises all species known as beans, being Phaseolus vulgaris L. the best known and the one that has numerous varieties such as carioca, purple, mulatinho, black, among others (Pires et al., 2005).

Vertical silos are structures commonly used by industries, agricultural and mineral sectors to store and conserve in bulk, granular or powdery solid products (Bandeira *et al*., 2021; Dornelas *et al*., 2021). Vertical silos (bulk carriers) are widely used in Brazil and provide mechanized loading and unloading facilities, such as elevators and conveyor belts, cleaning machines and dryers, aeration and thermometry systems (Baroni et al., 2017). According to Ding (2014) and Fank et al. (2018), the pressures that occur during the discharge are not perfectly understood, taking into account that the pressure at the beginning of the discharge is very close to the pressure at the end of the discharge. A discrepancy existing between the calculated and experimentally measured pressure at the upper end of the hopper can also be noted. The biggest significant problem in silo design is the exact prediction of load distribution in the silo body, with special attention to the pressures exerted on the walls due to the buoyancy of the stored product and friction that the material exerts during loading and unloading.

These pressure distributions depend on the behavior of the product, the interaction between the stored product and the silo wall, and also the flow properties during the loading and unloading process (Martinez et al., 2002; Costa, 2013; Tascón, 2017; Ayres et al., 2020).

MATERIALS AND METHODS

All shear tests were performed, as well as the empirical determination of pressures along the silo body, in the Rural Constructions and Ambience Laboratory (LaCRA) of the Agricultural Engineering Department of the Federal University of Campina Grande (UFCG), Campus de Campina Grande – PB, Brazil. In this research we used three bean cultivars, carioquinha (Phaseolus vulgaris L.), black (Phaseolus vulgaris L.) and macassar bean (Vigna unguiculata), with moisture content of 2.91%, 3.53% and 3.03% (bs), respectively, all being classified as coarse grain (Figure 1).

Figure 1. Types of beans analyzed, (a) Carioquinha beans, (b) Black beans and (c) Macassar beans

Figure 2. Jenike equipment used to determine flow properties

Flow properties were determined: consolidated specific weight (γ), internal friction angle (ϕ), effective internal friction angle (δ) and friction angle of the product with the wall (ϕ w). Adopting the methodology recommended by the OPERATING INTRODUCTION FOR THE TRANSLATIONAL SHEAR TESTER (TSG – 70/140) using the "Jenike Shear Cell" device Figure 2. Two tests were performed: product shear and product shear with the wall material (smooth steel, rough steel, acrylic and aluminum), in order to determine the internal friction angle, effective internal friction angle, the friction angle with the wall and the cohesion of the product. We used the methodology established by the EUROCODE 1 (2006) standard to calculate the pressures in the silo body, with the following equations:

$$p_{hc} = \frac{\gamma \, x \, A}{\mu \, x \, U} \qquad p_{hd} = p_{hc} \, x \, ch$$

$$p_v = \frac{p_{hc}}{k} \qquad p_{wc} = p_{hc} \, x \, \mu$$

$$p_{wd} = p_{wc} \text{ x cw} \qquad U = \frac{A}{p}$$

$$k = 1{,}1 \, x \, (1 - sen \, \emptyset_e) \qquad \mu = tg \, \emptyset_w$$

Where,

γ - Consolidated Specific Weight (N/m³)
A - Silo Cross Section Area (m²)
μ - Friction Coefficient
p - Silo Perimeter (m)
U - Hydraulic Radius (m)
Φe - Effective Internal Friction Angle (°)
k - Ph and Pv ratio
Phc - Horizontal Loading Pressure (Pa)
ch - Overpressure Coefficient
Phd - Horizontal Discharge Pressure (Pa)
Pv - Vertical Pressure (Pa)
Pwc - Loading Friction Pressure (Pa)
cw - Overpressure Coefficient
Pwd - Discharge Friction Pressure (Pa)

RESULTS AND DISCUSSION

In Table 1, the results of the flow properties of the bean cultivars, necessary to determine the pressure exerted by the material in the storage silo, are presented. The results of the consolidated specific weight (γ) carioquinha, black and macassar beans presented mean values of 7991.3412 N/m³, 8086,1640 N/m³ and 8058.8567 N/m³, respectively. The average consolidated specific weight of carioquinha beans is within the AS 3774 (1996) and EUROCODE 1 (2006) standard, where the upper limit is 8000 N/m³, however, black beans and macassar are slightly above the established limit by the standards. Two different types of steel were analyzed for making the storage silo, thus measuring the friction angle of the product with the selected confection material, shown in Table 2.

Table 1. Flow properties of the analyzed products

Cultivars	γ (N/m³)		Φe (°)		Φi (°)		C (Pa)
	inf	sup	inf	sup	inf	sup	
Carioquinha	7923,34	8072,12	28	30	29	31	250,667
Black bean	8055,04	8106,09	26	27	27	28	50
Macassar	8008,54	8147,5	24	25	24	25	64

(γ) = Consolidated specific weight; (Φi) = Angle of internal friction; (Φe) = Effective internal friction angle; C = Cohesion; inf = lower limit; sup = upper limit.

Table 2. Angle of internal friction with the wall of the analyzed materials

Angle of Internal Friction with the wallΦ_W(°)				
Material		Carioquinha	Black bean	Macassar
Smooth steel	Bottom	8,6	2,8	6,8
	Higher	11	8	8,7
Rough steel	Bottom	2,9	11,9	13,2
	Higher	14,2	16,6	15,8

Using the information obtained, shown in Table 2, applying them to the sets of standardized equations, we were able to theoretically measure the pressures along the body of the silo, which are shown in Figures 3, 4 and 5, for carioquinha, black and macassar beans, respectively. We observed overestimated values for the normalized theoretical pressures, due to the imposed and cumulative safety coefficients throughout the calculation, which often do not agree with those found experimentally. Couto et al. (2013), Gallego (2015), Wójcik et al. (2017), Fank et al. (2018) and Meira et al. (2020) in their work observed this superiority in theoretical pressures when compared to experimental pressures, due to the safety coefficient used in the determination of pressures, which in turn extrapolates the pressures measured experimentally.

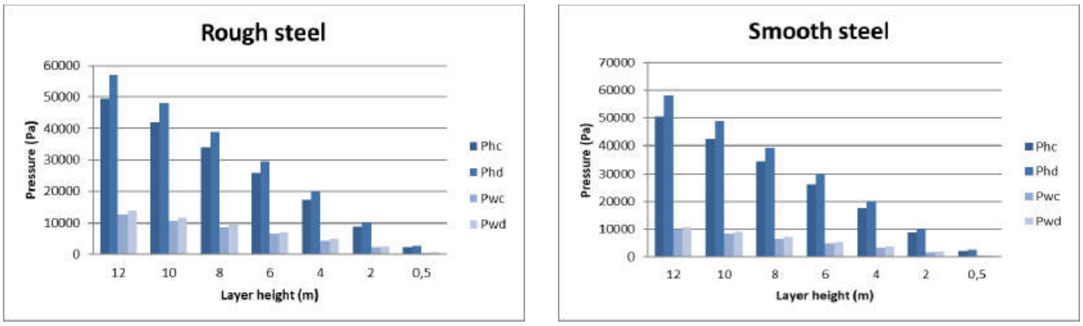

Figure 3. Graphic representation of the behavior of carioquinha bean pressures on the silo walls for the different types of steel analyzed.

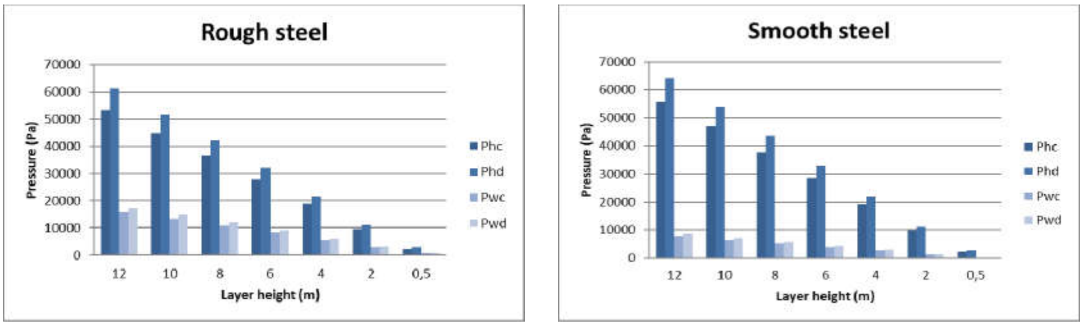

Figure 4. Graphic representation of the behavior of black bean pressures on the silo walls for the different types of steel analyzed.

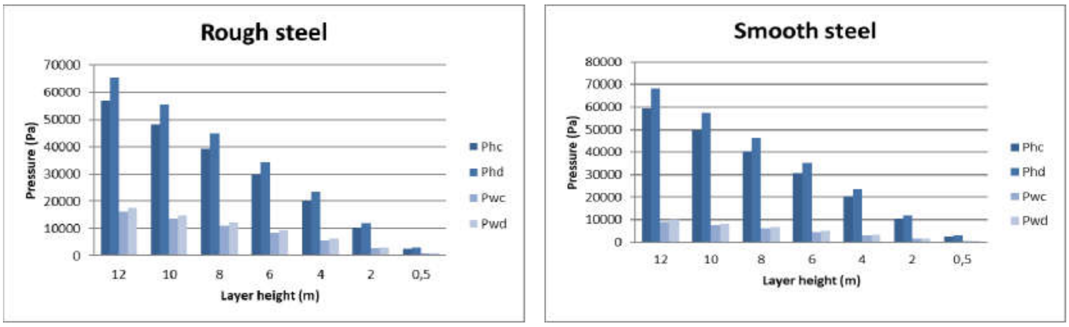

Figure 5. Graphic representation of the behavior of macassar bean pressures on the silo walls for the different types of steel analyzed.

We also observed that as suggested by the international standard BS EN 1991/4 (2006), the horizontal unloading pressures in all products were higher than the horizontal loading pressures, since this is obtained by multiplying an overpressure coefficient stipulated by the standard for the unloading on the horizontal pressure loading. The same observed by Couto et al. (2013), who found variations regarding the elevation of values obtained through the BS EN 1991/4 standard during unloading. When we observe the friction pressure of the product stored with the silo construction material, we observe an increase in pressure when we change the smooth steel to the rough steel, due to the resistance imposed by the roughness of the material, thus increasing the friction and consequently the loads on the silo body.

CONCLUSION

Considering the use of the overpressure coefficient during the unloading of stored products, and that the Eurocode 1 standard recommends some specific physical and flow properties for each product, we experimentally verified that the variables are slightly higher than the normalized values. As the roughness of the material increases, the friction pressures of the stored product tend to vary, due to the change in the resistance that the material imposes on the product flow. We also suggest experimental work to support data and validate the standards in force.

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