AgriEngineering

Article

Evaluation of the Flow Properties of *Coffea canephora* During Storage as Affected by Roasting Level, Particle Size, and Storage Temperature

Gabriel Henrique Horta de Oliveira [1,*], Paulo Cesar Corrêa [2], Ana Paula Lelis Rodrigues de Oliveira [1], Guillermo Asdrúbal Vargas-Elías [3] and Carlito Calil Junior [4]

1 Instituto Federal de Educação, Ciência e Tecnologia do Sudeste de Minas Gerais–Campus Manhuaçu, Manhuaçu 36909-300, Brazil; ana.lelis@ifsudestemg.edu.br
2 Departamento de Engenharia Agrícola, Universidade Federal de Viçosa, Viçosa 36570-900, Brazil; copace@ufv.br
3 Centro de Investigaciones en Granos y Semillas (CIGRAS), Facultad Ciencias Agroalimentarias, Universidad de Costa Rica, San Pedro de Montes de Oca, San José 2060, Costa Rica; guillermo.vargaselias@ucr.ac.cr
4 Escola de Engenharia de São Carlos, Departamento de Estruturas, Universidade de São Paulo, São Carlos 13566-590, Brazil; calil@sc.usp.br
* Correspondence: gabriel.oliveira@ifsudestemg.edu.br

Abstract: The powdered products industry demands certain parameters for the transport of these products, such as flowability. This has a direct impact on actions within the industry and in machinery development. For *Coffea canephora*, this information is absent in the relevant literature. Thus, the present study aimed to analyze alterations in the flow properties of *Coffea canephora* due to the degree of roasting, particle size, and storage temperature. Two degrees of roasting were used: medium light (ML) and moderately dark (MD). Later, the coffee was divided into four particle size categories: whole roasted coffee and coffee ground to fine, medium, and coarse sizes. These lots were kept at 10 °C and 30 °C and the flowability parameters were studied throughout the storage period (0, 30, 60, 120, and 180 days). The angle of internal friction presented higher values for higher degrees of roasting and lower values for larger particle sizes. The MD and fine coffee samples presented higher values for the wall friction angle. Steel provided the lowest values for the wall friction angle. Unground roasted coffee was classified as free-flowing, whilst coffee with a coarse or fine particle size was classified as having an easy flow and a cohesive flow, respectively. According to the K coefficient, coffee roasted to MD required storage containers that were more robust, such as having thicker silo walls or being constructed of a material with a higher resistance, to prevent the storage container from collapsing during transport.

Keywords: friction; post harvest; silo; Agtron; milling; robusta

check for updates

Academic Editor: Marcello Biocca

Received: 31 January 2025
Revised: 2 March 2025
Accepted: 10 March 2025
Published: 18 March 2025

Citation: Oliveira, G.H.H.d.; Corrêa, P.C.; Oliveira, A.P.L.R.d.; Vargas-Elías, G.A.; Calil Junior, C. Evaluation of the Flow Properties of *Coffea canephora* During Storage as Affected by Roasting Level, Particle Size, and Storage Temperature. *AgriEngineering* **2025**, *7*, 84. https://doi.org/10.3390/agriengineering7030084

1. Introduction

Coffee production is carried out widely, primarily in countries near the equator, which have more favorable climatic conditions for this crop. Most of these countries are developing nations, and they face challenges related to the transportation of goods due to long distances and the lack of adequate infrastructure for ports and consumption centers.

For this reason, a large portion of Brazil's coffee commercialization involves raw beans, produced through the peeling, cleaning, and drying of coffee cherries. In 2023, raw coffee represented 90.4% of the total export value, with instant coffee (9.3%) ranking second and roasted and ground coffee (0.3%) ranking third [1]. Therefore, a significant reduction was observed in the potential value for coffee growers and agents in the coffee agribusiness chain, as they do not carry out the subsequent processing stages due to a lack of resources, short methods, and various problems such as the transport of powdered coffee. Moreover, the movement of coffee powder is a valuable consideration in the daily operations of coffee processing businesses, because it affects the product's quality, increasing operational costs and decreasing company profits [2].

To transport and handle roasted and ground coffee satisfactorily between the production site and the consumption/export destination, as well as to move the product within the industry, information about certain flow properties of coffee is essential. In cases where these are not known, issues regarding coffee transportation can arise, increasing the final costs and the possibility of product quality loss, as well as potential accidents for the personnel involved. The cost of handling and moving a product can reach 50% of the total manufacturing value of the product [2]. Therefore, the goal is to minimize the number of necessary movements while maximizing operational efficiency.

To achieve this, studies on flow properties are mandatory. If not conducted, inadequate equipment designs may result, potentially leading to the failure of product discharge [3,4]. Furthermore, understanding the flow properties of coffee powder is of the utmost importance, as these properties play an important role in the behavior of pressures and flows in handling equipment [5]. Such knowledge is necessary for coffee-processing lines because, to produce the product, the movement of various raw materials at different stages of processing needs to be achieved. Determining flow properties is crucial for developing proper procedures in the industry, including movement in hoppers and silos and during dosing, transport, and packaging [6]. This information is scarce, and the lack of information is more pronounced for the species *Coffea canephora* (robusta coffee) compared to the most commercialized species of coffee *Coffea arabica* L.

Publications that deal with the effect of roasting, grinding, and storage temperatures on coffee are absent or scarce. The influence of anti-caking agents on the powder flow properties of ready-to-drink coffee during storage has been analyzed [7]; the flow properties of spent coffee grounds, as affected by the moisture content and particle size, have been determined to design conical hoppers [8]; and some flow properties have been used to model the effect of flow-induced mechanical erosion during coffee filtration [9]. Previous work from this research group analyzed the flow properties of coffee; however, this was performed for *Coffea arabica* L. [10]. Thus, it is clear that research regarding the flow properties of *Coffea canephora* is absent. The present work is justified because different species may present diverse behavior due to different chemical components, sizes, shapes, and hygroscopic features. Consequently, studying the flow properties of different coffee species and cultivars is required.

Various trends impact the flow properties of coffee. The degree of roasting, grinding level, and wall materials of storage facilities are some examples. Nevertheless, the storage of coffee powder is not recommended, as grinding breaks down the cell structure, which can lead to a greater loss of constituents and product quality. Still, studying the flow properties of coffee during storage is reasonable because of potential market obstacles. This can include the demand to store roasted and ground coffee because of transport issues, costs that hinder commercialization at that moment, and the necessity of formulating coffee blends.

In order to determine the correct layout for storage buildings specifically, it is valuable to understand the flow properties of coffee when in contact with the materials that these buildings are made of. The internal and external friction coefficients, the internal friction angle, the effective internal friction angle, the friction angle with the wall, and the coefficient K are important flow properties.

The internal and external friction coefficients are essential for ensuring the rational and safe design of transport, processing, and storage equipment [11]. External friction refers to the friction between the stored product and the silo or equipment wall material, while internal friction refers to the friction between the stored particles (grain–grain) [12]. These properties play a critical role in the behavior of pressures and flow in silos [13].

The internal friction angle is the angle between the normal forces and shear stresses in each stress state at a point. It is related to the normal force applied to the beans, with the opposing strength being a combination of sliding and rolling pressures between the grains [14]. This angle is closely linked to the inherent specifications of the stored product, varying with the average pressure applied to the entire product [15].

During the calculation of the hopper slope, values for the internal friction angle and the effective internal friction angle are required to prevent blockages that could impair the proper discharge of the stored products [16]. The latter is the angle formed by the line that passes through the origin and the axis of normal stresses.

The coefficient K is the fraction concerning the vertical and horizontal pressures at any location within a granular mass. In addition, it is recognized as the lateral pressure coefficient. The coefficient K is important for estimating the pressure exerted by the granular mass on the walls and floor of a storage facility.

Considering the above, the aim of this study was to assess the flow properties (internal and external friction coefficients, internal friction angle, effective internal friction angle, friction angle with the wall, and coefficient K) of robusta coffee throughout the storage process. Additionally, this study aimed to evaluate the impact of various roasting levels and particle sizes on coffee's flow properties.

2. Materials and Methods

2.1. Coffee Beans

For this research, coffee beans (*Coffea canephora*) from "bica corrida" (unsorted) obtained from coffee producers located at Viçosa, MG, were used. Then, they were peeled and dried. The coffee beans were carefully selected to eliminate those that were spoiled, broken, or infested, ensuring a uniform raw material with very few imperfections.

2.2. Roasting and Grinding

The coffee beans underwent a roasting procedure after being sorted. A pre-heated, liquefied petroleum gas (LPG) direct roaster with a rotary cylinder was used, capable of handling 350 g of raw coffee. The roaster (brand: Gouvea Materiais de Construção, model: PATPROVA2T, Itaperuna, Brazil) operated at a speed of 45 revolutions per minute (rpm) to roast the coffee.

The roasting level of each coffee batch was assessed by a trained expert, who evaluated the color of the samples and compared it to the Agtron/Specialty Coffee Association of America (SCAA) roast color reference scale. Two roasting levels were achieved: medium light (ML) and moderately dark (MD), pertaining to Agtron numbers #65 and #45 of the SCAA (Specialty Coffee Association of America), respectively [17].

After the roasting procedure, the coffee beans were ground in a mill (Mahlkönig, model K32 S30LAB, Seattle, WA, USA) to achieve 3 particle sizes: fine (0.59 mm), medium (0.84 mm), and coarse (1.19 mm). Additionally, a lot of coffee was kept as intact beans.

The coffee batches were then stored in polypropylene bags and kept at two temperatures (10 °C and 30 °C). The different temperatures were used to understand the effect of temperature on the flow properties of coffee. It is known that lower temperatures provide better conservation for agricultural products, especially in terms of quality aspects; thus, it is important to verify if there is a similar effect on the flow properties. The batches were analyzed for five storage periods (0, 30, 60, 120, and 180 days).

2.3. Shear Test

Whole and ground roasted coffee were analyzed regarding their flow properties, the determination of which was made by using a shear device (model TSG 70/140), Zeppelin manufacturer, Friedrichshafen, Germany, based on a Jenike shear tester. The methodology applied was previously proposed in [14], and the tests were conducted following British standard recommendations [3,15,18,19] as well as the operation manual for the TSG 70–140 machine.

The test consisted of applying a normal force to the cell that held the product, and then measuring the force required to shear the sample. The shear cell was circular in shape and consisted of a base, ring, and lid. The normal force was obtained by means of steel washers on a hanger that rested at the center of the lid. Jenike's direct shear apparatus promoted the shear action by moving horizontally at a speed between 1 and 3 mm min^{-1}, pulled through the lid.

For the shear test, two steps were required: the first was the preparation of the sample, and the second was the actual measurement of the shear stresses. The first part aimed to prepare the critical consolidation of the sample for the development of a shear zone, within which steady-state flow occurred, where the density and shear stress remained constant during the test. This part is called pre-shear. In the second part of the test, the shear stresses were measured with normal load values, determining the shear forces necessary for the product to slide. Finally, the results are presented graphically in a diagram of normal stress and shear stress, which was used to calculate the remaining flow properties.

2.3.1. Flow Properties

To calculate the hopper angle and prevent the formation of blockages that could hinder the good flow of the stored product, determining the values of the internal friction angle and the effective internal friction angle is necessary [16].

2.3.2. Internal Friction Angle, Effective Internal Friction Angle, and Friction Angle with the Wall

The angle formed between the yield locus straight line and the horizontal axis represents the internal friction angle (ϕ_i). The effective internal friction angle (ϕ_e) was determined in the same way as ϕ_i, but under the condition of a free-flowing product. In practice, ϕ_e is constructed by drawing a line from the origin to the point of intersection with the largest Mohr's circle.

The wall friction angle (ϕ_w) is the angle formed between the wall yield locus straight line and the horizontal axis. To quantify the wall friction angle, the base of the shear cell was switched with cells made of rough steel, wood, or concrete.

The friction angle between the coffee and the wall material (ϕ_w) was the angle formed by the wall yield locus straight line and the horizontal axis. To quantify the wall friction angle, the base of the shear cell was replaced by a sample made of rough steel, wood, or concrete materials.

The product placed in the higher segment of the shear cell was cut off from the material sample under varying normal stresses of 50, 40, 30, 20, 10, and 0 N, while the corresponding shear stress values were recorded.

2.3.3. Internal and External Friction Coefficients

The μ'_i′ and μ'_e of whole and ground roasted coffee under varying conditions (roast level, particle size, and storage time) were calculated using Equation (1) and Equation (2), respectively.

$$\mu_i^{'} = tan\ \phi_i \quad (1)$$

$$\mu_e^{'} = tan\ \phi_w \quad (2)$$

in which ϕ_i = the angle of internal friction in degrees; ϕ_w = the angle of friction with the wall in degrees; μ'_i = the internal friction coefficient, a dimensionless value; and μ'_e = the external friction coefficient, also dimensionless.

2.3.4. Flow Function

The flow function (FF) represents the unconfined yield strength (σ_{ic}) and measures the product's resistance to flow on a free surface under the maximum consolidation pressure. Because of this parameter, the product can form a stable arch or exhibit a tube effect [20]. The flow function is defined by Equation (3), and its values are the average of three repetitions for each tested condition.

$$FF = \frac{\sigma_1}{\sigma_{ic}} \quad (3)$$

in which FF = the flow function, dimensionless; σ_1 = the maximum consolidation stress, kPa; and σ_{1c} = the unconfined slip resistance, kPa.

2.3.5. K Coefficient

The German standard DIN 1055-6 (2005) [21] defines the K value using Jaky's expression, incorporating a weighting coefficient of 1.2 (Equation (4)). This equation provides the closest approximation to the experimental data for the K coefficient [15].

$$K = 1.2(1 - sin\varnothing_e) \quad (4)$$

in which K = the lateral pressure coefficient, dimensionless, and ϕ_e = the effective angle of the internal friction of the product, in degrees.

As per DIN 1055-6, the factor of 1.2 was selected to guarantee that more accurate and complete pressure curves were obtained, especially at lower heights of the stored product, such as near the top of the silo.

2.4. Experimental Design

This research was carried out using a split-plot design, where a storage duration was assigned to the main plots and a $2 \times 4 \times 2$ factorial arrangement was applied to the subplots (comprising two degrees of roasting, four levels of grain particle sizes, and two storage temperatures), with a varying number of replicates for each response variable analyzed.

The experimental data regarding the flow properties investigated for each storage duration were subjected to an analysis of variance, with the means compared using Tukey's test at a 5% significance level. For the storage time, the model selection was based on the significance of the regression coefficients, evaluated through a "*t*" test at the 1%, 5%, and 10% levels; the coefficient of determination; and the observed behavior under investigation.

3. Results and Discussion

3.1. Roasted and Ground Coffee

The average value for the initial moisture content of raw coffee was 14.80% (db). It was gravimetrically verified with the aid of a forced-air oven (Tecnal Equipamentos Científicos, model TE-394/2-MP, Piracicaba, Brazil) at 105 ± 1 °C for 24 h [22].

Roasting standardization was accomplished using the mass loss parameter. With a roasting temperature of 296 °C, the coffee beans lost 55.49 g with a duration of 11.64 min (average) for the ML roast. For the MD roast, the coffee reduced by 67.03 g and required 14.24 min (average).

3.2. Internal Friction Angle, Effective Internal Friction Angle, and Friction Angle with the Wall

Figure 1 shows the variation in the values of the internal friction angle (ϕ_i) of the different coffee batches. Figure 2 demonstrates the behavior of the effective internal friction angle of roasted, whole, and ground coffee as a function of storage time for *Coffea canephora*.

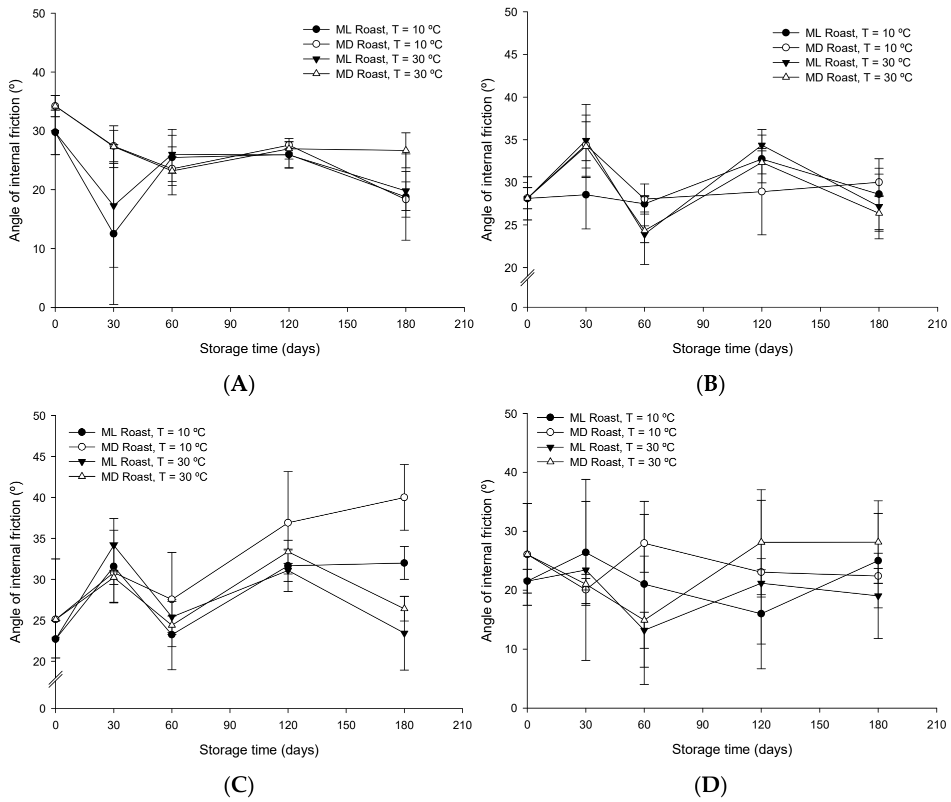

Figure 1. Observed and estimated median values for the internal friction angle of roasted *C. canephora* with whole (**A**), fine (**B**), medium (**C**), and coarse (**D**) granulometry during storage at 10 and 30 °C.

By observing Figures 1 and 2, it was noted that roasted coffee kept intact presented a distinct performance from the roasted and ground coffee. While the latter exhibited an increase in the values of ϕ_i and ϕ_e from harvest to 30 days of storage, whole roasted coffee showed a decrease from harvest onwards.

During the first 30 days, since the coffee beans were not ground, they had a greater capacity to maintain their components and moisture content. This trend is explained by the physical obstacle resulting from unbroken cells or minor-intensity fissures. Crushing, on the other hand, breaks down this obstacle, increasing the speed of alterations within the coffee and the atmosphere that surrounds it. This leads to the agglomeration effect due to the absorption of water from the environment. This occurs quickly at the start because of the low moisture content after the roasting process, which leads to a higher hygroscopic capability, with greater humidity absorption at this point. Hence, accumulation reduces the flowability of the coffee, increasing the values of ϕ_i and ϕ_e.

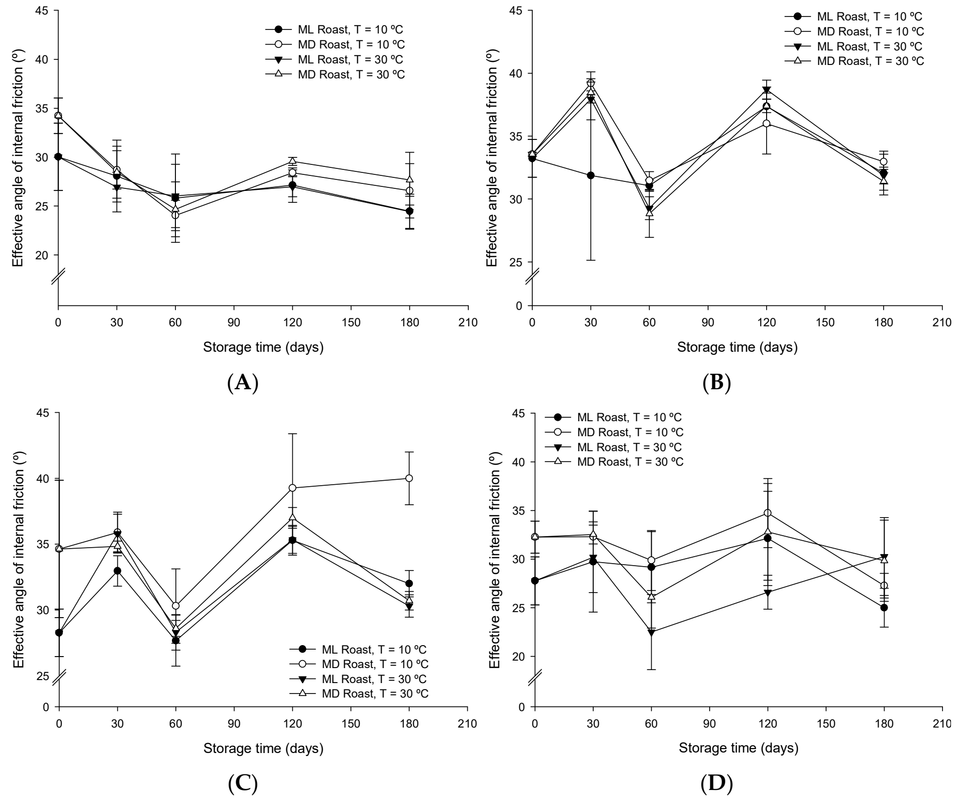

Figure 2. Observed and estimated median values of effective internal friction angle of roasted *C. canephora* with whole (**A**), fine (**B**), medium (**C**), and coarse (**D**) granulometry during storage at 10 and 30 °C.

During storage, there is an increase and decrease in ϕ_i and ϕ_e, with a tendency for their values to be closer together after 180 days of storage. This variation can be explained by different aspects. The first is that wetter samples present a greater cohesive strength among the individual constituents of coffee grains, leading to these constituents grouping together. Subsequently, this trend increases the internal friction. Another aspect is that, for agricultural foodstuffs in particular, there is an increase in the surface roughness with higher moisture contents, leading to greater resistance to the sliding of one element of the product mass against another, consequently increasing ϕ_i and ϕ_e [11,23]. The inverse behavior (a decrease in ϕ_i and ϕ_e) occurs because, for elevated moisture contents, particularly for powdered foodstuffs, a superficial coat is formed, serving as a lubricant through the submission of the shear force. This reduces the internal friction in the shear zone [24].

By analyzing Figures 1 and 2, it can be observed that the storage temperature did not impact the flow properties. In addition, the larger the size of the coffee grounds, the lower the ϕ_i and ϕ_e values at a constant storage time. The larger the particles, the lower the total number of particles in the product mass, reducing the cohesive forces between product/product [25].

Typically, the most strongly roasted samples (MD) presented elevated values of ϕ_i and ϕ_e throughout the storage period. More roasting resulted in an increase in the crumbliness of the coffee elements [26], i.e., they were more prone to collapse, thus forming reduced fragments.

For granular materials, the angle of internal friction is generally considered to be approximately equivalent to the angle of effective friction [27]. However, this is not an absolute rule, as it can vary depending on factors such as the shape of the particles and other influencing conditions.

Figure 3 describes the behavior of the angle of friction with the wall material (ϕ_w) of roasted, whole, and ground coffee, as a function of storage time, for *Coffea canephora*.

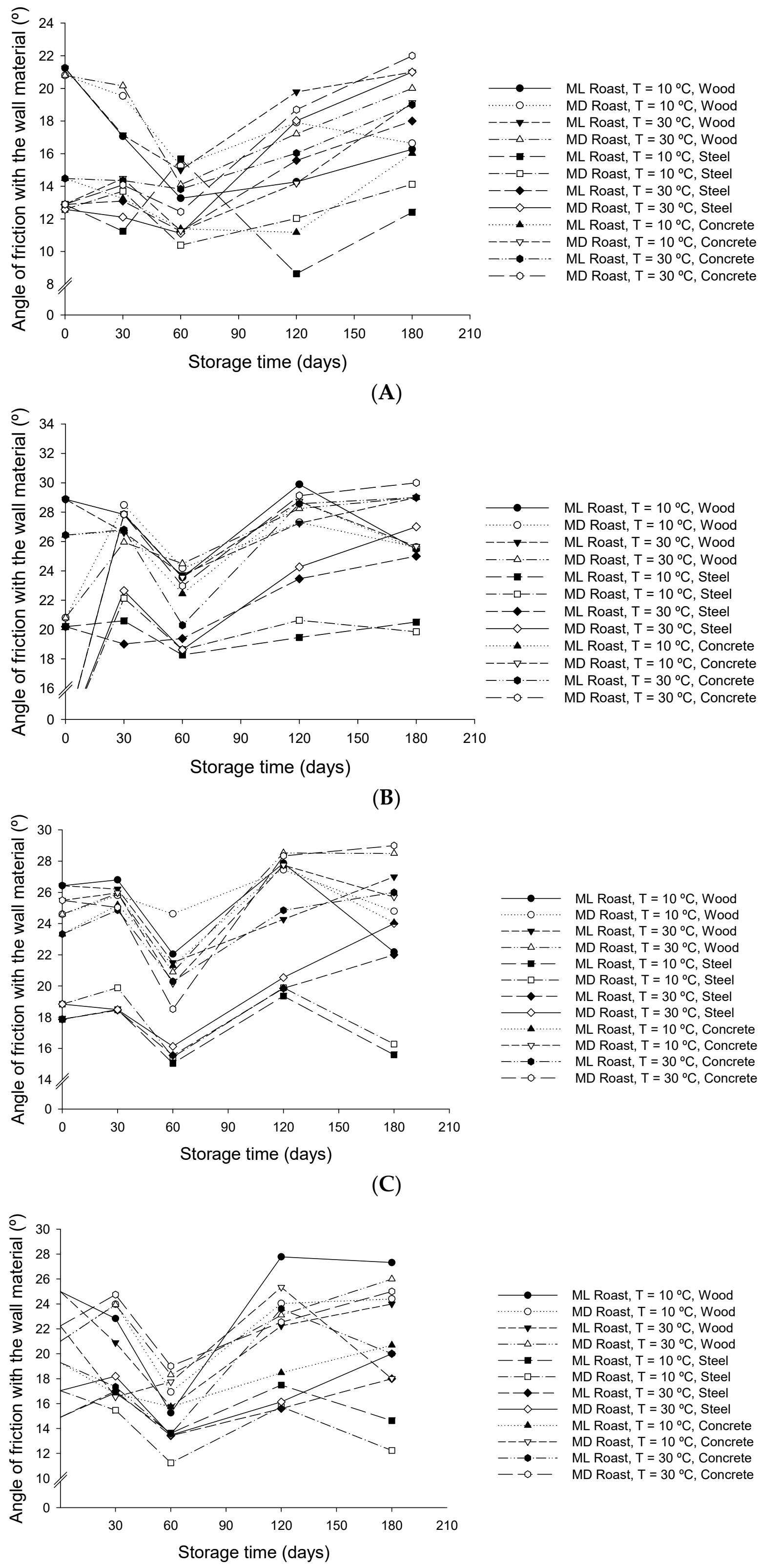

Figure 3. Observed and estimated median values of the angle of friction with the wall material for roasted *C. canephora* with whole (**A**), fine (**B**), medium (**C**), and coarse (**D**) granulometry during storage at 10 and 30 °C.

The samples stored at a temperature of 30 °C generally produced higher ϕ_w values than the coffee stored at 10 °C (Figure 3). This trend is also related to the moisture content present in the samples: products with a higher water content (coffee stored at 30 °C) have a greater cohesive power among the elements that make up the coffee mass, inclining to these elements combining. Therefore, they increase the angle of friction with the wall. Another factor, also related to the angle of internal friction and the effective angle of internal friction, is that an increase in the roughness of the product's surface due to the higher water content leads to greater resistance to the sliding of one particle of the product mass against another, increasing ϕ_w.

During storage, an increase and decrease in ϕ_w can be observed, with no characterized comportment. The variation stated can be explained by the ϕ_i and ϕ_e.

Figure 3 also shows that, regarding the wood, steel, and concrete wall materials, the ϕ_w values were greater when the wall material analyzed was wood. Then, the ϕ_w values were greater for concrete and, finally, for steel. This distinction was correlated with the surface roughness of the substances assessed. Previous work [28] has verified the friction coefficients of unhulled, husked, and polished rice grains in relation to wall materials identical to those utilized in this study, concluding that the friction coefficients calculated were greater for wood, and then concrete and steel, validating the outcomes presented. These authors associated this variance to the surface roughness of the material, which was 0.64 μm for steel. Concrete has a surface roughness of 3.22 μm and wood has a surface roughness of 3.56 μm.

3.3. Internal and External Friction Coefficients

The internal friction coefficient (μ'_i), which describes the relationship between the friction and the normal force on the external part of the coffee, rose throughout the storage time (Table 1).

As occurred for the internal friction angle, the μ'_i numbers were, in general, increased for the batches roasted at the MD level, finely ground, or stored at 30 °C when compared with the ML roast at the medium, coarse, or whole particle sizes and at a temperature of 10 °C. This trend is justified by the larger friability of the MD batch, the cohesive force of the coffee fragments, and the moisture content.

Table 1. Values of coefficient of internal friction (μ'_i) of *C. canephora* for medium light (ML) and moderately dark (MD) roasts, using coffee kept whole or ground to a fine, medium, or coarse particle size, during storage at two temperatures (T).

Roast	T (°C)	Storage Time (Days)	Particle Size			
			Whole	Fine	Medium	Coarse
ML	10	0	0.5742 ± 0.0888	0.5349 ± 0.0577	0.4188 ± 0.0465	0.3950 ± 0.0405
		30	0.2294 ± 0.2263	0.5459 ± 0.0890	0.6177 ± 0.1061	0.5064 ± 0.1941
		60	0.4798 ± 0.1048	0.5200 ± 0.0214	0.4313 ± 0.0900	0.4008 ± 0.2822
		120	0.4876 ± 0.0475	0.6442 ± 0.0680	0.6174 ± 0.0461	0.2926 ± 0.1798
		180	0.3436 ± 0.1406	0.5479 ± 0.0970	0.5496 ± 0.0444	0.3480 ± 0.0917
	30	0	0.5742 ± 0.0888	0.5349 ± 0.0577	0.4188 ± 0.0465	0.3950 ± 0.0405
		30	0.3180 ± 0.1996	0.7024 ± 0.1133	0.6809 ± 0.0834	0.5840 ± 0.0834
		60	0.4897 ± 0.0691	0.4432 ± 0.0206	0.4753 ± 0.0407	0.2350 ± 0.0569
		120	0.4869 ± 0.0486	0.6845 ± 0.0465	0.6043 ± 0.0610	0.3877 ± 0.0462
		180	0.3610 ± 0.0664	0.5151 ± 0.0841	0.4355 ± 0.0924	0.3490 ± 0.1415

Table 1. *Cont.*

Roast	T (°C)	Storage Time (Days)	Particle Size			
			Whole	Fine	Medium	Coarse
MD	10	0	0.6811 ± 0.0469	0.5349 ± 0.0281	0.4744 ± 0.1547	0.4981 ± 0.1852
		30	0.5201 ± 0.0597	0.6862 ± 0.0683	0.5992 ± 0.0881	0.3754 ± 0.2231
		60	0.4367 ± 0.0449	0.5329 ± 0.0398	0.5258 ± 0.1285	0.5344 ± 0.1120
		120	0.5228 ± 0.0124	0.5558 ± 0.1152	0.7609 ± 0.1793	0.4400 ± 0.2479
		180	0.3320 ± 0.0582	0.5778 ± 0.0384	0.6191 ± 0.0703	0.4124 ± 0.0334
	30	0	0.6811 ± 0.0469	0.5349 ± 0.0281	0.4744 ± 0.1547	0.4981 ± 0.1852
		30	0.5186 ± 0.0791	0.6832 ± 0.0948	0.5829 ± 0.0205	0.3940 ± 0.2193
		60	0.4602 ± 0.0599	0.4540 ± 0.0850	0.4538 ± 0.0236	0.2730 ± 0.2064
		120	0.5092 ± 0.0385	0.6333 ± 0.0330	0.6589 ± 0.0359	0.5472 ± 0.2127
		180	0.5246 ± 0.0369	0.4963 ± 0.0464	0.4967 ± 0.0327	0.5419 ± 0.1532

The data for the coefficient of external friction (μ'_e), which is the relationship between the friction and the normal force on the surface of the material used in the structure of the storage tower, altered with the material employed, the roasting degree, the coffee granulometry, and the storage duration (Tables 2–4). For the last three factors, the behavior was similar to that detected for μ'_i.

Table 2. Values of external friction coefficient (μ'_e) of *C. canephora* stored in wood; for medium light (ML) and moderately dark (MD) roasts; with coffee kept whole (A) or ground to a fine (B), medium (C), or coarse particle size (D); and during storage at two temperatures (T).

Roast	T (°C)	Storage Time (Days)	Particle Size			
			Whole	Fine	Medium	Coarse
ML	10	0	0.3848 ± 0.0035	0.5488 ± 0.0072	0.5003 ± 0.0081	0.4614 ± 0.0053
		30	0.3106 ± 0.0033	0.5261 ± 0.0069	0.5044 ± 0.0034	0.4240 ± 0.0028
		60	0.2380 ± 0.0021	0.4352 ± 0.0022	0.4125 ± 0.0077	0.2733 ± 0.0057
		120	0.2572 ± 0.0031	0.5773 ± 0.0024	0.5315 ± 0.0082	0.5308 ± 0.0036
		180	0.2903 ± 0.0016	0.4704 ± 0.0054	0.4046 ± 0.0041	0.5163 ± 0.0044
	30	0	0.3848 ± 0.0035	0.5488 ± 0.0072	0.5003 ± 0.0081	0.4614 ± 0.0053
		30	0.3079 ± 0.0020	0.4995 ± 0.0067	0.4921 ± 0.0043	0.3798 ± 0.0018
		60	0.2667 ± 0.0039	0.4337 ± 0.0067	0.3879 ± 0.0073	0.2857 ± 0.0035
		120	0.3639 ± 0.0041	0.5143 ± 0.0045	0.4478 ± 0.0029	0.4084 ± 0.0041
		180	0.3865 ± 0.0031	0.0.5513 ± 0.0073	0.5095 ± 0.0044	0.4473 ± 0.0021
MD	10	0	0.3752 ± 0.0116	0.5235 ± 0.0078	0.4529 ± 0.0053	0.3825 ± 0.0042
		30	0.3498 ± 0.0053	0.5391 ± 0.0045	0.4799 ± 0.0062	0.4430 ± 0.0054
		60	0.2777 ± 0.0044	0.4493 ± 0.0042	0.4524 ± 0.0067	0.3040 ± 0.0019
		120	0.3250 ± 0.0018	0.5176 ± 0.0068	0.5224 ± 0.0029	0.4428 ± 0.0036
		180	0.3002 ± 0.0016	0.4807 ± 0.0065	0.4620 ± 0.0021	0.4558 ± 0.0021
	30	0	0.3752 ± 0.0116	0.5235 ± 0.0078	0.4529 ± 0.0053	0.3825 ± 0.0042
		30	0.3689 ± 0.0043	0.4939 ± 0.0062	0.4865 ± 0.0032	0.4413 ± 0.0025
		60	0.2543 ± 0.0039	0.4494 ± 0.0055	0.3839 ± 0.0053	0.3308 ± 0.0039
		120	0.3090 ± 0.0030	0.5366 ± 0.0045	0.5500 ± 0.0056	0.4273 ± 0.0031
		180	0.3686 ± 0.0041	0.5604 ± 0.0087	0.5422 ± 0.0034	0.4906 ± 0.0033

Table 3. Values of external friction coefficient (μ'_e) of *C. canephora* stored in concrete; for medium light (ML) and moderately dark (MD) roasts; with coffee kept whole (A) or ground to a fine (B), medium (C), or coarse particle size (D); and during storage at two temperatures (T).

Roast	T (°C)	Storage Time (Days)	Particle Size			
			Whole	Fine	Medium	Coarse
ML	10	0	0.2413 ± 0.0222	0.4855 ± 0.0358	0.4381 ± 0.0380	0.3282 ± 0.0199
		30	0.2165 ± 0.0172	0.4977 ± 0.0373	0.4364 ± 0.0303	0.2893 ± 0.0186
		60	0.2297 ± 0.0250	0.4373 ± 0.0215	0.3563 ± 0.0295	0.2701 ± 0.0181
		120	0.1954 ± 0.0182	0.5130 ± 0.0336	0.4098 ± 0.1000	0.3430 ± 0.0183
		180	0.2558 ± 0.0287	0.5008 ± 0.0210	0.3401 ± 0.0935	0.3477 ± 0.0271
	30	0	0.2413 ± 0.0222	0.4855 ± 0.0358	0.4381 ± 0.0380	0.3282 ± 0.0199
		30	0.2367 ± 0.0189	0.4951 ± 0.0253	0.4577 ± 0.0268	0.3132 ±0. 0307
		60	0.2292 ± 0.0177	0.3832 ± 0.0131	0.3471 ± 0.0217	0.2660 ± 0.0237
		120	0.2789 ± 0.0264	0.5680 ± 0.0203	0.3944 ± 0.0601	0.4399 ± 0.0251
		180	0.3425 ± 0.0225	0.5123 ± 0.1154	0.4545 ± 0.0297	0.3747 ± 0.0238
MD	10	0	0.2241 ± 0.0100	0.2296 ± 0.0175	0.4596 ± 0.0397	0.3580 ± 0.0441
		30	0.2450 ± 0.0217	0.5514 ± 0.0229	0.4877 ± 0.0216	0.2782 ± 0.0182
		60	0.1985 ± 0.0218	0.4215 ± 0.0162	0.3986 ± 0.0298	0.3093 ± 0.0195
		120	0.2505 ± 0.0113	0.5373 ± 0.0243	0.4154 ± 0.0960	0.4873 ± 0.0136
		180	0.3162 ± 0.0272	0.4686 ± 0.0395	0.3649 ± 0.1009	0.3610 ± 0.0344
	30	0	0.2241 ± 0.0100	0.2296 ± 0.0175	0.4596 ± 0.0397	0.3580 ± 0.0441
		30	0.2387 ± 0.0152	0.5396 ± 0.0133	0.4670 ± 0.0425	0.4604 ± 0.0169
		60	0.2366 ± 0.0154	0.3946 ± 0.0258	0.3193 ± 0.0141	0.3714 ± 0.0233
		120	0.3186 ± 0.0175	0.5493 ± 0.0173	0.4344 ± 0.0910	0.4091 ± 0.0056
		180	0.3866 ± 0.0205	0.5699 ± 0.0329	0.4978 ± 0.0491	0.4441 ± 0.0331

Table 4. Values of external friction coefficient (μ'_e) of *C. canephora* stored in steel; for medium light (ML) and moderately dark (MD) roasts; with coffee kept whole (A) or ground to a fine (B), medium (C), or coarse particle size (D); and during storage at two temperatures (T).

Roast	T (°C)	Storage Time (Days)	Particle Size			
			Whole	Fine	Medium	Coarse
ML	10	0	0.2314 ± 0.0167	0.3799 ± 0.0105	0.3216 ± 0.0231	0.2730 ± 0.0103
		30	0.1983 ± 0.0145	0.3919 ± 0.0146	0.3527 ± 0.0162	0.2960 ± 0.0084
		60	0.2754 ± 0.0148	0.3547 ± 0.0214	0.2801 ± 0.0143	0.2632 ± 0.0189
		120	0.1562 ± 0.0183	0.3545 ± 0.0109	0.3519 ± 0.0079	0.3300 ± 0.0147
		180	0.2211 ± 0.0092	0.3960 ± 0.0194	0.2842 ± 0.0158	0.2769 ± 0.0139
	30	0	0.2314 ± 0.0167	0.3799 ± 0.0105	0.3216 ± 0.0231	0.2730 ± 0.0103
		30	0.2290 ± 0.0097	0.3458 ± 0.0176	0.3659 ± 0.0356	0.3123 ± 0.0293
		60	0.1995 ± 0.0109	0.3705 ± 0.0166	0.2909 ± 0.0138	0.2713 ± 0.0284
		120	0.2823 ± 0.0163	0.4292 ± 0.0272	0.3604 ± 0.0079	0.2943 ± 0.0134
		180	0.3295 ± 0.0132	0.4588 ± 0.0312	0.4266 ± 0.0209	0.3490 ± 0.0210
MD	10	0	0.2222 ± 0.0092	0.2314 ± 0.0085	0.3505 ± 0.0120	0.3239 ± 0.0157
		30	0.2401 ± 0.0187	0.4057 ± 0.0193	0.3640 ± 0.0209	0.2840 ± 0.0122
		60	0.1932 ± 0.0234	0.3318 ± 0.0351	0.2921 ± 0.0139	0.2251 ± 0.0240
		120	0.2249 ± 0.0126	0.3749 ± 0.0299	0.3606 ± 0.0060	0.2965 ± 0.0129
		180	0.2470 ± 0.0127	0.3631 ± 0.0198	0.3018 ± 0.0085	0.2385 ± 0.0209
	30	0	0.2222 ± 0.0092	0.2314 ± 0.0085	0.3505 ± 0.0120	0.3239 ± 0.0157
		30	0.2144 ± 0.0110	0.4051 ± 0.0117	0.3612 ± 0.0505	0.3385 ± 0.0204
		60	0.2102 ± 0.0123	0.3589 ± 0.0199	0.3041 ± 0.0134	0.2622 ± 0.0200
		120	0.3141 ± 0.0100	0.4536 ± 0.0264	0.3795 ± 0.0046	0.3111 ± 0.0191
		180	0.3732 ± 0.0100	0.5097 ± 0.0242	0.4614 ± 0.0144	0.3826 ± 0.0172

Regardless of the type of coffee evaluated, the storage temperature, the degree of roasting, or the grinding grade performed, the numbers for μ'_e were greater for wood, followed by concrete and steel. This outcome is comparable to that found in previous research [28] working with unhulled, hulled, and polished rice grains. This fact, as clarified in the preceding section, is caused by the roughness of the surface of the material.

3.4. Flow Function

The flow function (FF) uses certain limit values to classify the product regarding its flowability [29]. These values are FF < 2 (very cohesive products with no flow); 2 < FF < 4 (cohesive products); 4 < FF < 10 (products that flow easily); and FF > 10 (free-flowing products) [3]. Roasted whole coffee is classified as free-flowing (FF > 10), regardless of its MD or ML status or storage temperature.

The ground coffee grain sizes had different classifications. The FF estimates increased as the particle size became greater (coarse), implying that the lower the coffee breakage, the more easily the coffee can move. Based on the measured numbers, coarse-ground coffee can be categorized as a product with an easy flow (4 < FF < 10), whereas the medium-ground coffee shifted between this category and that of a cohesive product (2 < FF < 4) as the storage time progressed. The finely ground samples were consistently classified as a cohesive product. Previous work [10] has indicated the same trend for arabica coffee, indicating that the impacts of coffee processing on flow function are greater than differences due to the coffee species.

Coffee roasted to the ML degree had lower numbers of FF than the batches roasted to the MD degree, a trend explained by the coffee's moisture content. Lower values of water content permit easier movement due to the reduced interaction between the coffee components. The samples stored at 10 °C had lower FF numbers than the batches kept at 30 °C. This is related to the high temperature, which implies less moisture in the surface layers of the product, facilitating movement among the coffee components.

3.5. K Coefficient

The K coefficient is a key parameter required to determine the pressures exerted by the product on the walls and floor of a silo [10]. The roasting intensity significantly changed the K coefficient values compared to the other variables, and the storage temperature did not affect these results. Thus, two separate tables were made to present the K coefficient values: coffee roasted to ML (Table 5) and MD (Table 6).

Table 5. K coefficient values of *C. canephora* for a medium light roast, across four particle sizes (fine, medium, coarse, and whole coffee) throughout the storage period.

Storage Time (Days)	Particle Sizes [1]			
	Whole Coffee	Fine	Medium	Coarse
0	0.600 ± 0.055 abcB	0.542 ± 0.024 cAB	0.632 ± 0.030 bA	0.665 ± 0.073 abA
30	0.646 ± 0.047 abAB	0.516 ± 0.098 cdAB	0.532 ± 0.034 cB	0.602 ± 0.072 bA
60	0.676 ± 0.066 aAB	0.597 ± 0.021 aA	0.637 ± 0.028 aA	0.679 ± 0.093 aA
120	0.654 ± 0.024 abAB	0.461 ± 0.022 cdB	0.506 ± 0.017 cB	0.613 ± 0.080 bA
180	0.703 ± 0.023 aA	0.565 ± 0.025 bA	0.595 ± 0.015 bAB	0.596 ± 0.072 bA

[1] Each value is expressed as the mean ± SD, with $n = 6$. Means sharing the same lowercase letters across rows and the same uppercase letters in columns are not significantly different, according to the Holm–Sidak method ($p < 0.05$).

Table 6. K coefficient values of *C. canephora* for a moderately dark roast, across four particle sizes (fine, medium, coarse, and whole coffee) throughout the storage period.

Storage Time (Days)	Particle Sizes [1]			
	Whole Coffee	Fine	Medium	Coarse
0	0.525 ± 0.028 aD	0.536 ± 0.002 aAC	0.520 ± 0.079 aBC	0.560 ± 0.026 aB
30	0.638 ± 0.045 aB	0.448 ± 0.014 dB	0.506 ± 0.020 cBC	0.557 ± 0.032 bB
60	0.705 ± 0.039 aA	0.598 ± 0.035 bA	0.610 ± 0.037 bA	0.590 ± 0.098 bAB
120	0.619 ± 0.013 aBC	0.483 ± 0.030 bBC	0.460 ± 0.047 bB	0.564 ± 0.072 aB
180	0.654 ± 0.051 aAC	0.561 ± 0.018 bA	0.587 ± 0.013 abAC	0.646 ± 0.030 aA

[1] Each value is expressed as the mean ± SD, with $n = 6$. Means sharing the same lowercase letters across rows and the same uppercase letters in columns are not significantly different, according to the Holm–Sidak method ($p < 0.05$).

From Tables 5 and 6, it can be seen that whole coffee had higher values for the K coefficient. This was expected since this parameter relates to the flow property. After 60 days of storage, the different grinding levels of ground coffee became similar to each other in terms of flow. This behavior can be explained by the hygroscopicity of coffee, which leads to moisture gain until achieving equilibrium with the environment. Moisture directly impacts the flowability of powdery agricultural products, with higher moisture leading to caking and more friction between the components. This trend was observed for all the samples except for the MD coffee with a medium particle size. In addition, a coarse particle size provided more homogeneous K coefficient values throughout the storage period, regardless of the degree of roasting. The other particle sizes (fine and medium) did not demonstrate behavior directly linked to coffee's hygroscopicity, as stated before. Thus, whole coffee and coarse coffee require storage structures that support higher pressures.

4. Conclusions

Considering the results obtained and the conditions under which the experiment was carried out, it can be inferred that the values of the internal friction angle and the effective internal friction angle varied according to the particle size and roasting level, and they did not present a defined behavior during storage.

The roasting level and particle size influenced the values of the wall friction angle, for which more intense roasting and a lower particle size led to higher values of this property. The wood sample exhibited the highest values for the wall friction angle, followed by the concrete and steel samples.

The internal friction coefficient was affected by the factors evaluated, for which the MD roasting level, a higher degree of grinding, and a higher storage temperature resulted in greater values of this coefficient, along with the external friction coefficient. The external friction coefficient altered according to the wall material employed, with lower values for steel, than concrete and wood.

Whole coffee is classified as free-flowing; for the coffee batches that were ground, the higher the degree of grinding, the closer the coffee powder was to exhibiting the flow of a cohesive product. The values of the K coefficient presented a behavior opposite to that obtained from the effective internal friction angle.

Future work may include an analysis of different anti-caking agents on coffee powder and their relationship with the sensory quality and flow properties, with the aim of reducing the cost of coffee-storage structures.

Author Contributions: Conceptualization, G.H.H.d.O. and P.C.C.; methodology, G.H.H.d.O., G.A.V.-E. and C.C.J.; software, C.C.J.; validation, A.P.L.R.d.O., P.C.C. and C.C.J.; formal analysis, G.H.H.d.O.; investigation, G.H.H.d.O. and A.P.L.R.d.O.; resources, G.H.H.d.O. and P.C.C.; data curation, G.H.H.d.O.; writing—original draft preparation, G.H.H.d.O.; writing—review and editing, P.C.C. and A.P.L.R.d.O.; visualization, A.P.L.R.d.O. and C.C.J.; supervision, P.C.C.; project administration, G.H.H.d.O. and P.C.C.; funding acquisition, P.C.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG), grant numbers PPM-00427-13 and APQ-02120-16, and by Conselho Nacional de Desenvolvimento Científico e Tecnológico–CNPq, grant numbers 483622/2012-5, 309025/2017-6, and 309603/2023-4.

Data Availability Statement: The data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. ABIC. Available online: https://estatisticas.abic.com.br/wp-content/uploads/2023/12/2023.12.SumarioCafe.pdf (accessed on 13 November 2024).
2. Robberts, T.C. *Food Plant Engineering Systems*; CRC Press: New York, NY, USA, 2002; 268p.
3. Jenike, A.W. *Storage and Flow of Solids*; Bulletin 123; University of Utah: Salt Lake City, UT, USA, 1964; 89p.
4. Jenike, A.W.; Johanson, J. *Flow Factor Tester and Consolidating Bench Operating Instructions*; Jenike & Johanson, Inc: Tyngsborough, MA, USA, 1979; 40p.
5. Gandia, R.M.; Gomes, F.C.; Paula, W.C.; Oliveira Junior, E.A.; Rodriguez, P.J.A. Static and dynamic pressure measurements of maize grain in silos under different conditions. *Biosyst. Eng.* **2021**, *209*, 180–199. [CrossRef]
6. Knowlton, T.M.; Klinzing, G.E.; Yang, W.C.; Carson, J.W. The importance of storage, transfer and collection. *Chem. Eng. Prog.* **1994**, *90*, 44–54.
7. Aslan Türker, D.; Göksel Saraç, M.; Doğan, M. The influence of anti-caking agents on powder flow properties of ready-to-drink coffee during storage. *Harran Tarım Gıda Bilim. Derg.* **2024**, *28*, 258–266. [CrossRef]
8. Massaro Sousa, L.; Schulz, C.G.; Condotta, R.; Ferreira, M.C. On the design of conical hoppers for spent coffee grounds: Moisture content and particle-size effects. *J. Food Eng.* **2021**, *300*, 110537. [CrossRef]
9. Mo, C.; Johnston, R.; Navarini, L.; Ellero, M. Modeling the effect of flow-induced mechanical erosion during coffee filtration. *Phys. Fluids* **2021**, *33*, 093101. [CrossRef]
10. Oliveira, G.H.H.; Corrêa, P.C.; Oliveira, A.P.L.R.; Vargas-Elías, G.A.; Calil Júnior, C. Arabica coffee flow properties assessed using different roasts and particle sizes during storage. *Braz. J. Food Technol.* **2022**, *25*, e2021026. [CrossRef]
11. Mohsenin, N.N. *Physical Properties of Plant and Animal Materials*; Gordon and Breach Publishers: New York, NY, USA, 1986; 841p.
12. Boumans, G. *Grain Handling and Storage*; Elsevier Science Publishers: Amsterdam, The Netherlands, 1985; 436p.
13. Silva, F.S. Propriedades Físicas dos Grãos de Café Como Subsídio em Projetos de Equipamentos e de Silos Utilizando a Metodologia de Jenike. Ph.D. Thesis, Universidade Federal de Viçosa, Viçosa, Brazil, 2003.
14. Gaggero, M.R.; Trein, C.R.; Ippoliti, G. Influência de sistemas de preparo e pastejo nas características físicas do solo. *Rev. Prog. Ciênc. Agro-Ambient.* **2002**, *1*, 1–16.
15. Chithra, S.; Indupriya, G. Contributions of Different Standards and Codes for the Design of Silo: A Review. *Asian Rev. Civ. Eng.* **2016**, *5*, 27–33. [CrossRef]
16. Naka, S. Determinação das Propriedades Físicas dos Grãos de Mamona 'Guarani' Visando Armazenagem em Silos Verticais. Master's Thesis, Universidade Estadual de Campinas, Campinas, Brazil, 2010.
17. Malaquias, J.V.; Celestino, S.M.C.; Xavier, M.F.F. Optimization of the roasting conditions of arabica coffee cultivated in the cerrado area of Brazil. *Braz. J. Food Technol.* **2018**, *21*, e2016162. [CrossRef]
18. Milani, A.P. Determinação das Propriedades de Produtos Armazenados para Projetos de Pressões e Fluxo em Silos. Ph.D. Thesis, Universidade de São Paulo, São Paulo, Brazil, 1993.
19. BMHB—British Materials Handling Board. *Draft Code of Practice for the Design of Silos, Bins, Bunkers and Hoppers*; British Materials Handling Board: London, UK, 1985.
20. Jan, S.; Ghoroi, C.; Saxena, D.C. Characterization of bulk and shear properties of basmati and non-basmati rice flour. *J. Sci. Food Agric.* **2018**, *98*, 667–673. [CrossRef] [PubMed]
21. *DIN 1055-6: 2005-03*; Actions on Structures, Part—6 Design Loads for Buildings: Loads in Silo Bins. German Standard: Dubai, United Arab Emirates, 2005.

22. Brasil, Ministério da Agricultura e Reforma Agrária, Secretaria Nacional de Defesa Agropecuária. *Regras para Análise de Sementes*; Secretaria Nacional de Defesa Agropecuária: Brasília, Brazil, 2009.
23. Baryeh, E.A. Physical properties of bambara groundnuts. *J. Food Eng.* **2001**, *47*, 321–326. [CrossRef]
24. Duffy, S.P.; Puri, V.M. Flowability parameters and flow functions for confectionery sugar and detergent powder at two moisture contents. *App. Eng. Agric.* **1996**, *12*, 601–606. [CrossRef]
25. Geldart, D.; Abdullah, E.C.; Verlinden, A. Characterisation of dry powders. *Powder Technol.* **2009**, *190*, 70–74. [CrossRef]
26. Medeiros, M.L.; Lannes, S.C.S. Propriedades físicas de substitutos de cacau. *Ciênc. Tecnol. Alim.* **2010**, *30*, 243–253. [CrossRef]
27. Tomasetta, I.; Barletta, D.; Lettieri, P.; Poletto, M. The measurement of powder flow properties with a mechanically stirred aerated bed. *Chem. Eng. Sci.* **2012**, *69*, 373–381. [CrossRef]
28. Silva, F.S.; Corrêa, P.C.; Goneli, A.L.D.; Ribeiro, R.M.; Afonso Júnior, P.C. Efeito do beneficiamento nas propriedades físicas e mecânicas dos grãos de arroz de distintas variedades. *Rev. Bras. Prod. Agroind.* **2003**, *5*, 33–41. [CrossRef]
29. Jenike, A.W. *Storage and flow of solids*; University of Utah: Salt Lake City, UT, USA, 1980; 197p.