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# Arabica coffee flow properties assessed using different roasts and particle sizes during storage

*Propriedades de fluxo de café arábica em diferentes torras e granulometrias durante o armazenamento*

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## Abstract

Flowability of agricultural products is an important factor to be considered at post-harvest, thus impacting directly on number of operations and the design of machinery. This study aimed to evaluate and determine the K coefficient and flow properties as a function of different levels of roasting, grain size, temperature and storage. Coffee beans were roasted at medium light and moderately dark, then ground at fine, medium and coarse sizes. An additional coffee lot was not ground. Samples were stored at 10 ºC and 30 ºC and analyzed during storage (0, 30, 60, 120 and 180 days), regarding internal and external friction coefficients, angle of internal friction, effective angle of internal friction, wall friction angle (concrete, rough steel and wood) and lateral pressure coefficient (K coefficient). Angle of internal friction varied significantly due to particle size and roast degree. Moderately dark roast with fine particle size led to higher values (about 29.5 º) of wall friction angle. The wood sample was the material with the highest values of wall friction angle, followed by the concrete and steel samples, when compared at the same storage temperature, roast degree and particle size. Whole coffee was classified as free-flowing. Fine particle size leads to cohesive flow characteristic, according to the flow function. Coffee roasted at medium light, kept whole requires storage facilities with higher pressure support, accordingly to the K coefficient values.

**Keywords:** *Coffea arabica*; Friction; Post-harvest; Silo; Agtron; Milling.

## Resumo

A escoabilidade dos produtos agrícolas é importante fator a ser considerado na pós-colheita, impactando diretamente no número de operações e no dimensionamento de maquinários. Assim, objetivou-se avaliar e determinar o coeficiente K e as propriedades de fluxo de grãos de café em função de diferentes níveis de torra, granulometria, temperatura e tempo de armazenamento. Grãos de café foram torrados nos níveis média clara e moderadamente escura, e depois moídos nas granulometrias fina, média e grossa. Um lote adicional de grãos de café não foi moído. As amostras foram armazenadas a 10 °C e 30 °C e analisadas durante o armazenamento (0, 30, 60, 120 e 180 dias) em relação aos parâmetros: coeficientes interno e externo de atrito, ângulo de atrito interno, ângulo de atrito interno efetivo, ângulo de atrito com a parede (concreto, aço e madeira) e o coeficiente de pressão lateral (coeficiente K). O ângulo de atrito interno variou significativamente com a granulometria e o nível de torra. A torra moderadamente escura e a granulometria fina obtiveram maiores valores (ao redor de 29,5 °) de ângulo de atrito com a parede. Quanto ao material em que as amostras foram colocadas, a madeira foi o material no qual as amostras apresentaram os maiores valores de ângulo de atrito com a parede, seguidas pelas amostras colocadas no concreto e no aço, quando comparadas na mesma temperatura de armazenamento, no mesmo nível de torra e na mesma granulometria. Os grãos de café inteiros foram classificados como de fluxo livre. A granulometria fina levou a um fluxo coesivo, de acordo com a função fluxo. Café torrado em média clara, inteiro, requer estruturas de armazenagem que suportem maior pressão, de acordo com os valores do coeficiente K.


**Palavras-chave:** *Coffea arabica*; Atrito; Pós-colheita; Silo; Agtron; Moagem.

## 1 Introduction

Coffee is a commodity that plays an important role in the world economy, especially for countries at the Equator line. The total world production in 2019/20 was 168678 thousand 60-kg bags of coffee beans, with a growth projection of 1.9% in 2020/21 (International Coffee Organization, 2021). Production of Arabica coffee bean (*Coffea arabica* L.) represents 60.4%, whilst robusta coffee (*Coffea canephora* Pierre) represents the remaining 39.6% (International Coffee Organization, 2021).

Brazil is in the first position of coffee producer and exporter in the world reported in crop year 2018/2019 (International Coffee Organization, 2021). World coffee trade occurs in the form of green or raw beans, obtained by the peeling, cleaning and drying of the coffee bean, and in Brazil is no different. According to the Brazilian Coffee Industry (Associação Brasileira da Indústria de Café, 2021), green coffee accounts for 88.5% of total exports, followed by instant coffee (10.8%) and ground roasted coffee (0.3%). This trend occurs at every producer country. Thus, there is a loss of the added value potential of the coffee for producers and professionals working in the coffee agribusiness chain, as they do not perform the remainder of processing due to lack of capital, inadequate techniques and difficulties in transportation and handling of the pulverulent product.

Material handling is an important factor in the routine operation of coffee processing industries and can considerably affect the quality of the product, directly influencing the cost of operation and the profit of the company (Robberts, 2002). These problems, according to Iqbal & Fitzpatrick (2006), may manifest as unreliable inconsistent flow that reduces production rate, or even no flow, where powder is trapped in the silo due to cohesive arching or the formation of a stable rat-hole.

To perform the transportation and handling of the roasted and ground coffee between the place of production and the place of consumption/export in a satisfactory manner and to move the product within the processing plant, knowledge of some flow properties of the product are of great value. If these properties are unknown, problems during product movement may occur, increasing the final cost, the risk of product damage, and accidents with the personnel involved. The moving and handling costs of the products can reach up to 50% of the total manufacturing cost of the final product (Robberts, 2002).

Without studies on flow properties, there may be inadequate equipment project designs, which may result in lack of product flow (Jenike, 1964; Jenike & Johanson, 1979). Knowledge of the flow properties of stored products is of great importance (Silva et al., 2008), as these properties play important roles in pressure and flow behaviors on handling equipment and on storage facilities (Lopes Neto et al., 2013). Such equipment is needed in the coffee processing line, as the final product output requires the handling of different raw materials at different processing levels. Determination of these properties is important because it provides adequate knowledge to industrial operations, such as flow in hoppers and silos, blending, transportation and packaging (Knowlton et al., 1994). However, flowability is not an inherent material property, but the result of the combination of material physical properties that affect flow and the equipment (material) used for its handling and processing (Fadeyibi et al., 2014). Thus, the study of the flow properties of agricultural products in contact with different materials is needed.

Particularly for storage structures, knowledge about the flow properties of the coffee in contact with the particular material composing these structures is important for their correct design. Among the main flow properties, internal and external friction coefficients, the angle of internal friction, the effective angle of internal friction, the wall friction angle and the K coefficient are highlighted.

Different factors affect coffee flow properties, such as roasting, grinding, and storage. However, the latter is not indicated for powdery products because grinding promotes cell rupture and, therefore, allows a greater loss of constituents and product quality. However, the study of the flow properties of roasted and ground coffee during storage is justified due to possible market difficulties. Among these difficulties, the need to store the already processed product due to unavailability of transportation, prices that prevent immediate sale and the need to formulate blends should all be mentioned.

Previous work investigated the flow properties of different agricultural products, such as flour, tea and whey permeate powders (Iqbal & Fitzpatrick, 2006), cassava and yam starch–glycerol composites (Fadeyibi et al., 2014), wheat flour (Bian et al., 2015) and corn stover (Crawford et al., 2016). The physicochemical properties of coffee powders and its impact on sensory properties and flowability was studied (Doğan et al., 2019), whilst the use of spent coffee ground. However, it was not found in the literature, research of the flow properties of roasted and grinded coffee and its variations related with storage, silo wall material, and milling degree.

Given the above, the present study aimed to evaluate and determine some flow properties (i.e., internal and external friction coefficients, angle of internal friction, effective angle of internal friction, wall friction angle and K coefficient) of Arabica coffee during storage and to evaluate the influence of different levels of roasting and grain size on these properties.

## 2 Material and methods

### 2.1 Raw material

Peeled and dried raw coffee beans (*Coffea arabica* L.) were purchased at the local market in *Zona da Mata*, in the state of Minas Gerais (MG). The coffee beans were sorted to remove deteriorated, damaged, and bored coffee beans to obtain a homogeneous raw material with minimal defects. Coffee beans that were derived from “bica corrida” (unsorted) cherries were used.

### 2.2 Sample preparation

Coffee beans were subjected to the roasting process after sorting. A 350-g raw-coffee capacity pre-heated, Liquefied Petroleum Gas (LPG) direct roaster with a rotary cylinder operated at 45 rpm was used to roast the coffee (brand Gouvea Materiais de Construção, model PATPROVA2T, Brazil).

The degree of roasting of each coffee roast was determined by a trained professional by monitoring the sample color and comparing it with the Agtron/Specialty Coffee Association of America (SCAA) standard roast number. Two roasting degrees were obtained: Medium Light (ML); and Moderately Dark (MD), corresponding to Agtron numbers of SCAA#65 and SCAA#45, respectively (Corrêa et al., 2016).

Following the roasting process, the coffee beans were processed in a mill (Mahlkönig, model K32 S30LAB, Germany) to one of three particle sizes: fine (0.59 mm) medium (0.84 mm), ;and coarse (1.19 mm). A batch of coffee was maintained as whole coffee.

The prepared samples were then placed in polypropylene bags and refrigerated at one of two storage temperatures (10 and 30 ºC). The treatments were sampled and analyzed at five time points (0, 30, 60, 120, and 180 days) over the course of six months.

## 2.3 Shear test

The determination of the flow properties of whole and ground roasted coffee was conducted with the use of a shear device model (TSG 70/140) based on a Jenike shear tester. The methodology used was proposed by Milani (1993), and for the execution of the test, the British standard recommendations were used (Jenike, 1964; British Materials Handling Board, 1985), including the Operation Manual for the TSG 70-140 machine.

### 2.3.1 Flow properties

According to Naka (2010), for the calculation of the hopper tilt, to avoid the formation of obstructions that may prevent proper flow of the stored product, the values of the angle of internal friction and the effective angle of internal friction are required.

The angle formed by the yield locus straight line and the horizontal is the angle of internal friction ($\phi_i$). The effective angle of internal friction ($\phi_e$) is obtained in the same manner as $\phi_i$, when free-flowing product is considered. In practice, $\phi_e$ is always built with a line between the origin and the intersection with the largest Mohr's circle.

The angle of friction between the coffee and the wall ($\phi_w$) is the angle formed by the wall yield locus straight line and the horizontal. To measure the wall friction angle, the base of the shear cell was replaced by a sample made of different materials: rough steel; wood; and concrete.

The product contained in the upper part of the shear cell was sheared on the material sample under different normal stresses of 50, 40, 30, 20, 10 and 0N, and the shear stress values were measured.

The internal and external friction coefficients of the whole and ground roasted coffee under different conditions (degree of roast, grain size and storage time) were mathematically determined by Equations 1 and 2, respectively.

$$\mu'_i = \tan \varnothing_i \tag{1}$$

$$\mu'_e = \tan \varnothing_w \tag{2}$$

where: $\phi_i$ = angle of internal friction, degree; $\phi_w$ = angle of friction with the wall, degree; $\mu_i$' = internal friction coefficient, dimensionless; and $\mu_e$' = external friction coefficient, dimensionless.

Flow Function (FF) is the unconfined slip resistance or pressure ($\sigma_{ic}$) and a measure of the product resistance to flowing on a free surface at the maximum consolidation pressure function. Thus, due to this property, the product is capable of forming a stable arc or a tube effect (Calil Júnior, 1990). FF is defined by Equation 3 and values are a result of an average of three repetitions at each condition tested.

$$FF = \frac{\sigma_1}{\sigma_{ic}} \tag{3}$$

where: $FF$ = flow function, dimensionless; $\sigma_1$ = maximum consolidation stress, kPa; and $\sigma_{1c}$ = unconfined slip resistance, kPa.

The German standard DIN 1055-6 from 2005 sets the K value using Jaky's expression, considering a weighting coefficient equal to 1.2 (Equation 4). This equation best approximates the K coefficient experimental data (Nascimento & Calil Júnior, 2009).

$$K = 1.2\left(1 - \sin \varnothing_e\right) \tag{4}$$

where: $K$ = lateral pressure coefficient, dimensionless; and $\phi_e$ = effective angle of internal friction of the product, degree.

According to DIN 1055-6, the factor 1.2 was chosen to ensure that at small heights of the stored product, that is, at the top of the silo, more nearly complete pressure curves are found.

### 2.4 Statistical analysis

The study was conducted in a split plot design, with storage time in plots and a 2 × 4 × 2 factorial in subplots (two degrees of roasting, four grain size levels and two storage temperatures), with a different number of repetitions for each analyzed variable response.

The experimental data of the flow properties analyzed for each storage time were subjected to analysis of variance, and the means were compared by Tukey's test at a 5% probability level. For the storage time, the models were chosen based on the significance of the regression coefficients using the "t" test at the 1, 5 and 10% levels; on the coefficient of determination, $R^2$ (obtained from the relationship between the sum of squares of the regression and the sum of squares of the treatment); and on the behavior under study.

## 3 Results and discussion

### 3.1 Roasting procedure

The mean initial water content of the coffee beans (raw material) was 12.61% on a dry basis (db), which was determined gravimetrically using a forced-air oven at 105 ± 1°C for 24h (brand Tecnal Equipamentos Científicos, model TE-394/2-MP, Brazil) (Brasil, 2009).

The mass loss parameter was determined to ensure roasting uniformity, and the coffee beans lost, on average, 15.85 and 18.74 grams of mass under ML and MD roasting, respectively, at a temperature of 285 ºC (Vargas-Elías, 2011). Roaster temperature and roasting time tests were performed to evaluate their influence on mass losses. In average, 15.67 and 18.43 minutes, for ML and MD roasting, respectively. The product was removed from the roaster when reaching the aforementioned degrees of roasting and immediately cooled to room temperature.

### 3.2 Flow properties

The angle of internal friction ($\phi_i$) is proportional to the normal force on the grains, and the counter force consists of a mixture of slip and rolling pressures between the grains (Gaggero et al., 2002). This angle is closely linked to the internal conditions of the stored product (Nascimento & Calil Júnior, 2009), depending on the amount of mean pressure applied to all grains. The angle of internal friction influences the different types of flow that occur inside silos and the generation of rupture planes within the stored material (Ramírez et al., 2009). Along with the effective angle of internal friction ($\phi_e$), it provides important information regarding the flow in different circumstances. This angle refers to the internal conditions of the stored product, depending on the amounts of mean pressures applied to all grains. The increase in confining pressure makes the product sample denser. Thus, $\phi_i$ increases with the specific weight or with a decrease in the void ratio.

Storage temperature did not significantly alter $\phi_i$ and $\phi_e$ values; thus, a mean value for each grain size and roast level was used. During storage, $\phi_i$ and $\phi_e$ increase and decrease, and their values tend to become closer to each other at the end of 180 days of storage (Figures 1 and 2). Different aspects explain this behavior. First, wetter samples show greater cohesion force between the particles or individual components that compose the mass, tending to aggregate these particles and consequently, increasing internal friction. Additionally, in certain products, there is increased surface roughness with higher water content, resulting in higher slip resistance of one product particle against another, consequently increasing $\phi_i$ and $\phi_e$ (Mohsenin, 1986; Baryeh, 2001). According to Duffy & Puri (1996), the opposite behavior (decreased $\phi_i$ and $\phi_e$) occurred because for high water contents, especially for pulverulent products, a surface layer forms that acts as a lubricant during the application of shear force, thus reducing the internal friction in the shear zone.

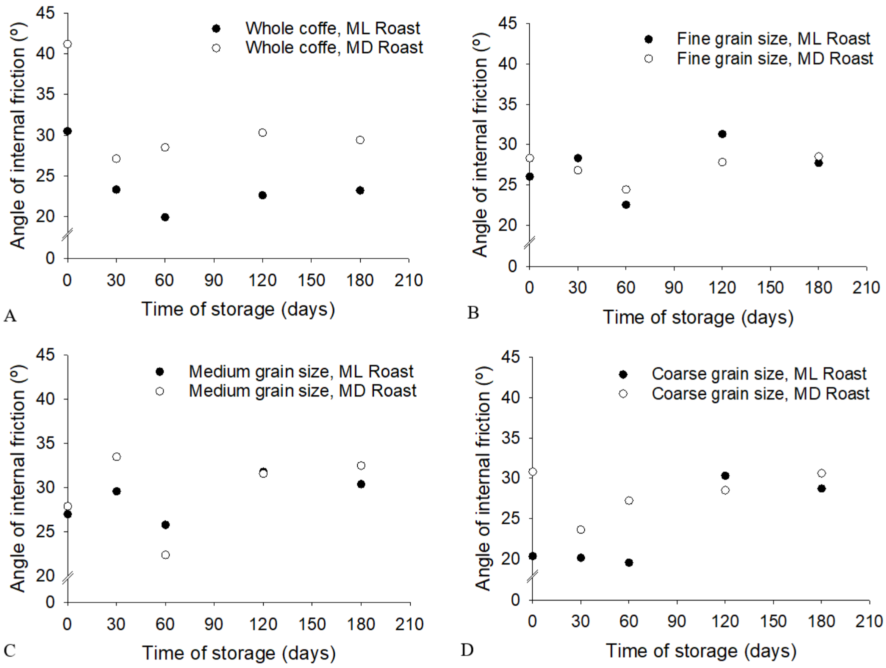


**Figure 1.** Values of angles of internal friction of roasted *C. arabica*, whole coffee (A), fine particle size (B), medium particle size (C) and coarse particle size (D), during storage.

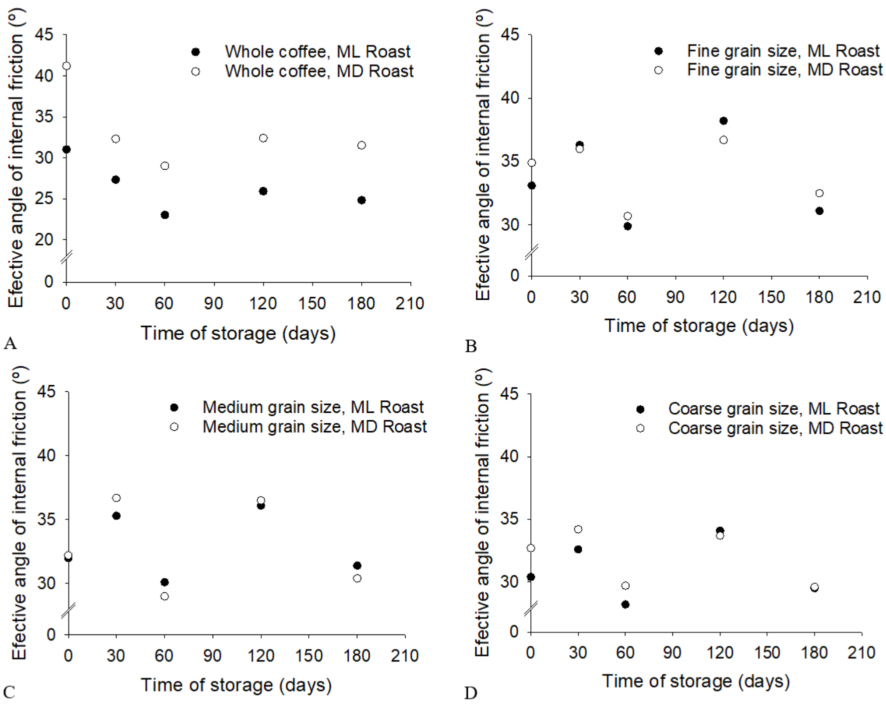


**Figure 2.** Values of effective angles of internal friction of roasted *C. arabica,* whole coffee (A), fine particle size (B), medium particle size (C) and coarse particle size (D), during storage.

Figure 2 show that whole roasted coffee, presented a different behavior from ground roasted coffee. Ground roasted coffee presented increases in the $\phi_e$ values from harvest to 30 days of storage, while whole roasted coffee presented decreases in those values after harvest (Figure 2). The whole coffee had a higher capacity to preserve its constituents when compared to grounded coffee, and its water content was greater due to the physical barrier derived from the intact cells and/or the low degree of rupture. Grinding allows this barrier to be broken, increasing the speed of exchanges between the product and the environment surrounding it (Corrêa et al., 2016), leading to agglomeration effect due to absorption of environmental moisture. This process occurs more abruptly at the beginning due to the low water content after roasting (the product becomes more hygroscopic), with higher moisture absorption at this stage. Thus, agglomeration decreases coffee flowability, increasing the $\phi_e$ values, as can be seen in Figure 2 for grinded coffee, regardless of the grain size.

In general, the more intensely roasted samples (MD) had higher values of $\phi_i$ and $\phi_e$ during storage. A higher degree of roasting involves an increase in friability of the product particles (Medeiros & Lannes, 2010); that is, they are more likely to crumble and, therefore, to form smaller particles.

According to Calil Junior & Cheung (2007), for granular products, the angle of internal friction was approximately equal to the effective angle of friction; however, this tendency is not an absolute truth, as the angles may depend on the particle shape and other factors. These values were different in the present study.

Whole roasted coffee, regardless of the wall material used, had lower values of $\phi_w$ than those of ground roasted coffee, with $\phi_w$ values ranging between 11.1 and 22.0º, 19.0 and 29.5º, 15.7 and 29.1º, and 12.6º and 25.5º, respectively, for whole coffee and fine, medium, and coarse ground coffee (Figure 3). This result is associated with the roughness of whole coffee. These samples had lower surface roughness compared with ground samples because they were preserved intact after roasting, as grinding causes breakage of the product into smaller particles of different shapes, increasing the adherence of the product to the wall material and, finally, increasing $\phi_w$.

Upon analyzing Figure 3, it can be observed that in general, the coffee samples roasted to the MD level had higher $\phi_w$ values than the samples roasted to the ML level for whole coffee. It is expected that products with higher water content (ML roast) present greater difficulty in flowing; that is, they have higher $\phi_w$ values. However, the opposite behavior was noted in this study, possibly due to the increase in friability of the product particles; that is, they become more likely to crumble when more intensely roasted, thus forming smaller particles, which in turn increase the product/wall adherence (Medeiros & Lannes, 2010). For coffee powder, independently of the particle size, roasting has a lower influence over $\phi_w$.

Also with respect to Figure 3, one can see that the smaller the size of the coffee particles, the higher the $\phi_w$ values are. Three types of feed with different grain sizes were evaluated (Lopes Neto et al., 2007), and the authors also concluded that smaller grain sizes led to higher values of $\phi_w$ due to the high degree of contact between the specific surface of the particles and the walls, increasing the adherence of the product to the wall surfaces.

During storage, $\phi_w$ increases and decreases, with no defined behavior. This trend was observed for flour (Iqbal & Fitzpatrick, 2006); however, these same authors observed that occurred an increase of $\phi_w$ values for tea powder and whey powder throughout storage. These conclusions indicated that each agricultural product presents a different behavior of $\phi_w$ during storage. The variation with no defined behavior reported is due to the same reasons previously explained for the angle of internal friction and the effective angle of internal friction.

Also apparent from Figure 3, specifically between wall materials (i.e., wood, steel or concrete), the $\phi_w$ values were higher when the wall material was wood, followed by concrete and then steel. This difference is related to the surface roughness of the evaluated materials. The coefficients of friction of grains of rice as paddy, peeled and polished grains against the same wall materials used in this study was evaluated (Silva et al., 2003), which the authors concluded that the coefficients of friction were higher when the material used was wood, followed by concrete and steel, corroborating the present results. These authors linked this difference to the surface roughness of the material, with values of 0.64, 3.22 and 3.56 μm for steel, concrete, and wood, respectively.

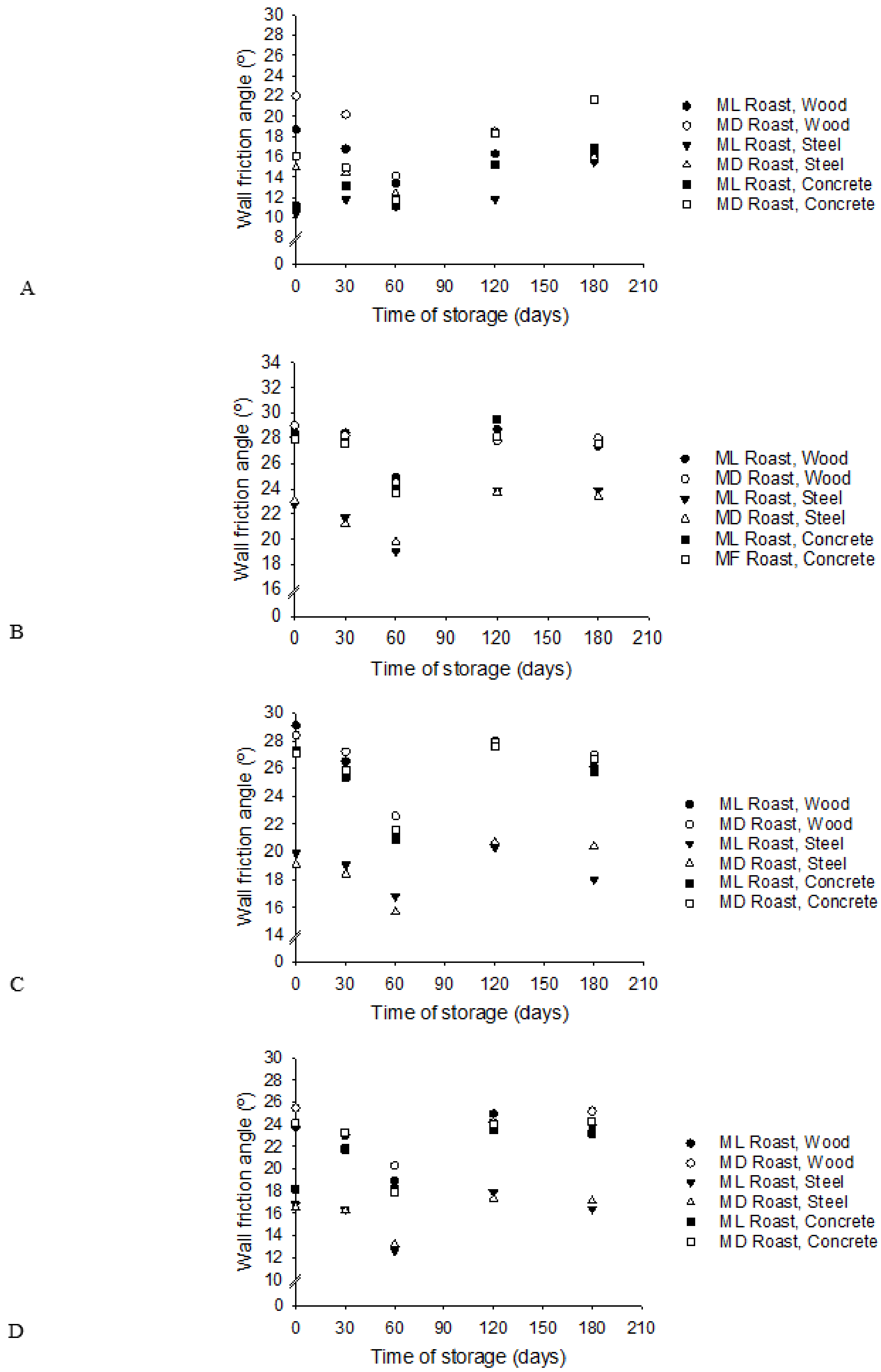


**Figure 3.** Values of the angle of friction with the wall material of roasted *C. arabica*, whole coffee (A), fine particle size (B), medium particle size (C) and coarse particle size (D), during storage.

The coefficient of internal friction ($\mu_i$') (Figure 4), which represents the relationship between the friction force and the normal force on the surface of the coffee bulk, increased during storage, ranging between 0.3554 and 0.8765. These results are in the range reported for sugar, barley, maize, soya and wheat flour, with concrete and steel materials (Ramírez et al., 2009).

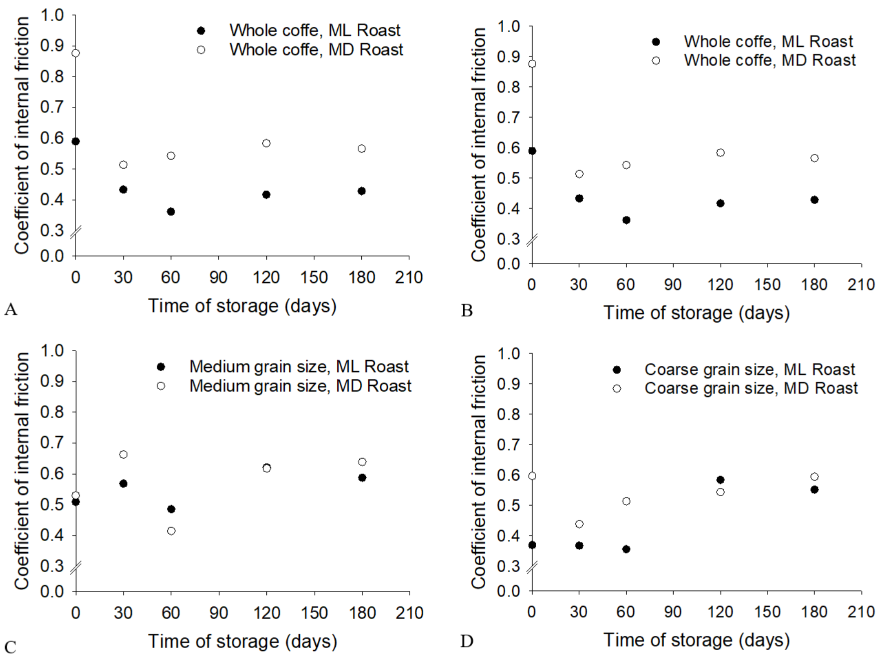


**Figure 4.** Values of coefficient of internal friction of roasted *C. arabica*, whole coffee (A), fine particle size (B), medium particle size (C) and coarse particle size (D), during storage.

The $\mu_i$' values were generally higher for the samples roasted to the MD level (from 0.4144 to 0.8765), fine ground (from 0.4134 to 0.6084), when compared to the ML roast (from 0.3554 to 0.6209) and coarse (from 0.3554 to 0.5969). This behavior is due to the increased friability of the MD roasted coffee, the cohesive strength of the coffee particles and the water content of the product.

The values of the coefficient of external friction ($\mu_e$'), which represent the relationship between the friction force and the normal force on the surface of the material used in the construction of the silo wall, changed as a function of the material used, the roast level, the coffee grain size and the length of storage. For these last three factors, the behavior was similar to that observed for $\mu_i$'.

Regardless of the storage temperature, the roast level and the degree of grinding, the $\mu_e$' values were higher for wood, followed by concrete and steel, a result similar to that reported for paddy, peeled and polished rice (Silva et al., 2003). This, observation, as explained in the previous section, is due to the surface roughness of the material. The range of $\mu_e$' values ranged from 0.1964 to 0.5774, 0.1425 to 0.5095, and from 0.1964 to 0.5669, respectively, for wood, steel and concrete.

According to Jenike (1980), the FF could be classified according to certain limit values or indices, as this property represented a direct relationship between the consolidation pressure and the unconfined resistance (i.e., the slip resistance). For the analysis of the product flow behavior under different conditions of roast, grain size and storage, the limit values of the FF are used: FF<2 (very cohesive products, no flow); 2<FF<4 (cohesive products); 4<FF<10 (products that flow easily); FF>10 (free-flowing products) (Jenike, 1964).

When the results are compared with the limit values, it is concluded that the roasted whole coffee can be considered as free-flowing (FF>10), regardless of the roast level and storage temperature. Other research also considered different agricultural products as free-flowing (Ramírez et al., 2009), classified as cohesive (Bian et al., 2015) and very cohesive [9,11], indicating the need to investigate different agricultural products under different conditions.

The ground coffee grain sizes, however, showed a different behavior to that observed for the whole samples. The FF values decreased as the grinding became more intense (fine particle size), indicating that the higher the degree of coffee grinding, the greater the difficulty of the product to flow. According to the values measured, coarse ground coffee can be classified as a product that flows easily (4<FF<10), while the medium ground coffee alternated between that classification and one of a cohesive product (2<FF<4) as the storage time increased. Regarding the fine ground samples, they were only classified as a cohesive product.

Roasting and storage temperature influenced the product flow. In general, the samples roasted to the ML level had higher values of this property than those roasted to the MD level, a fact closely linked to the product water content. However, the samples stored at 10 ºC had higher FF values than those stored at 30 ºC. This fact is due to the low temperature, which results in less interaction with the environment and, consequently, less adsorption of water by the coffee during storage.

The K coefficient is defined as the ratio between horizontal and vertical pressures at any point of a granular mass, also known as the lateral pressure coefficient. The K coefficient is one of the parameters needed to calculate the pressures the product applies on the wall and the bottom of a silo. The K coefficients were calculated only based on the effective angle of internal friction rather than the wall materials used (wood, concrete and steel), as their roughness does not have much influence in the determination of K (Nascimento & Calil Júnior, 2009).

An exploratory analysis was made previously to identify the variables that are not significant for the dependent variable (K coefficient). Storage temperature did not significantly alter this parameter, however, storage period, grain size and roast degree influenced the values of K coefficient. Roast degree significantly altered these values throughout the entire remaining variables; thus, two tables, separated by means of roast degree, were made to facilitate the discussion. K coefficient values of coffee at medium light roast are presented at Table 1, whilst values of this coefficient at moderately dark are presented at Table 2.

**Table 1.** K coefficient values of *C. arabica*, at medium light roast level and four particle sizes (fine, medium, coarse and whole coffee) during storage.

| Time(days) | Particle sizes | | | |
|---|---|---|---|---|
| | **Fine** | **Medium** | **Coarse** | **Whole Coffee** |
| 0 | 0.5441 ± 0.0102 aBC | 0.5643 ± 0.0299 aBC | 0.5928 ± 0.0001 aAC | 0.5820 ± 0.0189 aA |
| 30 | 0.4892 ± 0.0236 aAB | 0.5078 ± 0.0336 abcAB | 0.5538 ± 0.0560 cAB | 0.6496 ± 0.0531 dB |
| 60 | 0.6019 ± 0.0396 bC | 0.5981 ± 0.0278 abcC | 0.6340 ± 0.0454 bcC | 0.7329 ± 0.0711 dC |
| 120 | 0.4588 ± 0.0168 aA | 0.4932 ± 0.0294 abA | 0.5286 ± 0.0444 bcA | 0.6754 ± 0.0302 dBC |
| 180 | 0.5802 ± 0.0048 bC | 0.5754 ± 0.0090 abcBC | 0.6102 ± 0.0511 bcBC | 0.6974 ± 0.0258 dBC |

Each value is the mean ±SD, n=6. Means followed by the same lower-case letters on the lines and capital letters in a column do not differ significantly by the Tukey's test ($p < 0.05$).

**Table 2.** K coefficient values of *C. arabica*, at moderately dark roast level and four particle sizes (fine, medium, coarse and whole coffee) during storage.

| Time(days) | Particle sizes | | | |
|---|---|---|---|---|
| | **Fine** | **Medium** | **Coarse** | **Whole Coffee** |
| 0 | 0.5141 ± 0.0203 bCD | 0.5612 ± 0.0143 bCD | 0.5515 ± 0.0408 bA | 0.4104 ± 0.0572 aA |
| 30 | 0.4975 ± 0.0203 aBD | 0.4831 ± 0.0489 aAD | 0.5280 ± 0.0728 aA | 0.5597 ± 0.0770 aB |
| 60 | 0.5883 ± 0.0166 aC | 0.6186 ± 0.0437 aC | 0.6052 ± 0.0176 aA | 0.6213 ± 0.0977 aB |
| 120 | 0.4831 ± 0.0400 aAD | 0.4859 ± 0.0238 aBD | 0.5345 ± 0.0344 aA | 0.5577 ± 0.0591 aB |
| 180 | 0.5546 ± 0.0051 aCD | 0.5934 ± 0.0091 aC | 0.6074 ± 0.0305 aA | 0.5751 ± 0.0684 aB |

Each value is the mean ±SD, n=6. Means followed by the same lower-case letters on the lines and capital letters in a column do not differ significantly by the Tukey's test ($p < 0.05$).

From Tables 1 and 2, it is apparent that the opposite behavior is reported for the effective angle of internal friction according to grain size, storage time and roast level factors. This behavior is expected, as the K coefficient depends on that flow property. However, a strict trend was not observed for K coefficient, regarding roast and grinding degree. In general, the K coefficient values were higher at ML roast level samples. Exceptions were for medium coffee in stored for 60 days, medium coffee stored for 180 days, fine coffee stored for 30 days, fine coffee stored for 120 days and fine coffee stored for 180 days. Thus, coffee roasted to the ML level while whole requires storage structures that support higher pressures. Particularly for roasted and ground coffee, lower grinding levels lead to the need for structures that absorb higher pressure during the post-harvest operations. The K coefficient values ranged between 0.4546 and 0.7396, 0.4104 and 0.6520, 0.4104 and 0.7263, 0.4104 and 0.7396, 0.4104 and 0.7396, 0.4546 and 0.6107, 0.4672 and 0.6244, and then between 0.5071 and 0.6484, respectively, for the coffee samples roasted to the ML and MD levels, for whole coffee, fine, medium and coarse particle sizes.

## 4 CONCLUSIONS

Based on the results obtained and the conditions in which the experiment was conducted, it can be concluded that milling is the main factor that defines the flow behavior. Roasting significantly altered the values of the angle of internal friction, effective angle of internal friction, wall friction angle and coefficient of internal friction, specially at the coffee lot that was not ground. These differences between fine, medium and coarse coffee particle sizes are lower. More intense roasting and smaller grain sizes led to higher values of wall friction angle. The wood sample was the material with the highest values of wall friction angle, followed by the concrete and smooth steel samples; thus, steel is indicated as the material to be used to construct storage facilities, since it permits a higher flowability of coffee, facilitating transport of this product. Moderately dark roasting and higher grind level resulted in higher values of this property, as well as for the coefficient of external friction. The coefficient of external friction changed as a function of the wall material used, showing higher values for wood, followed by concrete and steel. The coffee lot kept whole was characterized as free-flowing; for the ground coffee samples, as the grind level increased, the product approached the flow of the cohesive product. The K coefficient values showed an opposite behavior to that presented by the effective angle of internal friction, and the coffee samples of medium light roast, whole coffee are the samples that need storage structures that support higher pressures.

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