

## Compressive strength of corn kernels subjected to drying under different rest periods<sup>1</sup>

Resistência à compressão dos grãos de milho submetidos a secagem com diferentes tempos de repouso

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**ABSTRACT** - Mechanical properties of agricultural products are essential for a proper project design or processing equipment dimensioning, as well as for establishment of parameters on the supported load. An experiment was set up in a completely randomized design, with five treatments (continuous and intermittent drying under 4, 8, 12, and 16 h of rest period) and four replications, to evaluate the effect of intermittent drying. Corn kernels of the cultivar Cargo TL were harvested with a moisture content of 25.37% wb and submitted to drying in an experimental fixed bed dryer set to a temperature of 100 °C and an airflow of 1.5 m<sup>3</sup> min<sup>-1</sup> m<sup>-2</sup>. Drying was performed until the kernels reached a moisture content of 14±0.3% wb. The process was interrupted in the intermittent drying with a moisture content of 18±0.2% wb and continued after rest period until the final moisture content was reached. The analysis consisted of 10 kernels randomly selected per replication and submitted to the uniaxial compression test after determining their dimensions. Rupture force, maximum deformation, energy to rupture point, modulus of toughness, hardness, and drying rate during drying were evaluated. The increase in rest period promoted a linear increase in the rupture force and hardness. Modulus of toughness, energy to rupture point, and maximum deformation were not affected by the rest period. The increase in rest period contributed to increasing the drying rate.

**Key words:** Intermittent drying. Mechanical properties. Rupture force. Hardness. Drying rate.

**RESUMO** - As propriedades mecânicas de produtos agrícolas são fundamentais para o correto desenho de projetos ou dimensionamento de equipamentos de processamento e estabelecimento de parâmetros sobre a carga suportada. Para avaliar o efeito da secagem com intermitência, foi montado um experimento em delineamento inteiramente casualizado, com cinco tratamentos (secagem contínua e intermitente com 4; 8; 12 e 16 h de repouso) e quatro repetições. Os grãos de milho, cultivar *Cargo TL*, foram colhidos com teor de água de 25.37% b.u., submetidos a secagem em um secador experimental de camada fixa, ajustado à temperatura de 100 °C e fluxo de ar de 1.5 m<sup>3</sup> min<sup>-1</sup> m<sup>-2</sup>. A secagem decorreu até que os grãos atingissem o teor de água de 14±0.3% b.u. Para a secagem intermitente o processo foi interrompido com 18±0.2% de teor de água b.u. e prosseguiu após o repouso, até atingir o teor de água final. Para a análise foram selecionados aleatoriamente 10 grãos por repetição e submetidos ao teste de compressão uniaxial depois de determinar as suas dimensões. Avaliou-se a força de ruptura, deformação máxima, energia consumida até o ponto de ruptura, módulo de tenacidade, dureza e taxa de redução da água durante a secagem. Concluiu-se que, o aumento do tempo de repouso promoveu um aumento linear nos valores da força de ruptura e dureza; o módulo de tenacidade, energia e deformação não foram afetados pelo tempo de repouso; o aumento do tempo de repouso contribuiu para o aumento da taxa de redução da água.

**Palavras-chave:** Secagem intermitente. Propriedades mecânicas. Força de ruptura. Dureza. Taxa de redução da água.

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## INTRODUCTION

Corn treatment for human and animal feed requires several types of mechanical processing, making it important to know the physical and mechanical properties (BABIĆ *et al.*, 2013). This knowledge is essential for establishing better conditions for conservation, dimensioning, and correct construction of the equipment used in post-harvest processes. The inadequate equipment dimensioning can generate a loss of grain quality, thus depreciating the price at the time of commercialization (CORRÊA *et al.*, 2007; GELY; PAGANO, 2017; SANGAMITHRA *et al.*, 2016). A similar situation was also referred to in a study on mechanical and geometric properties of barley (MARKOWSKI *et al.*, 2010). According to Bagheri *et al.* (2011), cracks or breaks in agricultural products result from strains higher than their force capacity.

The evaluation of parameters related to the rupture or breaking of agricultural products is important to design efficient processing projects, which can be influenced by factors such as temperature, moisture content, and deformation rate (BABIĆ *et al.*, 2013; BALASTREIRE; HERUM; BLAISDELL, 1982).

Knowing the mechanical properties of agricultural products allows the estimation of the force they can withstand during a given operation without causing damage to their physical structure (ABASI; MINAEI, 2014; COUTO *et al.*, 2002). According to Sharma *et al.* (2017), grains with a higher fraction of corneous endosperm tend to have higher hardness and are more resistant to force application.

Moisture content, chemical composition, genotype, and drying air temperature are some examples of factors that may influence the susceptibility to grain breakage (GUNASEKARAN; PAULSEN, 1985). The most resistant grains to various impacts since harvesting, processing, and transportation can be destined for the most demanding market in quality, besides having higher storage potential.

Gunasekaran and Paulsen (1985) studied corn grain force as a function of the drying rate at different temperatures and concluded that the susceptibility to breakage and the percentage of broken grains are directly influenced by an increase in the drying rate and drying air temperature.

Abasi and Minaei (2014) evaluated the effect of drying air temperature on corn and found that an increase in temperature from 40 to 70 °C led to a reduction in the grain rupture force by about 21%, that is, from 345,405 to 271,198 N. According to these authors, a decrease in rupture force may be associated with the internal stress suffered by the grain, causing cracks or breaks during the drying process.

According to Couto *et al.* (2002), one of the ways to measure the capacity of the mechanical force of a given product to the load is through the uniaxial compression test, which consists of applying a gradually increasing force through a compression plate. Several studies have addressed the mechanical properties of agricultural products, including corn (ABASI; MINAEI, 2014), rice (BAGHERI *et al.*, 2011; RESENDE *et al.*, 2013), oat (ZHAO *et al.*, 2017), wheat (FERNANDES *et al.*, 2014), and sorghum (RODRIGUES *et al.*, 2019), but most of them relate these properties with differences in moisture content. In this context, this study aimed to evaluate the influence of the rest period during the drying of corn kernels on the drying rate and mechanical properties.

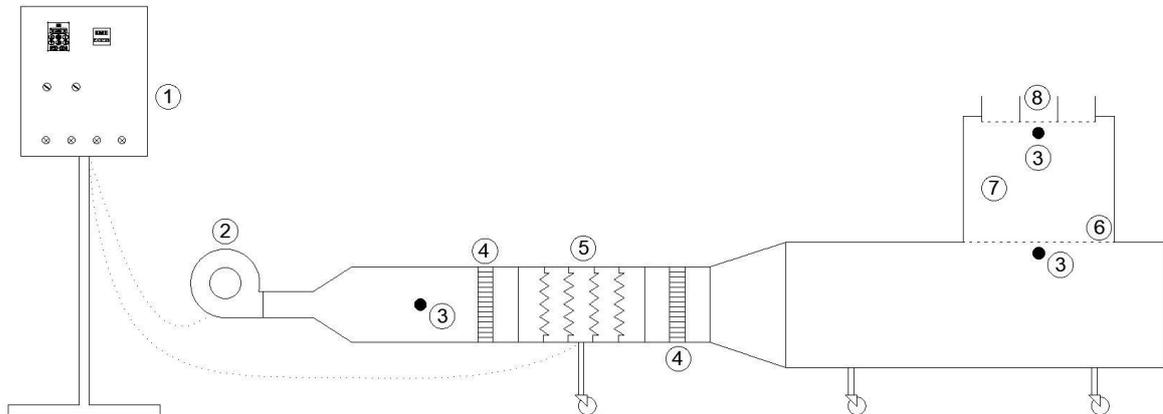
## MATERIAL AND METHODS

This study was carried out at the Laboratories of Post-Harvest Process (LPPC) and Pre-Processing and Storage of Agricultural Products (LAPREP) of the School of Agricultural Sciences (FCA) of the Federal University of Grande Dourados (UFGD), Dourados, MS, Brazil.

Initially, ears of corn of the cultivar Cargo TL produced at the FCA experimental farm, with a moisture content of 25.37% on a wet basis (wb) were manually harvested. These ears went through a manual threshing process. Subsequently, the corn was maintained in transparent polyethylene packaging in a cold chamber at 5 °C for 72 hours to standardize the moisture content of kernels, which was determined in a forced-air circulation oven at 105±1 °C for 24 h, in three replications of 15 g (BRASIL, 2009). Subsequently, the kernels were dried using an experimental fixed bed dryer (Figure 1) with precise temperature control and drying airflow system, considering five rest periods (treatments) of 0, 4, 8, 12, and 16 hours, where zero corresponds to continuous drying and the other times to intermittent drying. The drying air temperature (100 °C) was monitored by reading on the control panel, being also checked using a mercury thermometer placed in the drying chamber. The airflow (1.5 m<sup>3</sup> min<sup>-1</sup> m<sup>-2</sup>) was determined indirectly by measuring the drying airspeed using an anemometer (0.02 m s<sup>-1</sup>), considering a kernel volume of 0.035 m<sup>3</sup>, 0.283 m<sup>2</sup> of the base area in the drying chamber, and an initial kernel layer height of 0.124 m.

The kernel mass was turned over throughout the drying process to avoid the formation of gradients of temperature and moisture content at regular intervals of 10 min, corresponding to the times of control of moisture content reduction. Moisture content was monitored using three completely perforated polyethylene packages containing 100 g of product each and placed randomly in

**Figure 1** - Experimental fixed bed dryer used to dry corn kernels. (1) airflow and temperature control panel; (2) centrifugal fan; (3) temperature measurement point; (4) air homogenizers; (5) set of electrical resistance heaters; (6) perforated canvas for thick-layer drying; (7) thick-layer drying bed; and (8) set of trays for thin-layer drying



the kernel mass. The control of continuous drying was carried out until it reached a moisture content of  $14 \pm 0.3\%$  wb. On the other hand, the process of the other treatments was carried out in two stages, the first up to a moisture content of  $18 \pm 0.2\%$  wb and the second until it reached a moisture content of  $14 \pm 0.3\%$  wb after the rest period.

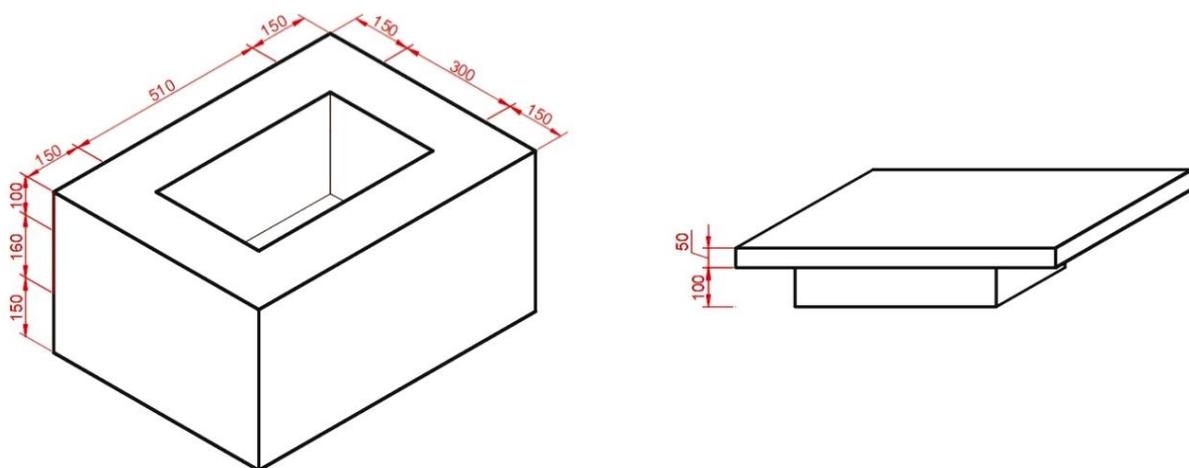
During the rest period, the corn was placed in an airtight box of expanded polystyrene fully closed to simulate the silo conditions and avoid interference from the outside environment as much as possible. Temperature and relative humidity conditions of the air inside the kernel mass were measured throughout the rest period using an HT-4010 digital data logger placed in the middle of the kernel mass. This equipment has the capacity for instantaneous records and an internal storage system,

which allows downloading the data to a computer using the HT Communication software.

The 100 -L expanded polystyrene box used to place the corn during the rest period was adapted to present dimensions of 0.51 m in length, 0.30 m in width, and 0.16 m in height, totaling a volume of 24.48 liters ( $24.48 \times 10^{-3} \text{ m}^3$ ) (Figure 2).

All walls of the expanded polystyrene box had a thickness of 0.15 m, which is equivalent to 1.1428 m of kernel mass thickness. This relationship was obtained considering the thermal conductivity of expanded polystyrene ( $0.024 \text{ W m}^{-1} \text{ }^\circ\text{C}^{-1}$ ) and corn kernels ( $0.183 \text{ W m}^{-1} \text{ }^\circ\text{C}^{-1}$ ) for temperature and moisture content conditions at the rest period (ANDRADE *et al.*, 2004; CHAI; CHEN, 2010).

**Figure 2** - Characteristics and dimensions of the expanded polystyrene box used to pack the corn during the rest period



### Average drying rate

The drying rate or the speed with which moisture was removed from the kernel was determined using Equation (1). The rate was recorded at the time the kernel was subjected to rest period and after its return. Subsequently, the average value of each treatment was determined for the entire effective period.

$$DR = \frac{X_0 - X_i}{t_i - t_0} = \frac{mw_0 - mw_i}{dm (t_i - t_0)} \quad (1)$$

Where: DR is the drying rate ( $\text{kg H}_2\text{O kg}^{-1} \text{ dm h}^{-1}$ ),  $X_0$  and  $X_i$  are the previous and current moisture content (decimal, wb),  $dm$  is the dry mass,  $mw_0$  and  $mw_i$  are the total previous and current mass of water (kg) and  $t_i$  and  $t_0$  are the total current and previous drying time (h).

Four replications of ten corn kernels were selected to evaluate the mechanical properties, which were subjected to the uniaxial compression test (ABASI; MINAEI, 2014; TARIGHI; MAHMOUDI; ALAVI, 2011). The dimensions of each grain subjected to the compression test were determined using a digital caliper with a 0.01 -mm resolution.

### Physical characteristics of kernels

The equivalent average volume of kernels was determined, considering the corn shape as a spheroid (Equations 2 and 3), by approximation previously tested using the volume determination tests by the displacement method with hexane, low-density fluid ( $0.658 \text{ g mL}^{-1}$ ), and penetration into the kernel. Thus, statistically equal results were found, validating the equations for the condition of this study (ABASI; MINAEI, 2014).

$$d_e = \sqrt[3]{abc} \quad (2)$$

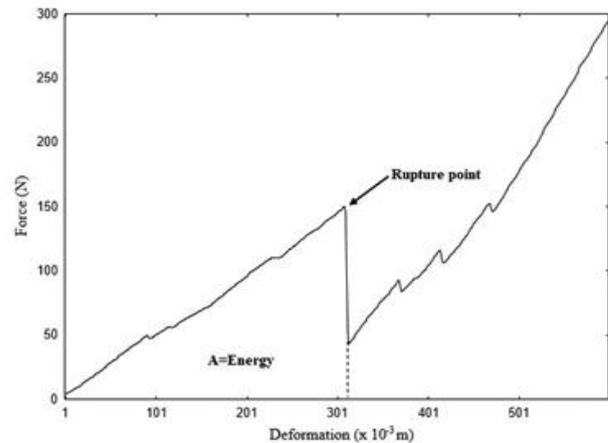
$$V_e = \frac{1}{6} d_e^3 \quad (3)$$

Where:  $d_e$  is the equivalent corn kernel diameter (mm),  $V_e$  is the equivalent corn kernel volume ( $\text{mm}^3$ ), and  $a$ ,  $b$ , and  $c$  represent the major, medium, and minor axis of the corn kernel, respectively (mm).

### Rupture force

The deformation force curves were obtained from grains submitted to the uniaxial compression test using the Texture Analyzer TA HD Plus, with a 750 -N load cell. Corn kernels were submitted to the compression test in their normal resting position, being adopted 1 mm as the maximum kernel deformation value and  $0.2 \text{ mm s}^{-1}$  as the test speed, obtained through the stability tests. The kernel rupture point was determined after obtaining the force curves as a function of deformation, as shown in Figure 3.

**Figure 3** - Example of the force curve as a function of corn kernel deformation with rupture point illustration



The rupture point corresponds to a continuous reduction in the upward behavior of the force values, simultaneously occurring a break or crack in the kernel that may be visible or not.

### Absorbed energy

The energy absorbed (E) or necessary for the deformation corresponds to the area under the force-deformation curve during the load (Figure 3), as shown in Equation (4) (TARIGHI; MAHMOUDI; ALAVI, 2011).

$$E = \frac{F_r D}{2} \quad (4)$$

Where:  $F_r$  is the rupture force and  $D$  is the deformation at the kernel rupture point.

### Modulus of toughness

According to the methodology described by Abasi and Minaei (2014), the modulus of toughness is the energy needed for the product to break or the energy absorbed by the product to the rupture point per unit of volume, being determined based on Equation (5).

$$P = \frac{\int F dx}{V_e} \quad (5)$$

Where:  $P$  is the modulus of toughness ( $\text{mJ mm}^{-3}$ ),  $F$  is the compressive force (N),  $dx$  is the deformation (m), and  $V_e$  is the equivalent corn kernel volume ( $\text{mm}^3$ ).

### Hardness

Hardness is the relationship between the compressive force and deformation at the rupture point, according to Equation (6) (OLANIYAN; OJE, 2002).

$$Q = \frac{F_r}{D} \quad (6)$$

Where:  $Q$  is the kernel hardness ( $\text{N mm}^{-1}$ ),  $F_r$  is the rupture force (N), and  $D$  is the deformation at rupture point (mm).

### Statistical analysis

The data were analyzed using the SigmaPlot 11.0 software. The regression model was constructed and analyzed according to the data trend, using the F-test at a 5% probability level, significance of coefficients, and coefficient of determination ( $R^2$ ). Pearson's correlation analyses were also performed at a 5% significance level. The analyses were performed considering a completely randomized design, with five treatments (one continuous drying and four rest periods) and four replications.

## RESULT AND DISCUSSION

The kernel characteristics are shown in Table 1. The data were relatively similar, leading to analysis with good accuracy for mechanical properties (ABASI; MINAEI, 2014).

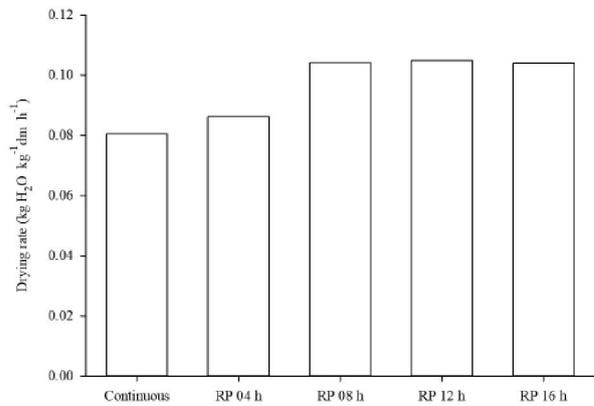
According to Couto *et al.* (2002), the force-deformation values depend on the size of the material submitted to compression, and the higher the kernel size, the higher the force necessary to generate the same deformation and, consequently, the higher the rupture force. Gunasekaran and Paulsen (1985) stated that kernels must be grouped in a way that their size does not influence the mechanical properties when performing the compression test.

The average drying rate increased as the kernel rest period increased (Figure 4). This situation reflects the compression between the diffusion of water and its evaporation during drying.

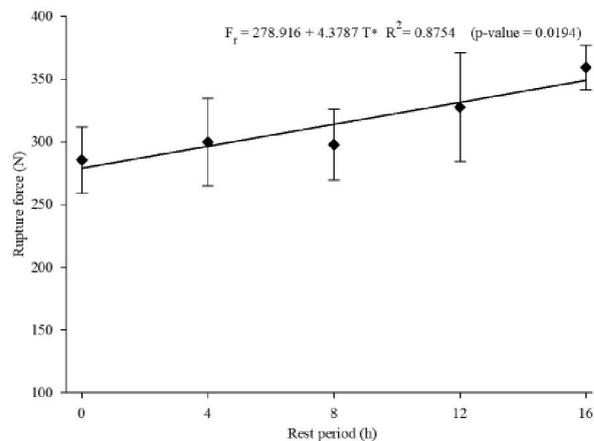
Figure 5 shows an increasing tendency of the rupture force due to an increase in the rest period during drying. This behavior is in line with the reduction of the

tensile forces exerted by water during the drying process for longer rest periods, which were converted into a reduction in the effective drying time and higher drying rate after rest period (Figure 4).

**Figure 4** - Average drying rate during drying as a function of rest period. RP - Rest period



**Figure 5** - Variation in the rupture force of corn kernels after drying under different rest period. \*Significant at 5% level by the F-test



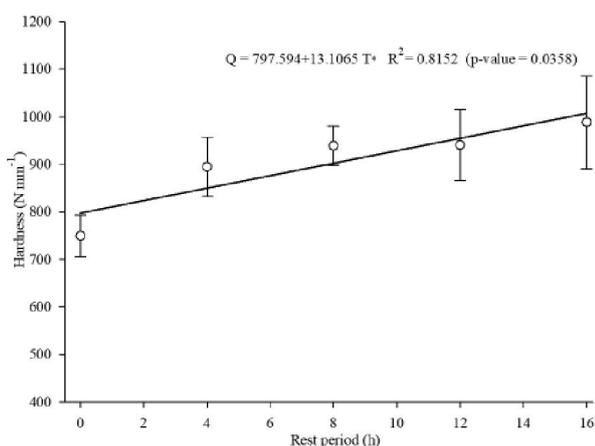
**Table 1** - Average values of kernel physical characteristics as a function of the rest period during continuous and intermittent drying. RP - rest period,  $M_u$  - unit kernel mass, a, b, and c - length, width, and thickness of the kernel,  $d_e$  - equivalent diameter,  $V_e$  - equivalent kernel volume

RP (h)	$M_u$ (g)	a (mm)	b (mm)	c (mm)	$d_e$ (mm)	$V_e$ ( $\text{mm}^3$ )
0	0.404	12.97	9.58	4.24	8.06	275.78
4	0.388	12.48	9.23	4.42	7.98	266.96
8	0.396	12.53	9.25	4.48	8.03	272.46
12	0.425	12.85	9.49	4.43	8.08	282.96
16	0.412	12.58	9.42	4.43	8.06	274.61

Although the relationship between the drying rate and its susceptibility to rupture, in which the highest drying rate was associated with a higher temperature, contrasts with the results of Gunasekaran and Paulsen (1985), rest period adoption increased water removal conditions and, consequently, a better resistance capacity of the kernel, less susceptibility to rupture, and crack formation in the endosperm, thus giving a higher resistance of the product to the application of force to rupture. However, a higher rupture force value of the kernel presupposes a higher resistance capacity of the kernel to rupture, i.e., the product with higher rupture force has a higher resistance capacity as a result of the lower stress exerted in the water removal (BAGHERI *et al.*, 2011).

Thus, an increase in the rest period led to a higher kernel hardening, which contributed to the need for higher rupture force, thus conferring a higher resistance or hardness (Figure 6).

**Figure 6** - Variation of corn kernel hardness after drying under different rest periods. \*Significant at 5% level by the F-test



The rupture force values are similar to those obtained by Abasi and Minaei (2014), who evaluated the effect of temperature on the mechanical properties of corn, and Seifi and Alimardani (2010), who studied the moisture content in two corn varieties.

Abasi and Minaei (2014) found that the increase in drying air temperature reduced the rupture force values with an increase in drying air temperature in the mechanical properties. According to the authors, this reduction may be associated with changes in the structure, chemical composition, and spatial disposition of biopolymers during the drying process with hot air due to the presence of a moisture gradient because of the reduction in kernel water, resulting in breaks, cracks, and discontinuity in the structure. This effect is similar to the phenomenon that occurred

with the reduction in rest period, in which water had a high difficulty to migrate from the center to the periphery because water diffusion is hampered with a reduction in moisture content, as it strongly adheres to the dry matter.

The increase in kernel rupture force with an increase in rest period in its intermittent drying may be associated with the internal stress suffered by the kernel during continuous drying or with shorter rest periods due to the lower reduction in the drying rate (Figure 4), as water is strongly bonded as the moisture content is reduced, hampering its diffusion from the center to the periphery of the kernel (ABASI; MINAEI, 2014).

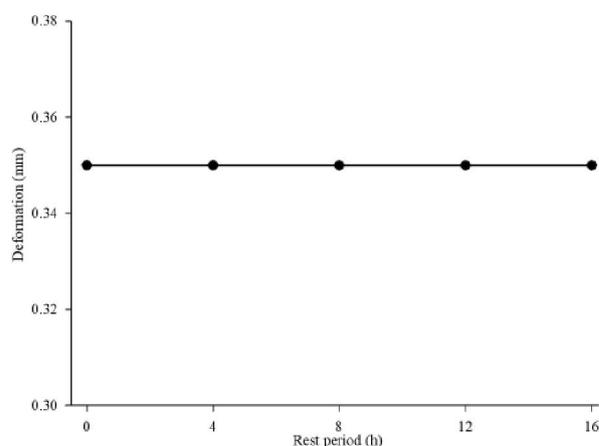
The highest hardness of the corn kernel (Figure 6) with an increase in its rest period presupposes high availability of time for water diffusion from the center to the periphery, contrary to what happens with the continuous drying. In this case, the pressure exerted by temperature to remove water provides a high risk of cracking, cell disruption, and kernel rupture.

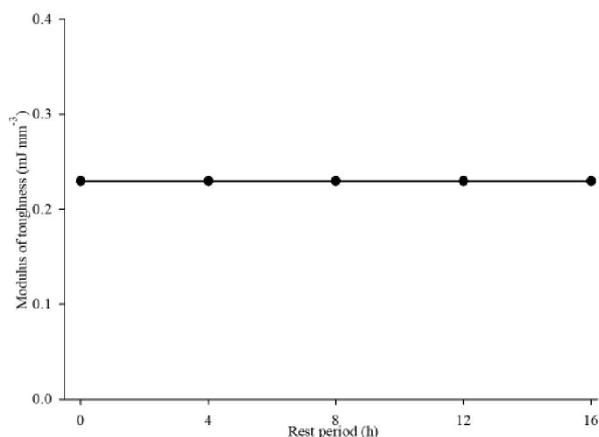
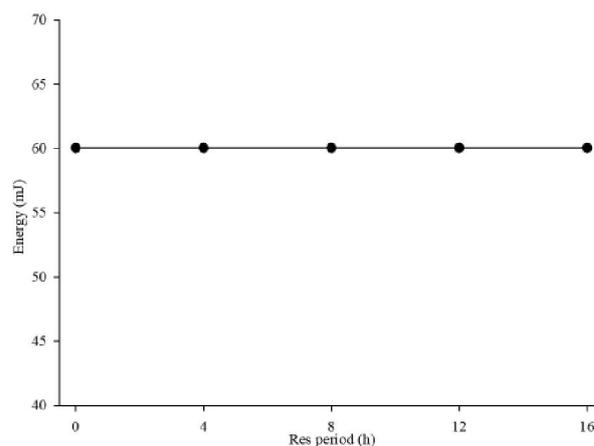
Couto *et al.* (2002), stated that the material hardness is associated with the slope of the line in the force-deformation graph. Therefore, the higher the hardness, the higher the intensity of the force for the same deformation.

Deformation, energy, and modulus of toughness did not affect the adoption of intermittent drying with different rest period (Figures 7, 8, and 9). The average values observed for deformation, energy, and modulus of toughness were 0.250 mm, 60.044 mJ, and 0.230 mJ mm<sup>-3</sup>, respectively.

The analyzed variables were positively correlated, except for hardness and deformation, in which the increase in one variable led to a reduction in the values of the other, but with no significant correlation (Table 2). Similarly,

**Figure 7** - Deformation of corn kernels at the rupture point after drying as a function of rest period



**Figure 8** - Modulus of toughness of corn kernels after drying as a function of rest period**Figure 9** - Energy required for rupture the corn kernel after drying under different rest periods**Table 2** - Pearson's correlation analysis between the variables rupture force, deformation, hardness, modulus of toughness, consumed energy, and equivalent volume of corn kernels. \*\* – significant Pearson's correlation at the 1% level by the t-test; \* – significant Pearson's correlation at the 5% level by the t-test; and ns – not significant Pearson's correlation by the t-test

	Deformation	Hardness	Toughness	Energy	Volume
Rupture force	0.485*	0.740**	0.686**	0.884**	0.150 <sup>ns</sup>
Deformation		-0.212 <sup>ns</sup>	0.624**	0.779**	0.212 <sup>ns</sup>
Hardness			0.278 <sup>ns</sup>	0.397**	0.058 <sup>ns</sup>
Toughness				0.780**	-0.234 <sup>ns</sup>
Energy					0.112 <sup>ns</sup>

the kernel volume showed no correlation with the other variables, possibly because the unit volume values were relatively similar, reinforcing the idea that the physical characteristics in an evaluation on mechanical properties must be similar (ABASI; MINAEI, 2014).

Although the energy showed no clear trend behavior as a function of rest period (Table 2), a strong and positive correlation was observed with the rupture force and deformation. Hardness was not very prevalent, but a higher level of hardness conferred higher energy expenditure due to the need to apply higher force for the rupture to happen.

In general, kernels subjected to a longer rest period showed higher hardness, thus being able to resist better the post-harvest processes of handling, separation, or classification and a higher drying rate. Thus, the storage unit that employs rest periods of 8, 12, or 16 hours will have a reduction in the effective drying time, resulting in energy savings and high efficiency. Thus, rest period will lead to a lower trend of loss of product quality due to the occurrence of a lower percentage of broken kernels.

## CONCLUSIONS

1. The increased rest period influenced positively and linearly the rupture force and hardness of kernels;
2. The adopted drying methods did not influence the energy, modulus of toughness, and deformation of kernels at the rupture point;
3. The drying rate during drying was positively influenced by an increase in the rest period of kernels during drying, with similar values at 8, 12, and 16 hours.

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