DOI: 10.5433/1679-0359.2017v38n1p185

Mechanical properties of baru fruit (*Dipteryx alata* Vogel)

Propriedades mecânicas dos frutos de baru (*Dipteryx alata* Vogel)

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Abstract

This paper aimed to verify the influence of moisture content and drying temperature on the values of maximum compression strength for fixed strains (1; 2; 3; 4; 5; 6; and 7 mm), rupture force, and proportional deformity modulus on the baru fruit (*Dipteryx alata* Vogel) under compression in a natural resting position. Baru fruits with a moisture content ranging from 0.333 to 0.053 (decimal dry basis – db) were used. The fruits were uniaxially compressed between two parallel plates, in the natural resting position, and the nuts were dried at temperatures of 60, 80, and 100 °C. The reduction in the moisture content during drying was monitored using a gravimetric method (weight loss) to determine the initial moisture content of the product and the final moisture content. Based on our results, the compression force needed to deform the baru fruit decreased with increasing moisture content, regardless of the drying temperature. The proportional deformity modulus increased with the reduction of moisture content for all the studied temperatures. The reduced moisture content increased the force required to rupture the baru fruit, regardless of the drying temperature. The rupture forces of temperatures of 60 to 100 °C may be represented by one model.

Key words: Rupture force. Proportional deformity modulus. Moisture content.

Resumo

Neste trabalho objetivou-se verificar a influência do teor de água e da temperatura de secagem nos valores da força máxima de compressão para deformações fixas (1, 2, 3, 4, 5, 6 e 7 mm), força de ruptura e no módulo proporcional de deformidade nos frutos de baru (*Dipteryx alata* Vogel), submetidos à compressão na posição natural de repouso. Foram utilizados frutos de baru com teores de água variando de 0,333 a 0,053 (decimal b.s.), secos nas temperaturas de 60, 80 e 100 °C. A redução do teor de água ao longo da secagem foi acompanhada pelo método gravimétrico (perda de massa), conhecendo-se o teor de água inicial do produto, até atingir o teor de água final. Concluiu-se que a força de compressão necessária para deformar os frutos de baru diminui com o aumento do teor de água, independentemente da temperatura de secagem. O módulo proporcional de deformidade aumenta com a redução do teor de água para todas as temperaturas estudadas. A redução do teor de água eleva a força necessária à ruptura dos frutos de baru, independentemente da temperatura de secagem. As forças de ruptura para as temperaturas de 60 e 100 °C podem ser representadas por um único modelo.

Palavras-chave: Força de ruptura. Módulo proporcional de deformidade. Teor de água.

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Received: Apr. 06, 2016 – Approved: Aug. 09, 2016

Introduction

Dipteryx alata Vogel is a fruit of the Cerrado and has had a good acceptance in the market due to its significant economic value and pleasant flavour mainly chestnut; (SANO et al., 2004). *Dipteryx alata* Vogel, also popularly known as cumbaru, cumaru, baru, barujo, feijão coco or emburena-brava, is a tree that occurs in the states of Goiás, Minas Gerais, Mato Grosso, Mato Grosso do Sul and São Paulo (LORENZI, 2008).

The fruits of baru are a drupe type and have a light brown colour with a single edible seed that has an elliptical shape and is dark brown; the seed is commonly called an almond. This seed has regional importance and has attracted scientific interest because of its nutritional composition. Almonds from baru have higher levels of monounsaturated fatty acids (51.1%) and lower levels of saturated fatty acids (BENTO et al., 2014). Almond from baru contain approximately 40% fat and 30% protein and have a high mineral content, especially iron, calcium, magnesium, potassium and zinc (SILVÉRIO et al., 2013).

Knowledge on the mechanical properties of native fruits of the Cerrado as a function of moisture content and drying temperature is essential for developing machine designs to assist in the processing of these fruits, particularly for adapting the equipment that is currently used to process other products.

In this regard, numerous studies have been developed to identify the mechanical properties of various agricultural products with different moisture contents, such as coffee fruit (COUTO et al., 2002; BATISTA et al., 2003), hazelnut (GÜNER et al., 2003), soybean (RIBEIRO et al., 2007), pistachios (GALEDAR et al., 2009), rice (RESENDE et al., 2013) and wheat (FERNANDES et al., 2014). However, information about the mechanical properties of baru fruits is not found in the literature.

Resende et al. (2007) note that information on the mechanical characteristics of agricultural products is essential for the development of new equipment to achieve a maximum efficiency without compromising the final quality. During the steps of processing and storage, agricultural products suffer from impacts, which may cause damage and, consequently, increase their susceptibility to decay (BARGALE et al., 1995).

Various factors, such as the drying conditions, moisture content, type of force applied and region in which the force is applied, directly affect the mechanical properties (MOHSENIN, 1986). Ribeiro et al. (2007) indicate that by using the "force-deflection" curve obtained from the compression test, parameters can be obtained that characterize the response of a material when it is subjected to a load. Among the various mechanical properties, the modulus of deformability allows relative strength comparisons between different materials (RESENDE et al., 2007).

Studying the mechanical properties of the baru fruit is important for assessing the strength required to break the pericarp of the fruit and obtain the almond extract and for checking the resistance of the fruit to the impacts that may occur during their processing. Generally, after the fruits are collected, the kernel is removed and processed. However, the fruits are collected with the highest moisture content and must be dried such that its quality is maintained.

The lack of information on the mechanical properties of baru fruits and the need to develop equipment that can be used more efficiently for processing led to the present work. The influences of moisture content and drying temperature on the full-strength compression for fixed deformations (1, 2, 3, 4, 5, 6 and 7 mm), tensile strength and proportional deformity modulus in baru fruits (*Dipteryx alata* Vogel), under compression in a natural resting position, are examined.

Materials and Methods

The experiment was conducted at the Laboratory of Postharvest Products Plant of the Federal

Institute of Education, Science and Technology Goiano – *Campus* Rio Verde and drying Laboratory and Storage Products Plant of the State University of Goiás (UEG) in Anapolis-GO. Baru fruit were used (*Dipteryx alata* Vogel) that had been collected manually in the municipality of Santa Helena de Goiás, Goiás, 17 °48' S 50º35' W, at altitude of 568 m, with an initial moisture content of 0.333 dry basis (dry basis, db). The geometrical dimensions of used baru fruits were 0.0528±0.0041; 0.0396±0.0033 and 0.0292±0.0026 m length, width and thickness, respectively.

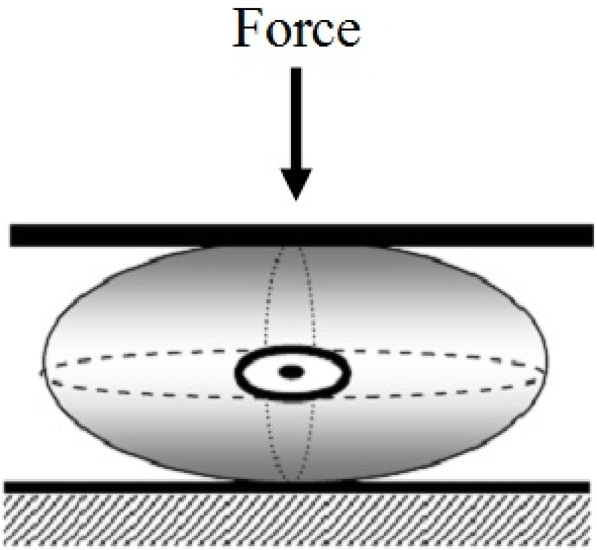
To conduct the experiment, the moisture content was obtained by drying the fruit in an oven with a forced ventilation air flow rate of 0.3313 m^3 s^{-1} and maintaining the fruit at temperatures of 60, 80 and 100 °C, which promoted an average relative humidity of 25.1; 12.2 and 5.3%, respectively. The whole fruits were dried in perforated trays that contained approximately 1 kg of product per temperature. The reduction of the moisture content during drying was monitored by gravimetric analysis (weight loss) to determine the initial moisture content of the product until it reached the final moisture content of 0.053 (db), using a semi-analytical scale with a resolution of 0.01 g.

The fruit moisture content was determined using the oven method at a temperature 105 ± 3 °C for 24 hours with three replicates (BRASIL, 2009). For each obtained moisture content, the samples were homogenized and submitted to compression tests.

The experimental compression tests were conducted, in which 15 fruits per temperature were tested individually using a universal testing machine test EMIC GR049 model with a 1000 kN load cell.

The fruits were subjected to uniaxial compression between two parallel plates. The compression was applied with the fruits in their natural resting position, as shown in Figure 1, with fifteen repetitions.

Figure 1. Guidance of baru fruit (*Dipteryx alata* Vogel) during the compression test in the natural resting position.



After obtaining the power curves for the fruit deformation, the strength and elongation at break were extract to provide the "bioyield point". This point is defined as the position on the curve where there is an increase in product deformation associated with a decrease in the compressive force (ASAE, 1974), which indicates the point where the product's structure begins to break and become disorganized.

The proportional deformity modulus of fruit (Ep) was determined, according to Equation 1, for deformations of $1x10^{-3}$, $2x10^{-3}$, $3x10^{-3}$, $4x10^{-3}$, $5x10^{-3}$, $6x10^{-3}$ and $7x10^{-3}$ m, and was adapted from the deformations used by Batista et al. (2003).

$$Ep = \frac{E}{\left(1\text{-}\mu^2\right)} = \frac{0{,}531 \times F}{D^{3/2}} \cdot \left[2 \cdot \left(\frac{1}{r} + \frac{1}{R}\right)^{1/3}\right]^{3/2} \qquad (1)$$

where

Ep: proportional deformity modulus, N m^{-2};

E: modulus of deformability, N m^{-2};

D: Total deformation (elastic and plastic) body at the contact points with the top and bottom plates, m;

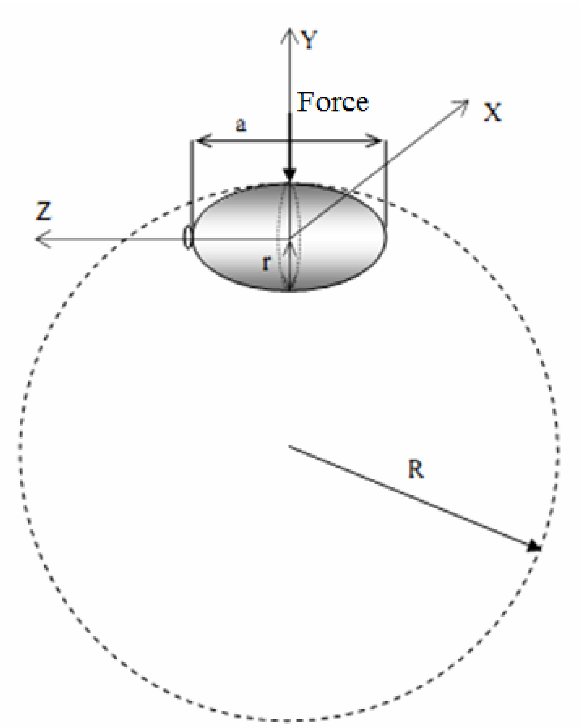
F: Strength, N;

μ: Poisson's ratio; and

R and r: radius of curvature at the contact point, m.

The values of the radii of curvature (r and R) of the fruit at the contact points were obtained by adjusting the curvature of the circumference of the object coordinate planes according to the relevant compression position (COUTO et al., 2002), as illustrated in Figure 2.

Figure 2. Radius of curvature of the fruits in the contact region between the fruit and the compression plate.



Source: Couto et al. (2002).

The experiment was conducted according to a factorial 3x5x7 (3 drying temperatures, 5 moisture content levels and 7 strains) in a completely randomized design with fifteen repetitions. The data were analysed with an analysis of variance and regression.

Results and Discussion

Table 1 shows the mean values and standard deviation of the radii of curvature of baru fruits for each temperature and moisture content used to determine the proportional deformity modulus. The radii of curvature varied as a function of moisture content; in contrast, for the drying temperature, there was no clear trend in relation to these variables. This result can be explained by the fact that the baru fruits do not present a homogeneous shape. Fernandes et al. (2014) studied the influence of moisture content on mechanical properties of wheat grain and observed similar behaviour.

Table 1. Mean and standard deviation values for the radii of curvature of baru fruit (*Dipteryx alata* Vogel) (x10^{-3} m) for each position and moisture content.

Moisture content (db)	Temperature					
	100 °C		80 °C		60 °C	
	R	r	R	r	R	r
0.333	41.23±2.07	24.54±2.91	43.23±1.31	23.86±1.86	43.47±1.80	25.42±2.54
0.250	42.42±2.27	25.68±2.32	46.04±2.81	26.70±2.07	42.53±2.46	24.96±2.14
0.177	42.68±1.35	24.81±2.42	41.63±1.88	25.54±2.74	43.26±1.80	24.63±2.82
0.111	45.62±3.32	25.458±3.03	41.60±1.97	24.56±2.45	43.36±1.99	26.05±2.47
0.053	42.15±2.05	26.63±2.70	43.15±2.30	24.15±2.71	43.24±1.85	24.40±2.52

Figure 3 shows the average values of the maximum compressive force in the three drying temperatures, depending on the moisture content, for various deformations. The compressive force required to deform the baru fruits decreased with increasing moisture content for all temperatures. Similar results were observed by Resende et al. (2007) and Ribeiro et al. (2007) for bean and soybean, respectively.

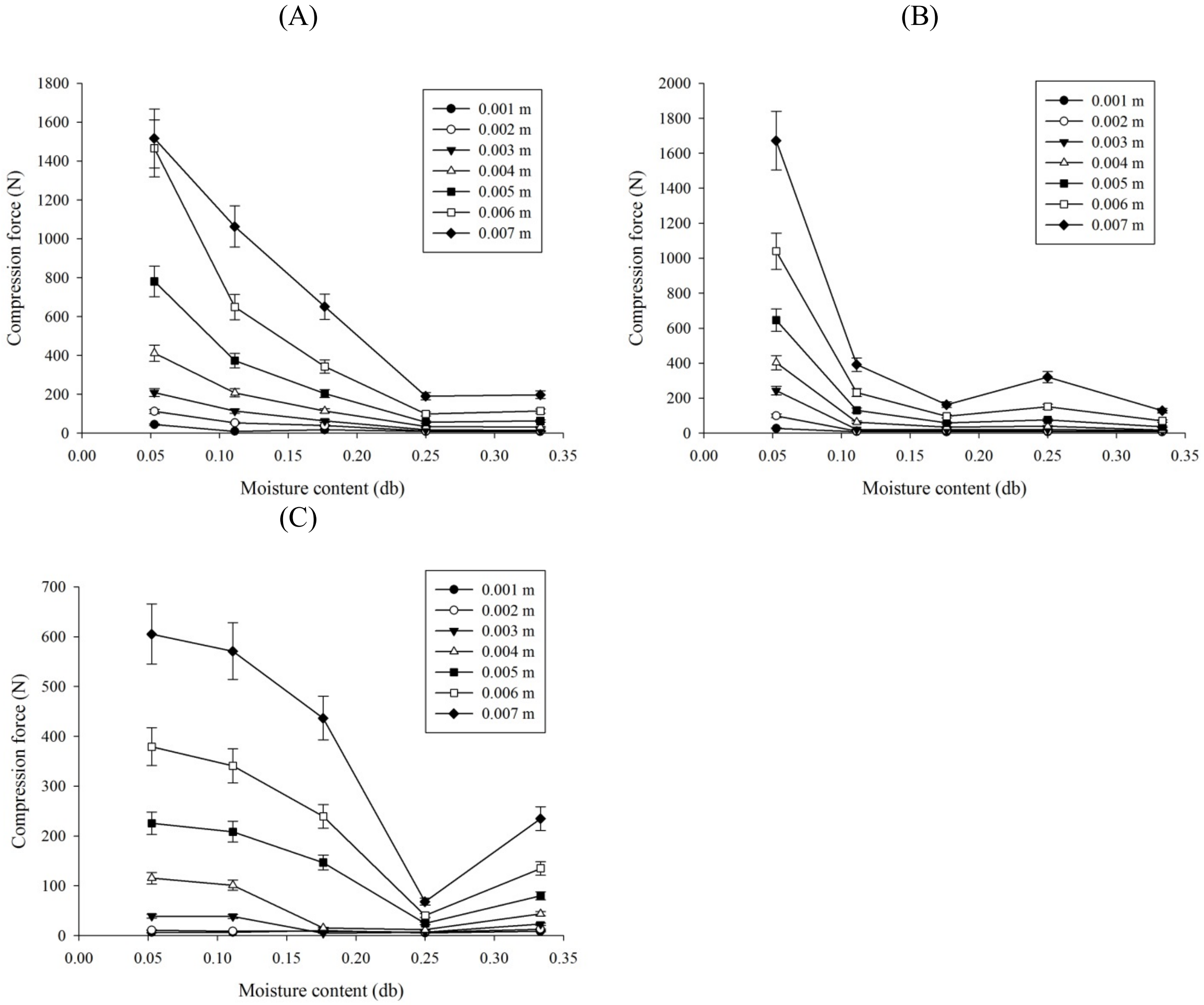
The average compressive force required for the different deformations due to the moisture content ranged from 8.09 to 1516.37 N, from 7.19 to 1672.25 N and from 5.06 to 605.33 C for 60, 80 and 100 °C, respectively (Figures 3A, B and C). Reducing the moisture content increased the force required to deform the fruit. This behaviour was observed for all of the studied temperatures. Increasing the compressive strength by reducing the moisture content may thus affect the integrity of the matrix by reducing the moisture content (GUPTA; DAS, 2000) and other characteristics that can influence the increase of the compressive strength and shrinkage of the fruit.

Vursavuş and **Özgüven** (2004) and Ribeiro et al. (2007) studied the mechanical properties of apricot fruit and soybean, respectively, and observed similar behaviour. When Resende et al. (2013) studied the mechanical properties of the rice grains with and without bark, they found different behaviours, in which the compression force values ranged somewhat randomly, regardless of the type of processing.

Using the compressive strength data, it was possible to determine the proportional deformity modulus, as shown in Figure 4, which showed the same behaviour as the compression force and was a function of moisture content and deformation.

Table 2 shows the regression equations fitted to the experimental values of the proportional deformity modulus of baru fruit, which depended on the moisture content and deformation for each drying temperature. By analysing the results, it was observed that the adjusted equations seem to be satisfactory, with high values of the coefficient of determination (R^2).

Figure 3. Mean maximum compression force values for drying temperatures of 60 (A), 80 (B) and 100 (C) °C versus moisture content for deformations of $1x10^{-3}$, $2x10^{-3}$, $3x10^{-3}$, $4x10^{-3}$, $5x10^{-3}$, $6x10^{-3}$ and $7x10^{-3}$ m.


(A)

(B)

(C)

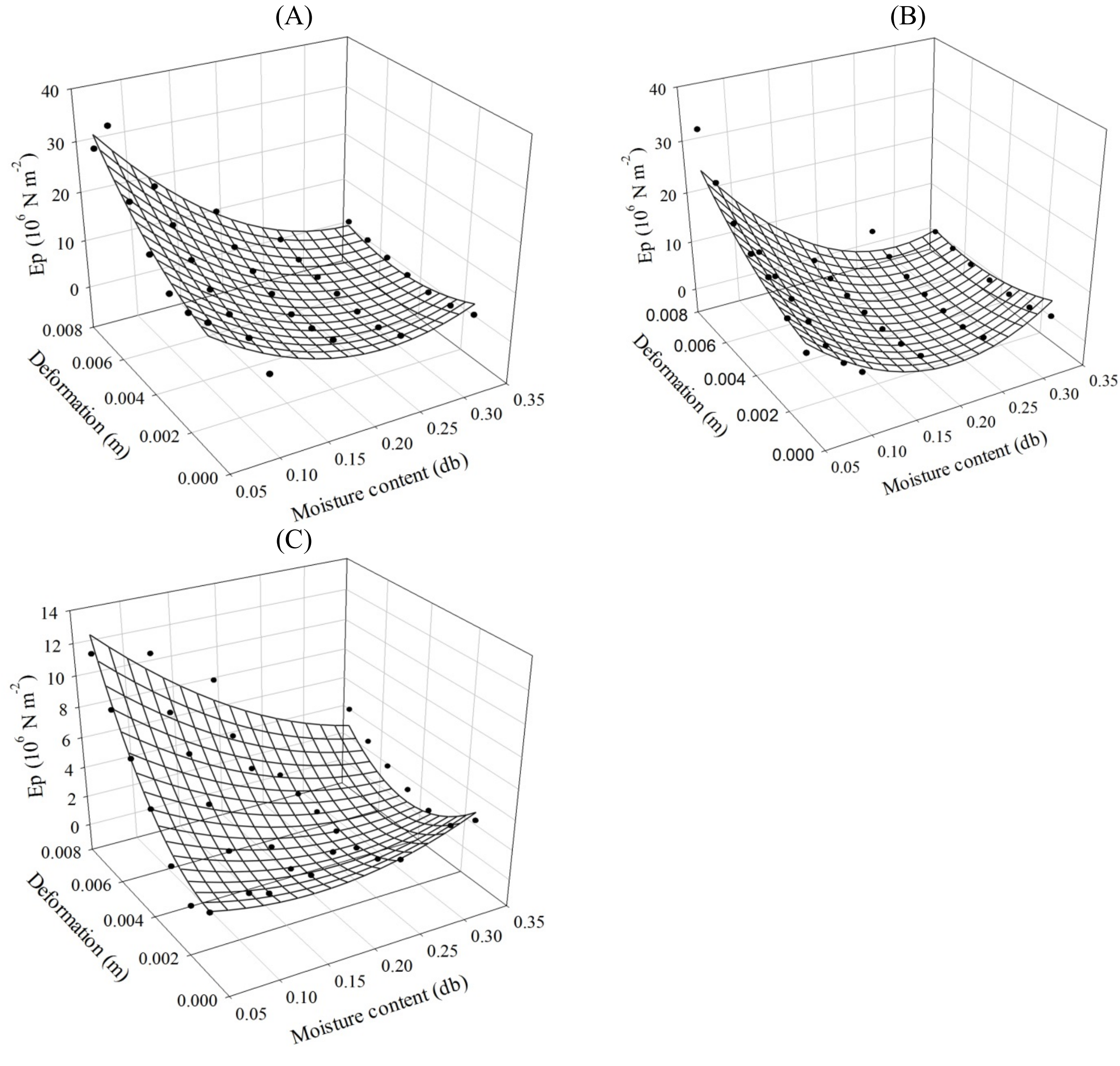
Table 2. Equations fitted to experimental values of the proportional deformity modulus of baru fruit (*Dipteryx alata* Vogel; Ep) as a function of the moisture content (X) and the deformation (D) for each drying temperature.

Temperature (°C)	Model	R^2 (%)
60	$Ep = 20.9643 – 167.1678 X + 1255.9089 D + 384.8782 X^2 + 338189.5976 D^2 – 12959.6428 X D$	93.47^*
80	$Ep = 20.5188 – 200.2462 X + 922.2225 D + 490.4072 X^2 + 263175.0655 D^2 – 10540.6016 X D$	82.13^*
100	$Ep = 3.1422 – 17.3821.X – 29.4599 D + 74.6832.X^2 + 274936.9633 D^2 – 6520.3826 X D$	84.90^*

[*] Significant to 5% by F test.

Figure 4 illustrates the response surfaces adjusted in accordance with the equations obtained; Table 2 shows the proportional deformity modulus of baru fruit, which depended on the moisture content and deformation for each drying temperature. Note that regardless of the drying temperature, the values of the proportional deformity modulus increased with the decrease in moisture content.

Figure 4. Mean proportional deformity modulus (Ep) of baru fruit (*Dipteryx alata* Vogel) as a function of moisture content and deformation for drying temperatures of 60 (A), 80 (B) and 100 (C) °C.



Resende et al. (2007) and Ribeiro et al. (2007) evaluated the proportional deformity modulus of bean and soybean, respectively, and found that the proportional deformity modulus increases with reduced moisture content and deformation. Batista et al. (2003) noted that a higher deformity modulus value with a lower moisture content indicates the need to apply a greater force for a certain deformation.

For the moisture contents studied, the values of the proportional deformity modulus ranged from 0.96 x 10^6 to 31.14 x 10^6, from 0.84 x 10^6 to 34.46 x 10^6 and from 0.5 x 10^6 to 12.15 x 10^6 N m^{-2} for 60, 80 and 100 °C, respectively. Batista et al. (2003) studied the proportional deformity modulus of coffee fruits (*Coffea arabica* L.) in three stages of maturation and three temperatures (40, 50 and 60 °C) for the moisture content range from 1.50 to 0.14 (bs) and found that the proportional deformity modulus of the coffee fruits varied by deformity and ranged from 2.0x10^7 to 18.0x10^7 N m^{-2} for the coffee cherry fruits, from 5.0x10^7 to 40.0x10^7 N m^{-2} for the green fruits and from 1.0x10^7 to 50x10^7 N m^{-2} for verdoengos fruit. Resende et al. (2013) found that the proportional deformity modulus of rice grains and dehulled rice, for the moisture content range from 0.30 to 0.12 (db), ranged from 5.5x10^9 to 7.4x10^9 N m^{-2} for the shelled rice grains and from 9.5x10^9 to 12.3x10^9 N m^{-2} to the rice grains in the husk.

Figure 4 shows that the proportional deformity modulus decreases with the decreasing deformation of the product. Different results were observed by Resende et al. (2007) and Fernandes et al. (2014) for beans and wheat, respectively.

Table 3 shows the parameters from the linear models that can be used to determine the rupture force as a function of moisture content for baru fruit for all of the studied drying conditions.

Table 3. Linear model parameters adjusted to the tensile strength of baru fruit (*Dipteryx alata* Vogel) under different drying conditions

Parameters	Temperature (°C)		
	60	80	100
A	9006.8778**	8028.1154**	9455.8561**
B	10186.6531*	10911.6666**	10192.6240**
R^2 (%)	91.79	97.39	94.72

**Significant at 1% by t test. * Significant at 5% by t test.

The linear equation adequately represents the experimental data and can be used to estimate the rupture force for the baru fruits; it presents high coefficients of determination (R^2). Resende et al. (2013) studied the rupture force of the rice grains both with and without shells during the drying process and found that the linear equation can be used to represent the rupture force. Bargale et al. (1995) found that the rupture force decreases linearly with the increased moisture content of both wheat grains and canola.

Thus, it proceeded to model identity test aiming to enable the use of a single linear model to represent the rupture force of the baru fruit, regardless of the drying temperature, according to the methodology described by Regazzi (2003).

The parameters of the linear model for rupture force at 60 (a_1 and b_1), 80 (a_2 and b_2) and 100 °C (a_3 and b_3) were compared to verify their equality. The following hypotheses were formulated:

$H_o^{(1)}$: $a_1 = a_2 = a_3 = a$ *versus* $H_a^{(1)}$: not all a_i are equal

$H_o^{(2)}$: $b_1 = b_2 = b_3 = b$ *versus* $H_a^{(2)}$: not all b_i are equal

$H_o^{(3)}$: $a_1 = a_2 = a_3 = a$ e $b_1 = b$ *versus* $H_a^{(3)}$: there is at least one inequality

The decision rule was based on the *chi*-square test (χ^2) according to the following expression:

$$\chi^2_{calculated} = -N \ln\left(\frac{SQR_\Omega}{SQR_{w_i}}\right) \tag{2}$$

where

N: number of observations;

SQR_Ω: sum of residual squares of the complete model; and

SQR_{Wi}: sum of residual squares restricted parameter space.

The tabulated value (χ^2) is a function of the level of significance α (p = 5%) and the number of degrees of freedom:

$$v = p_{\Omega} - p_{w_i} \quad (3)$$

where
v: degrees of freedom of the model;

p_{Ω}: number of complete model parameters; and

p_{wi}: number of model parameters with constraint.

Initially, the three air conditions at 60, 80 and 100 °C were tested. Then, the air conditions were compared in pairs. Table 4 presents the results of hypothesis analysed by a chi-square test.

The $\chi^2_{\text{calculated}}$ value for the tensile strength of the baru fruit at 60 and 100 °C was lower than the $\chi^2_{\text{tabulated}}$ value. Thus, the proposed hypothesis (H_o) was accepted, which suggested that the linear models used to determine the rupture force at 60 and 100 °C are not significantly different from each other. Thus, a single model may be used for both of these temperatures.

For the other combinations, the $\chi^2_{\text{calculated}}$ value was greater than the $\chi^2_{\text{tabulated}}$ values. Thus, we rejected the hypothesis formulated and noted that the tensile strength of the baru fruit differs for each temperature considered.

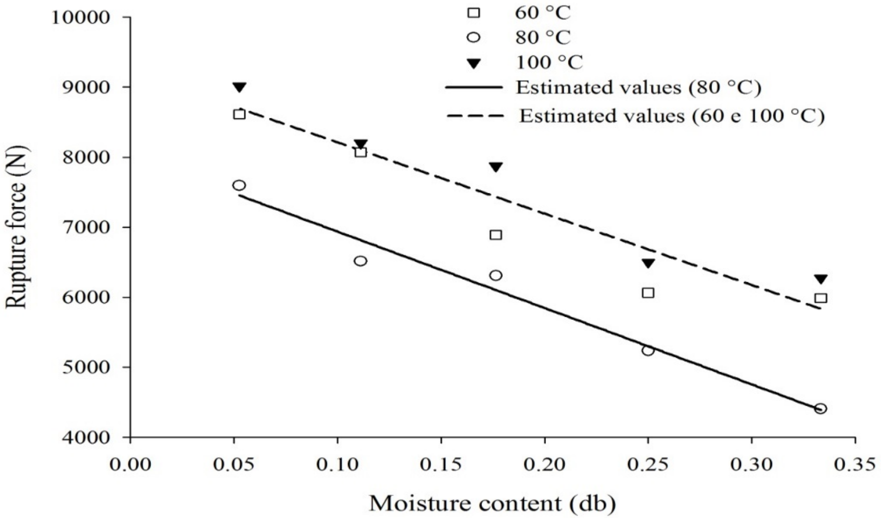
The average rupture force of baru fruits based on the moisture content and drying temperature are shown in Figure 5.

The reduction of moisture content for all temperatures resulted in a linear increase in the force required to achieve the "bioyield point"; this increase was from 5988.63 to 8609.82 N, from 4406.50 to 7594.96 N and 6274.28 to 9014.51 N at 60, 80 and 100 °C, respectively. The results confirm those obtained by researchers who worked with different agricultural products (GÜNER et al., 2003; VURSAVUŞ; ÖZGÜVEN, 2004, 2005; SAIEDIRAD et al., 2008; SHARMA et al., 2009; RESENDE et al., 2013). This behaviour may be related to the cell density, which changes upon the exit of water during the drying of baru fruit, that is, the cells of the fruit to approach; therefore, the resulting product will have a greater resistance to compression with a lower moisture content. Goneli (2008) indicated that reducing the moisture content promotes a change in cell integrity, which tends to become more organized and, thus, more resistant to compression.

Table 4. Test of hypothesis (H_o) using the chi-square test to determine the tensile strength of baru fruit (*Dipteryx alata* Vogel).

Hypotheses	GL	$\chi^2_{\text{tabulated}}$	$\chi^2_{\text{calculated}}$
60 e 80 °C	2	5.991	18.010
60 e 100 °C	2	5.991	5.157
80 e 100 °C	2	5.991	26.933
60. 80 e 100 °C	4	9.488	31.545

Figure 5. Mean values of tensile strength as a function of moisture content for baru fruit (*Dipteryx alata* Vogel) for all drying temperatures.



In addition, Figure 5 shows that the drying temperature influence the rupture force; however, there was no clear trend when comparing the drying temperatures: the lowest moisture content values were observed at 80 °C, and the highest were obtained at 100 °C. Liu et al. (1990) studied the mechanical properties of soybeans and found that the drying air temperature and moisture content influenced the mechanical performance of the product and that with a reduction of the drying air temperature, there was an increase in the force required to rupture the fruit; however, increasing the moisture content of the product reduced this force.

Table 5 presents the equations used to estimate the values of the rupture force (Rf) of the baru fruit to temperatures of 60-100 and 80 °C, due to the reduction of moisture content. All of the parameters were significant at the 1% level by a t-test and showed high coefficients of determination (R^2).

The results obtained for proportional deformity modulus and rupture strength show that baru fruit with lower moisture contents exhibit greater resistance to breakage during the stages of processing.

Table 5. Equations fitted to the experimental values of fruit baru rupture force (*Dipteryx alata* Vogel) (Br) as a function of moisture content (X) for each drying temperature

Temperature (°C)	Model	R^2 (%)
60 e 100	$Rf = 9231.3621^{**} - 10189.6179^{**} X$	89.15
80	$Rf = 8028.1154^{**} - 10911.6666^{**} X$	97.39

**Significant to 1% by F test.

Conclusions

The obtained results show that the compressive force required to deform the fruit, i.e., the proportional deformity modulus and tensile strength, decrease with increasing moisture content, regardless of the drying temperature; thus, there was greater resistance to impacts. The rupture force for drying temperatures of 60 to 100 °C may be represented by one model.

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