Revista Engenharia na Agricultura

MECHANICAL PROPERTIES OF COWPEA BEANS AT DIFFERENT MOISTURE CONTENTS

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Keywords:	ABSTRACT

ABSTRACT

Cowpea production has gained considerable ground in Brazil. Cowpea grain undergo different types of pressure and may crack and break during processing and storage, thus, there is a need to classify the mechanical properties of the beans. Therefore, this study aimed to evaluate the influence of the moisture content of cowpea beans on the maximum compressive force for fixed deformation and determine the proportional modulus of deformity under compression. The cowpea cultivars Novaera and Tumucumaque were evaluated at different moisture contents (0.12; 0.15; 0.18; 0.20; and 0.23 decimal d.b.). The experiment was arranged in completely randomized design for each moisture content and 10 deformation rates were applied (0.02; 0.04; 0.06; 0.08; 0.10; 0.12; 0.14; 0.16; 0.18; and 0.20 mm). The compression force was assessed using a universal testing machine and the proportional deformation modulus was determined. Following, hardness and elasticity of cowpea beans as a function of the moisture content were established. The compressive force required to deform cowpea beans decreases with increasing moisture content: between 2 and 105 N (Tumucumaque) and between 2 to 97 N (Novaera). The proportional deformation modulus of cowpea increased as the moisture content and deformation reduced, ranging from 4.9×10^7 to 31.9×10^7 Pa (Tumucumaque) and from 5.9×10^7 to 42×10^7 Pa (Novaera).

Palavras-chave:	PROPRIEDADES MECÂNICAS DE GRÃOS DE FEIJÃO-CAUPI EM DIFERENTES TEORES DE ÁGUA

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RESUMO

O feijão-caupi tem tomado bastante espaço na produção de grãos do Brasil, para tanto surge-se assim a necessidade de classifica-lo quanto a suas propriedades mecânicas, pois durante todo o processamento e armazenamento do grão, pode sofrer diferentes tipos de pressão que causam trincas e quebras no grão, portanto objetivou-se com este trabalho, determinar a influência do teor de água nos valores da força máxima de compressão para deformações fixas e determinar o módulo proporcional de deformidade de grãos de cultivares de feijão-caupi submetidos à compressão. Foram utilizados grãos de duas cultivares de feijão, a Novaera e Tumucumaque, nos teores de água de (0,12; 0,15; 0,18; 0,20 e 0,23 decimal b.s.), o trabalho foi conduzido em delineamento inteiramente casualizado, onde para cada teor de água, aplicou-se 10 deformações (0,02; 0,04; 0,06; 0,08; 0,10; 0,12; 0,14; 0,16; 0,18 e 0,20 mm). Logo após analisou-se a resistência à compressão com o auxílio de uma máquina de ensaio universal de teste modelo, em seguida, determinou-se o módulo proporcional de deformidade, com os valores de deformação avaliados, estabeleceu-se os valores de dureza e elasticidade dos grãos de feijão-caupi em função do teor de água. A força de compressão necessária para deformar o feijão-caupi diminui com o aumento do teor de água, sendo entre 2 e 105 N para a cultivar Tumucumaque e entre 2 a 97 N para a cultivar Novaera. O módulo proporcional de deformidade aumenta com a redução do teor de água e da deformação do produto, obtendo-se valores, para a faixa de umidade estudada, entre $4,9 \times 10^7$ a $31,9 \times 10^7$ Pa para a cultivar Tumucumaque e de $5,9 \times 10^7$ a 42×10^7 Pa para a cultivar Novaera.

INTRODUCTION

Brazilian grain production in the 2017/2018 harvest was estimated at 3166.2 thousand tons (CONAB, 2018), with 786.80 thousand tons of cowpea, accounting for 25.5% of the total bean production.

The classification of cowpea beans regarding color, shape, grain size, and hilum ring is important not only to describe cultivars, but also for commercial purposes (FREIRE FILHO *et al.*, 2011). The study of the mechanical properties can assist in the design or adaptation of equipment used to process other grain types (OLIVEIRA *et al.*, 2017), without compromising the cowpea final quality.

During the harvesting, handling, transportation, and storage, grain undergo a set amount of static pressures of different magnitudes and dynamics such as high-speed impacts that cause abrasion, crushing, and cracking of beans and increase susceptibility to deterioration during storage (BARGALE-PRAVEEN *et al.*, 1995). Therefore, it is essential to understand the production process as a whole to ensure the quality of the grain. Products may present cracks and breaks if they undergo physical stresses that exceed resistance (FERNANDES *et al.*, 2014).

Ribeiro *et al.* (2007) indicated that the force-deflection curve from compression tests can produce parameters that characterize material responses to a force load. Among the different mechanical properties, the deformation modulus allows comparisons of relative resistance between different materials (RESENDE *et al.*, 2007).

In this sense, several studies have identified the mechanical properties of numerous agricultural products with different moisture contents: coffee (COUTO *et al.*, 2002; BATISTA *et al.*, 2003), hazelnut (GÜNER *et al.*, 2003), soybean (RIBEIRO *et al.*, 2007), pistachio (GALEDAR *et al.*, 2009), rice (RESENDE *et al.*, 2013), wheat (FERNANDES *et al.*, 2014), *baru* fruit (OLIVEIRA *et al.*, 2017), and radish seeds (SOUSA *et al.*, 2018). However, there is very little information on the mechanical properties of cowpea beans.

This study aimed to determine the influence of the moisture content on the maximum compression force for fixed deformations and determine the proportional modulus of deformity for cowpea cultivars under compression.

MATERIAL AND METHODS

The experiment was carried out at the Post-harvest Laboratory of Vegetable Crops of the Federal Institute of Education, Science and Technology of Goiás - *Campus* Rio Verde (*IF Goiano - Campus Rio Verde*). The cultivars Novaera and Tumucumaque of cowpea (*Vigna unguiculata* (L.) Walp.) were used in the study.

Initially, the moisture content of the beans (0.12 decimal dry basis) was determined in a forced air circulation oven, at 105 ± 3°C for 24 hours, with three repetitions (BRASIL, 2009). Starting from the initial moisture content (0.12 decimal dry basis, d.b.), the grains were moistened in a B.O.D., at 20°C and 70% relative humidity. With the high water vapor in the environment, the beans absorbed water to the hygroscopic balance. Several researchers used grain moisture to determine the physical properties of plant products (GARNAYAK *et al.*, 2008; NIKOOBIN *et al.*, 2009; DI LANARO *et al.*, 2011). Mass gain was recorded by weighing the beans on a scale (0.01 g resolution) until the desired moisture content was reached (0.15; 0.18; 0.20 and 0.23 decimal d.b.). Temperature and relative humidity were monitored using a digital psychrometer in the BOD chamber. Uniaxial compression tests were carried out with 15g samples for each moisture content to determine compression resistance. The compression tests were individually analyzed using a TA Hdi Texture Analyzer universal test machine, with a 250N load cell. Beans were compressed at their natural rest position, i.e., in the thickness direction (smallest axis) (Figure 1) at 0.001 m s^{-1}.
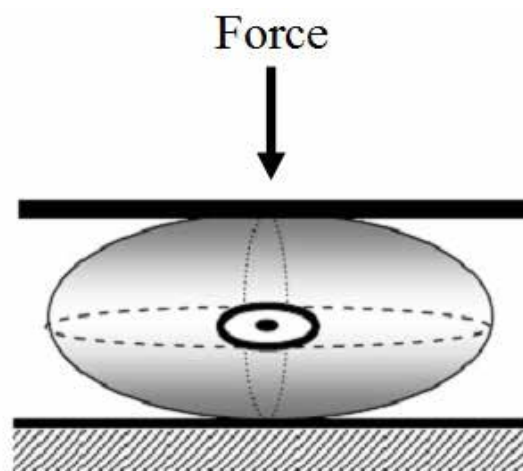
Source: Adapted from Resende *et al.* (2007)

Figure 1. Compression test of cowpea bean at the smallest thickness axis orientation

The software Sigma Plot 11.0 was used to plot the compressive force curves as a function of grain deformation for each moisture content. The following deformation values were used: 0.02; 0.04; 0.06; 0.08; 0.10; 0.12; 0.14; 0.16; 0.18, and 0.20 mm. The proportional deformity modulus was determined using Equation 1, according to Batista *et al.* (2003).

$$Ep = \frac{0.531 \times F}{D^{3/2}} \cdot \left[2 \cdot \left(\frac{1}{r} + \frac{1}{R} \right)^{1/3} \right]^{3/2} \tag{1}$$

where:
Ep = proportional modulus of deformity, N m^{-2};
F = compressive strength, N;
D = total deformation (elastic and plastic) of the bean at contact points with the upper and lower plates, m;
R, r = radius of curvature at the contact point, m.

The radius of curvature (r and R) of the beans at the contact point was obtained by adjusting the circumference to the body curvatures, according to the coordinate plane of the compression position, as shown in Figure 2.
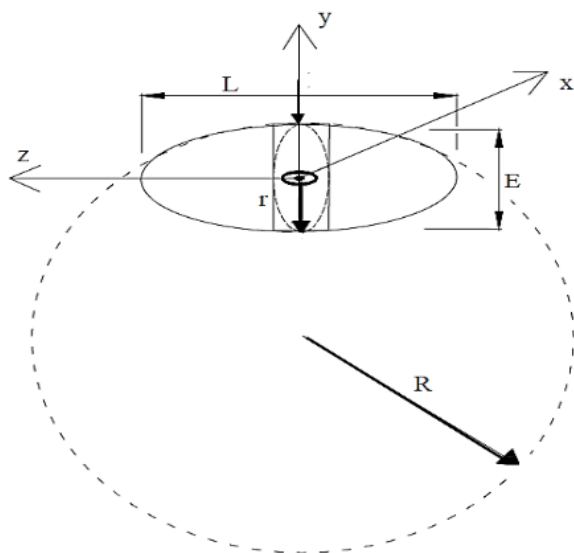
Source: Adapted from Resende *et al.* (2007)

Figure 2. Curvature radius of the cowpea bean (r and R) in the region of contact between the bean and the compression plate. L = length, E = thickness

The test was carried out in a completely randomized design with the 10 deformation values. The data were analyzed with analysis of variance and regression. The model was selected based on the significance of the regression coefficients, using the "t" test at 5% significance level, on the magnitude of the determination coefficient, mean relative error and considering the biological significance.

Hardness and elasticity of cowpea beans were determined as a function of the moisture content, using the Equation 2 suggested by Henry *et al.* (1996). This equation shows that the force required to deform biological materials can be described as a function of the deformation, according to the Taylor series,

$$F = d \cdot x + e \cdot x^2 + f \cdot x^3 \tag{2}$$

where:
x = deformation, mm;
d; e; f = model elastic coefficients, units of N mm^{-1}, N mm^{-2} and N mm^{-3}, respectively.

Figure 3 illustrates the force versus deformation curve obtained by Equation 1. This model identifies three distinct sections on the curve: the initial concave section, the intermediate section, which includes the inflection point, and the convex section in which the curve slope decreases.
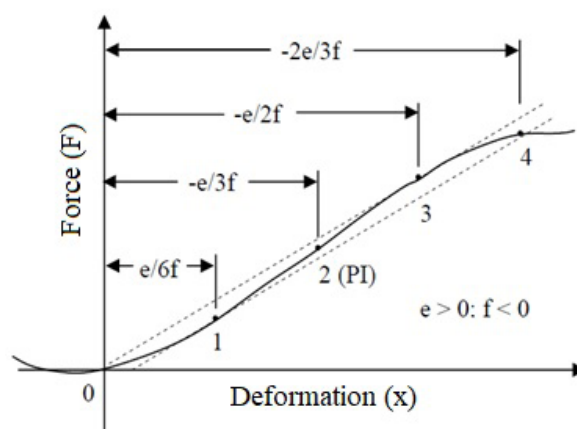

Figure 3. Force versus deformation curve of the model F = d · x + e · x²+f · x³; for e> 0; f <0; IP = inflection point (HENRY *et al.*, 1996)

The slope of the force x deformation curve for any point is the tangent (T), obtained from the first derivation of Equation 3:

$$T = d + 2e \cdot x + 3f \cdot x^2 \tag{3}$$

The maximum tangent was obtained at the inflection point of the curve, where $x = -e/3f$, which is considered an indicator of product hardness. The secant (S), which intersects the curve at origin and any point on the curve, is expressed as Equation 4:

$$S = d + e \cdot x + f \cdot x^2 \tag{4}$$

The maximum secant corresponded to the point where the deformation $x = -e/2f$, describing elasticity at different levels of deformation.

The software R Core Team (2017) was used for the statistical analysis and for model adjustments. Graphics were produced using the software SigmaPlot®11 (Systat Software Inc.).

RESULTS AND DISCUSSION

Figures 4a and 4b show that the compression force needed to deform cowpea beans decreased as the moisture content increased. The average force required for deformation as a function of the moisture content varied between 2 and 105 N for cultivar Tumucumaque and between 2 and 97 N for cultivar Novaera. Beans with higher moisture contents were less resistant to compression, but resistance increased in proportion to reduction in the moisture content.

In common bean, Resende *et al.* (2007) reported average compression force between 22.3 and 551.7 N for moisture contents between 0.13 and 0.42 bs. In soybean, Ribeiro *et al.* (2007) reported an average compression force from 21.72 to 110.86 N for moisture contents between 0.09 and 0.58 bs. In rice, Resende *et al.* (2013) found average compression force ranging from 131 to 171 N for moisture contents between 0.12 and 0.29 bs. Fernandes *et al.* (2014) found average compression force between 21.4 and 139.8 N for moisture content in the range of 0.14 to 0.26 bs for wheat grain, and Sousa *et al.* (2018) reported average compression force between 0.17 and 25.68 N for moisture contents ranging from 0.05 to 0.31 bs.

This tendency is probably due to a gradual change in the integrity of the cellular matrix with the reduction of the moisture content (GUPTA; DAS, 2000).

Table 1 shows the regression equations adjusted to the experimental values of the proportional modulus of deformity as a function of moisture content and deformation for each cultivar. The adjusted equations had high values of coefficient of determination (R^2), indicating a good fit for the model. Equations with high R^2 values were obtained by Fernandes *et al.* (2014), Oliveira *et al.* (2017) and Sousa *et al.* (2018).

Figures 5a and 5b show the response surfaces adjusted according to the equations in Table 1 for the proportional deformation modulus of cowpea beans as a function of moisture content and deformation for each cultivar. For both cultivars the values the of proportional deformation modulus increased with moisture content decrease.
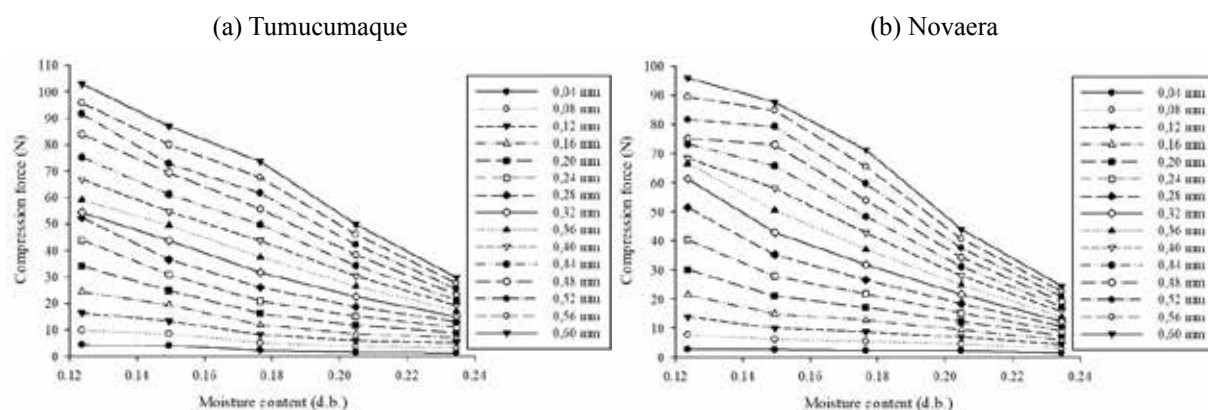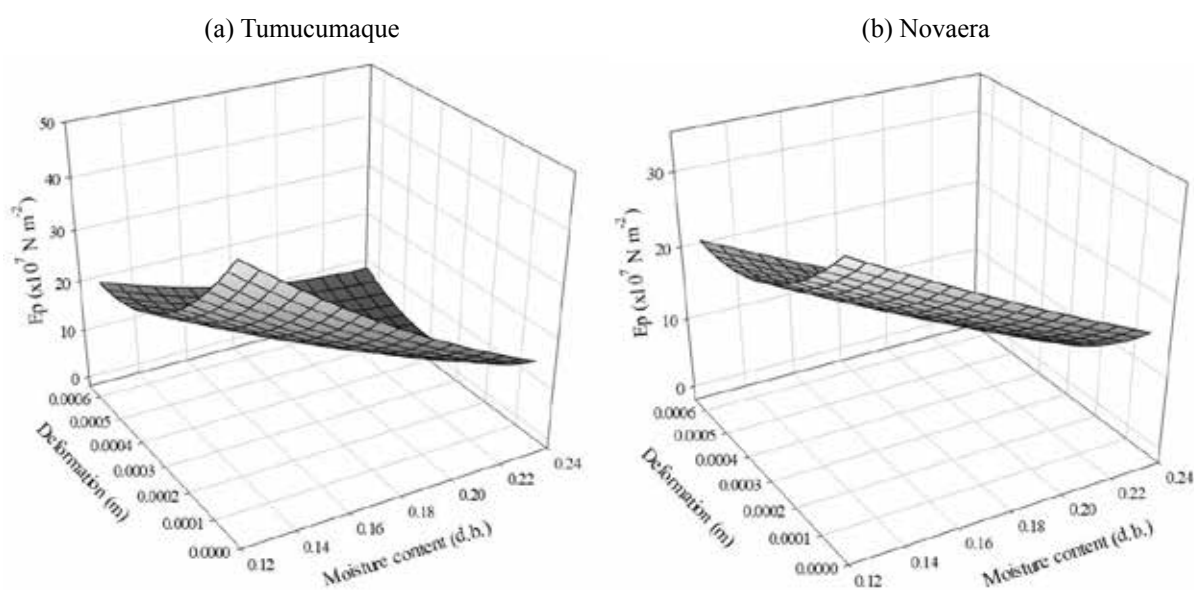
(a) Tumucumaque   (b) Novaera

Figure 4. Mean compression forces (N) as a function of the moisture content (d.b.) for the deformations 0.04; 0.06; 0.08; 0.10; 0.12; 0.14; 0.16; 0.18, and 0.20 mm of the cowpea cultivars BRS Tumucumaque (a) and BRS Novaera (b) *Vigna unguiculata* (L.) Walp.

Table 1. Equations adjusted to the proportional deformation modulus of cowpea (Ep) as a function of moisture content (X) and deformation (D), for the cultivars Novaera (5) and Tumucumaque (6)

Equation	Coefficient of determination (decimal form)	
Ep = 109.94 – 583.80 X – 143321.13 D + 796.19 X² + 89642842.87 D² + 337840.80 X D	0.8920**	(5)
Ep = 62.45 – 232.98 X – 59162.86 D + 169.87 X² + 52588137.01 D² + 30277.18 X D	0.8961**	(6)

** Significant at 1% by the F test

(a) Tumucumaque
(b) Novaera

Figure 5. Means of the proportional deformation modulus of cowpea beans BRS Tumucumaque (a) and BRS Novaera (b) (*Vigna unguiculata* (L.) Walp.) as a function of the deformations of 0.04; 0.06; 0.08; 0.10; 0.12; 0.14; 0.16; 0.18; and 0.20 mm (x 10⁻³m)

The values of the proportional deformation modulus for the moisture contents varied from 4.9 x 10⁷ to 31.9 x 10⁷ Pa for the cultivar Tumucumaque and from 5.9 x 10⁷ to 42 x 10⁷ Pa for the cultivar Novaera. For common beans, Resende *et al*. (2007) found proportional deformation modulus ranging from 4.1 x 10⁷ to 71.3 x 10⁷ Pa for moisture contents varying between 0.13 and 0.42 bs. For soybean, Ribeiro *et al*. (2007) reported deformation modulus ranging from 1.02 x 10⁷ to 5.43 x 10⁷ Pa for moisture content varying between 0.09 and 0.58 d.b.. Resende *et al*. (2013) found for husked rice, with moisture contents between 0.12 and 0.29 d.b. reported deformation modulus from 5.5 x 10⁹ to 7.4 x 10⁹ Pa. For wheat, Fernandes *et al*. (2014) found proportional deformation modulus ranging

from 8.9 x 107 to 51.2 x 107 Pa for moisture contents between 0.14 and 0.26 d.b., and for radish seeds, Sousa *et al*. (2018) reported proportional deformation modulus ranging from 0.11 x 10¹⁰ to 1.72 x 10¹⁰ Pa for moisture content from 0.05 to 0.31 d.b.

Figure 5a and Figure 5b also show that proportional deformation modulus increases with the reduction of the moisture content and with product deformation. These results are in accordance with the findings by Fernandes *et al*. (2014).

Table 2 shows the values of the elastic coefficients *d, e, f* obtained with Equation 2, and the values of the maximum tangent and maximum secant obtained with Equations 3 and 4, respectively, for the cultivars Tumucumaque and Novaera.

Table 2. Elastic coefficients *d, e, f* observed and maximum tangent and maximum secant from the deformation force curve for cowpea beans BRS Tumucumaque and BRS Novaera (*Vigna unguiculata* (L.) Walp.) for different moisture contents

Moisture content (decimal d.b.)	*d* (N mm^{-1})	*e* (N mm^{-2})	*f* (N mm^{-3})	Maximum tangent (N mm^{-1})	Maximum secant (N mm^{-1})
Tumucumaque					
0.1236	144.06	131.31	-142.86	184.291	174.233
0.1494	101.14	139.08	-114.12	157.641	143.515
0.1765	41.96	231.25	-160.53	153.002	125.241
0.2048	32.79	155.83	-120.23	100.118	83.287
0.2346	39.66	30.22	-22.79	53.018	49.678
Novaera					
0.1236	103.10	377.11	-498.19	198.249	174.461
0.1494	31.59	467.60	-454.82	191.838	151.776
0.1765	54.69	177.95	-118.85	143.497	121.294
0.2048	50.29	70.70	-54.14	81.068	73.375
0.2346	36.43	6.01	2.48	31.571	32.786

The maximum tangent and secant for the deformations were x = - 2e/3f and x = - e/6f, respectively. There was an increase in the maximum tangent and secant values with reduce in moisture content. Values of the maximum tangent were higher than the maximum secant for the same moisture content. These values are in agreement with the results of Ribeiro *et al*., (2007).

CONCLUSIONS

- The compressive force required to deform cowpea beans decreases with increase in moisture content of bean. Results between 2 and 105 N were found for the cultivar Tumucumaque and between 2 and 97 N for the cultivar Novaera.

- The proportional deformation modulus increases with the reduction of the moisture content and product deformation. The moisture contents assessed varied between 4.9 x 10^7 and 31.9 x 10^7 Pa for the cultivar Tumucumaque and between 5.9 x 10^7 and 42 x 10^7 Pa for the cultivar Novaera.

AUTHORSHIP CONTRIBUTION STATEMENT

GOMES, F.H.F.: acquisition of data, analysis and interpretation of data, drafting and revising the work; LOPES FILHO, L.C.: acquisition of data, analysis and interpretation of data, revising the work; OLIVEIRA, D.E.C.: acquisition of data, analysis and interpretation of data, drafting and revising the work; RESENDE, O.: supervision and conception of the research, analysis and interpretation of data, drafting and revising the work; SOARES, F.A.L.: was the supervisor of the first author, analysis and interpretation of data; DANTAS, L.R.: acquisition of data and drafting the work.

DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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