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CROP PRODUCTION

Moisture content on the mechanical behavior of crambe grains

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ABSTRACT: *This study aimed to verify the influence of moisture content on the values of maximum compressive strength, proportional deformity modulus, elastic coefficients d, e, and f beyond the tangent values, and maximum grain drying of crambe (Crambe abyssinica Hochst) under compression in natural resting position. Crambe grains with moisture contents ranging from 0.1547 to 0.0482 decimal db were dried at 40°C and uniaxially compressed between two parallel plates in the natural rest position. The gravimetric method was used to monitor reduction in moisture content during drying (weight loss). It was concluded that the compression force required to deform the crambe grains decreases as the moisture content increases. The proportional deformity modulus increases as the deformation decreases, yielding values between (0.09-0.27)×10^{2}MPa. Sigmoidal model described by Taylor series adequately represents the compression resistance of crambe grains in the natural rest position with moisture content lower than 0.0813db.*
Key words: *proportional deformity modulus, compressibility, mechanical properties.*

Influência do teor de água no comportamento mecânico dos grãos de crambe

RESUMO: *Neste trabalho objetivou-se verificar a influência do teor de água nos valores da força máxima de compressão, módulo proporcional de deformidade, coeficientes elásticos d, e, f, além dos valores da tangente e secante máximas nos grãos de crambe (Crambe abyssinica Hochst), submetidos à compressão na posição natural de repouso. Os grãos de crambe, utilizados com teores de água entre 0,1547 e 0,0482 (decimal b.s.), foram secos nas temperaturas de 40°C e comprimidos uniaxialmente entre duas placas paralelas, na posição natural de repouso, cuja redução do teor de água ao longo da secagem foi acompanhada pelo método gravimétrico (perda de massa). A força de compressão necessária para deformar os grãos de crambe diminui com o aumento do teor de água. O módulo proporcional de deformidade aumenta com a redução da deformação, obtendo-se valores entre 0,09 e 0,27 (x 10^{2}MPa), em que o modelo sigmoidal, descrito por meio da série de Taylor, representa adequadamente a resistência dos grãos de crambe à compressão na posição natural de repouso, para os teores de água menores que 0,0813 (b.s.)*
Palavras-chave: *módulo proporcional de deformidade, compressão, propriedades mecânicas.*

INTRODUCTION

Crambe (*Crambe abyssinica* Hochst) is a plant that belongs to the family *Brassicaceae*. With an average oil content of 36.42%, crambe can potentially be used as a raw material for industrial applications and biodiesel productions (DONADON et al., 2015). With the increasing demand for crambe every year, there is a necessity to develop handling techniques capable of enhancing productivity (VECHIATTO & FERNANDES, 2011).

The mechanical damage in crambe grains incurred during processing increases their susceptibility to deterioration during storage. Additionally, the mechanical damage shows a cumulative effect, which increases their impact, i.e., as the damage impact accumulates, the damaged grains and seeds become increasingly sensitive to further damage (PAIVA et al., 2000).

In this regard, numerous studies have been conducted to identify the mechanical properties of several agricultural products with different moisture contents. Some of these products are coffee fruit (COUTO et al., 2002; BATISTA et al., 2003), soybean (RIBEIRO et al., 2007), pistachio (GALEDAR et al., 2009), rice (RESENDE et al., 2013), and wheat (FERNANDES et al., 2014).

Hence, this study aimed to examine the influence of moisture content on the values of maximum compression force, proportional deformity

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modulus, elastic coefficients *d, e,* and *f,* in addition to the maximum tangent and secant values of crambe grains (*Crambe abyssinica* Hochst) subjected to compression in the natural resting position.

MATERIALS AND METHODS

The experiment was conducted in the Post-Harvest Vegetable Products Laboratory of Instituto Federal Goiano de Educação, Ciência e Tecnologia - Campus Rio Verde (IF Goiano – Campus Rio Verde) and in the Laboratory of Agricultural Products Physical Properties and Quality affiliated with the Centro Nacional de Treinamento em Armazenagem (CENTREINAR), in Universidade Federal de Viçosa (UFV).

Crambe grains (*Crambe abyssinica*), which had an initial moisture content of 0.1547db, were manually collected in the experimental area of IF Goiano – Campus Rio Verde s. The gravimetric method was used to determine the moisture content of the grains, using an oven at a temperature of 105±3°C for 24h in two repetitions (BRASIL, 2009). For each moisture content (0.1547, 0.1342, 0.1292, 0.1012, 0.0813, 0.0580, and 0.0482 decimal db), samples were homogenized and sent to compression test at a controlled temperature of 22±2°C.

Compressive strength of grains was determined by means of uniaxial compression tests, using a sample of 20 grains for each moisture content. A "TA Hdi Texture Analyzer" universal testing machine with a 500N load cell was used to perform the individually analyzed experimental compression tests of the grains.

Grains were compressed in their natural resting position, specifically, in the thickness direction (smaller axis), at 0.0001ms^{-1} constant speed (force application rate).

After the data was obtained, compression force curves were plotted as a function of grain deformation for each of the tested moisture contents using Sigma Plot 11.0 software. Based on the findings of BATISTA et al. (2003) and RESENDE et al. (2007), the deformations used for this study were (0.2, 0.4, 0.6, 0.8, and 1.0)×10^{-3}m. Furthermore, the moisture content versus compression force curves were plotted for each evaluated deformation.

The proportional deformity modulus was determined using the equation ($Ep = \frac{0,531 \times F}{D^{3/2}} \cdot \left[2 \cdot \left(\frac{1}{r} + \frac{1}{R}\right)^{1/3}\right]^{3/2}$) according to BATISTA et al. (2003), where: Ep: proportional deformity modulus, Pa; F: compression force, N; D: total deformation (elastic and plastic) of the body in contact points with superior and inferior plate, m; R and r: curvature radii in contact point, m.

The grain curvature radii values (r and R) in the contact point were obtained by adjusting the circumference to the body curvatures, according to the coordinate plan of the compression position.

The test was conducted for the five tested deformations using a completely randomized design. The data were examined by analyzing the variance and regression, and the selected model was based on the significance of the regression coefficients, using a t-test adopting a 5% significance level, on the magnitude of the determination coefficient and the relative mean error in addition to the consideration of the biological phenomenon evolution.

Finally, the hardness and elasticity values of the crambe grains were determined as a function of moisture content, using the equation ($F=d.x+e.x^2+f.x^3$) suggested by HENRY et al. (1996). This equation shows that the required force to deform biological materials can be described as a function of deformation, in accordance with the Taylor series, where x: deformation, mm, *d, e,* and *f* elastic coefficients of the model. Using this model allows the identification of the three distinct sections along the curve: the initial concave, the intermediate that includes the inflexion point, and the convex where the curve slope decreases.

The slope of the force x deformation curve at any point is the tangent (T) obtained from the initially derived equation ($T=d+2e.x+3f.x^2$), where the maximum tangent is obtained at the curve inflexion point, and $x=-e/3f$ is considered as an indicator of product hardness.

The secant (S), the slope of the straight line passing through the origin and any point on the curve, is expressed as follows ($S=d+e.x+f.x^2$) with the maximum secant corresponds to the point where the deformation value x is $-e/2f$, which describes the elasticity at different levels of deformation.

RESULTS AND DISCUSSION

Figure 1 shows the compression force curves as a function of deformation for the tested moisture content levels. It can be seen that higher force tends to act on grains with lower moisture content in order to obtain the same compression. This trend can probably be attributed to the gradual change in the integrity of the cell matrix that occurs when the moisture content decreases (GUPTA & DAS, 2000). In contrast, when the moisture content

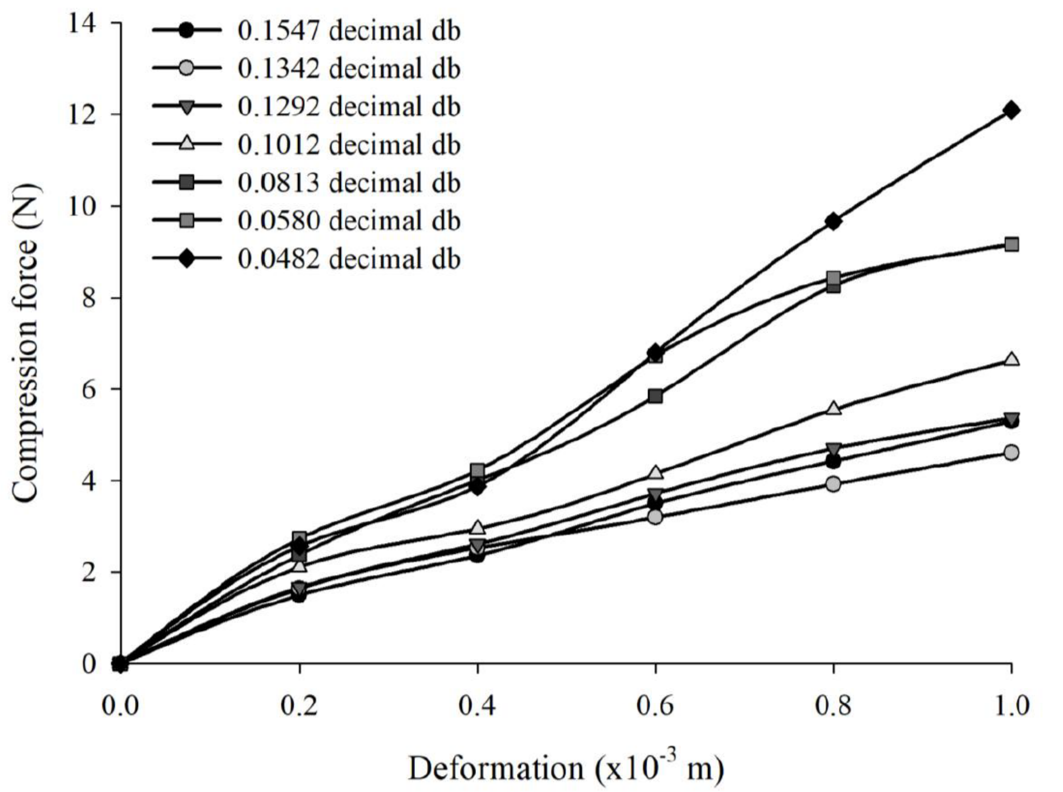

Figure 1 - Force as a function of deformation in crambe (*Crambe abyssinica*) grains with different moisture contents.

ranged between 0.1547 and 0.1342 decimal db, the compression force varied from 1.49 to 5.30 and 1.64 to 4.61N, respectively. When the moisture content was 0.1292, 0.1012, 0.0813, 0.0580, and 0.0482 decimal db, the force variation ranged from 1.66 to 5.37, 2.11 to 6.63, 2.38 to 9.16, 2.73 to 9.17, and 2.56 to 12.09N, respectively. Similar behavior was observed by GUPTA and DAS (2000) in their study of the mechanical properties of sunflower and RIBEIRO et al. (2007) investigation of soybeans.

The data presented in figure 2A, which displays the mean values of compression force as a function of moisture content (decimal db) for the various deformations, indicated that the required compression force to deform the crambe grains decreased as the moisture content increased, and the compression force fluctuated from 1.49 to 12.09N. FERNANDES et al. (2014) obtained a maximum compression force of 139.8 and 21.4N when they investigated the influence of moisture content on the mechanical properties of wheat grains. In this regard, RIBEIRO et al. (2007) and RESENDE et al. (2007) highlighted that the grains with higher moisture contents exhibited lower resistance to compression, as the resistance is inversely proportional to moisture content.

Grains with higher moisture content exhibited lower resistance to compression, which increases as the moisture content decreases. The previous research conducted on the mechanical properties of agricultural products generally reported that the deformation caused by a certain compressive strength is primarily dependent on the moisture content, which indicated that the higher the moisture content, the lower the force required to cause similar deformation. According to GUPTA and DAS (2000), this effect can possibly be attributed to the gradual change in the integrity of the cell matrix that occurs when the moisture content decreases.

To analyze the proportional deformity modulus, the values $(1.832 \text{ and } 1.530)\times10^{-3}$m for the curvature radii in contact with point r and R were used, respectively. The analysis of variance of the compression strength mean values as a function of the proportional deformity modulus revealed that the second-degree mathematical model adequately represents the variation of the

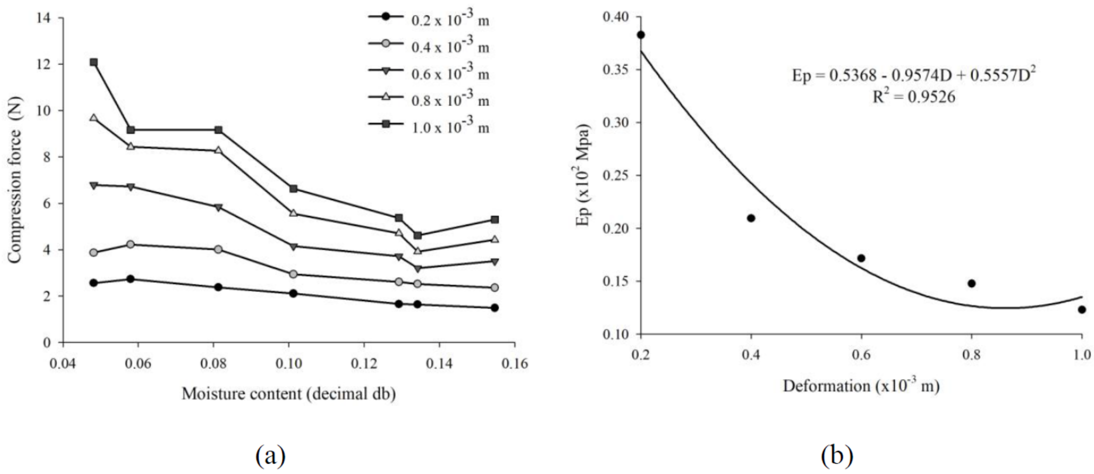

Figure 2 - Mean values of compression force (N) (a) and proportional deformity modulus (MPa) (b) of crambe (*Crambe abyssinica*) grains.

proportional deformity modulus as a function of deformation (Figure 2B).

Increase in deformation reduced the value range of the proportional deformity modulus, with variations ranging from (0.123-0.383)×10²MPa. A similar trend was reported by COUTO et al. (2002) and BATISTA et al. (2003) for coffee fruit and RESENDE et al. (2007) for beans.

The study conducted by BATISTA et al. (2003) revealed that the proportional deformity modulus of coffee fruits, which had a moisture content ranging between 0.14 and 1.50db in three maturation stages, decreased as the product deformation increased. Under these conditions, the value range of proportional deformity modulus was between (0.2-1.8)×10²MPa for cherry coffee fruits, (0.5-4.0)×10²MPa for unripe fruits, and (0.1-5.0)×10²MPa) for the slightly unripe fruits.

RESENDE et al. (2007) assessed the influence of different moisture contents of beans under different compression positions (smaller, medium and larger grain axis) on the proportional deformity modulus and obtained values ranged from (0.4-7.1)×10²MPa for the smallest axis, (0.3 to 5.6)×10²MPa for the medium axis, and (0.2-4.9)×10²MPa for the largest grain axis.

According to BATISTA et al. (2003), the high value of deformity modulus indicated that more force must be applied to the product in order to achieve certain deformation.

According to RESENDE et al. (2007), the model developed by HENRY et al. (1996) indicated that the signs of coefficients *e* and *f* identify the material properties and test special conditions. Therefore, the expected coefficient sign for non-damaged species shall be positive for *e* and negative for *f*. Additionally, a positive *d* value is always required for an initial positive curve slope.

Results listed in table 1 indicate that this condition regarding the signs of coefficients *e* and *f*

Table 1 - Observed values for elastic coefficients *d*, *e*, and *f*, and maximum tangent and secant obtained from force x deformation curve for crambe (*Crambe abyssinica*) grains with different moisture contents.

Moisture content (decimal db)	*d* (N mm^{-1})	*e* (N mm^{-2})	*f* (N mm^{-3})	Maximum Tangent (N mm^{-1})	Maximum Secant (N mm^{-1})
0.1547	7.5908	-4.1012	1.8299	4.5269	5.2929
0.1342	9.6736	-10.2010	5.1607	2.9523	4.6326
0.1292	8.4269	-4.5711	1.5513	3.9371	5.0596
0.1012	10.8876	-9.6082	5.4256	5.2159	6.6338
0.0813	10.1295	1.7205	-2.5664	10.5140	10.4179
0.0580	11.5174	1.8287	-4.1209	11.7879	11.7203
0.0482	9.8822	2.5959	-0.2941	17.5198	15.6104

was only satisfied when the moisture contents was below 0.1012 decimal db, whereas the parameter *d* exhibited a positive sign for all tested levels of moisture contents.

Therefore, we can confirm that the data follow a sigmoidal behavior for moisture contents of 0.0813, 0.0580, and 0.0482 decimal db, and such behaviors can be expressed by the HENRY et al. (1996) equation. According to HENRY et al. (2000), among other factors, grains with high moisture content hampers achieving the expected signs for the elastic coefficients *e* and *f* because the higher the moisture content of the grain, the less likely to reach the rupture point owing to the softness of the grain.

The maximum tangent values for moisture content levels of 0.0813, 0.0580, and 0.0482 decimal db were higher than the maximum secant values, confirming the findings obtained by several studies that assessed the mechanical properties of similar agricultural products, such as HENRY et al. (2000) and RIBEIRO et al. (2007). These researchers also reported that both the maximum tangent and maximum secant are typically inversely correlated with the moisture content, as confirmed by this study.

CONCLUSION

The compression force required for deforming the crambe grains decreases as the moisture content increases. The proportional deformity modulus of the crambe grains increases as its respective deformation decreases. And the sigmoidal model described by the Taylor series adequately represents the compressive strength of crambe grains with moisture content below 0.0813 decimal db.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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