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Mechanical properties of *Raphanus sativus* L. seeds[1]

Propriedades mecânicas das sementes de *Raphanus sativus* L.

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ABSTRACT - The objective of this study is to determine the effect of moisture content on rupture strength, maximum strength, and rupture deformation for fixed deformations, and determine the proportional deformation modulus of seeds of *Raphanus sativus* subjected to compressive loading. Seeds with a moisture concentration of 0.31, 0.18, 0.12, 0.08, and 0.05 decimal (dry basis, d.b.) were maintained in the natural resting position and were subjected to uniaxial compressive loading between two parallel plates at an application rate of 0.002 m s^{-1}. The rupture strength necessary to deform the seeds was increased from 15.03 to 27.08 as moisture levels decreased. Deformation was increased from 0.12^{-3} m to 0.15×10^{-3} m as moisture content decreased. The maximum rupture strength and proportional deformation modulus in fixed deformations were increased as moisture concentration decreased.

Key words: Radish. Deformation module. Moisture content.

RESUMO - Objetivou-se no presente trabalho verificar a influência do teor de água nos valores da força de ruptura, força máxima e deformação de ruptura, para deformações fixas, bem como determinar o módulo proporcional de deformidade de sementes de *Raphanus sativus* submetidos à compressão. Foram utilizadas sementes com teores de água de 0,31; 0,18; 0,12; 0,08 e 0,05 (decimal b.s.) submetidas a esforços de compressão uniaxial entre duas placas paralelas, aplicados em sua posição natural de repouso, a uma taxa de aplicação de força de 0,002 m s^{-1}. A força de ruptura necessária para deformar a semente aumenta com a redução do teor de água, com valores que variam de 15,03 a 27,08. A deformação aumenta com a redução do teor de água variando de 0,12 a 0,15 x 10^{-3} m. A força máxima de ruptura e módulo proporcional de deformidade nas deformações fixas aumenta com a redução do teor de água.

Palavras-chave: Nabo forrageiro. Módulo de deformidade. Teor de água.

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INTRODUCTION

Knowing the entire production process to obtain high-quality seeds is essential because cracks and breaks occur in seeds when the efforts to which they are subjected exceed the strength of the material. Therefore, mechanical characteristics have been studied to predict seed characteristics as a function of moisture content and temperature under different types of stress (LIU *et al*., 1990).

The determination of the mechanical properties of plant products is necessary for designing equipment and achieving maximum efficiency without compromising the final quality of the product (CORRÊA *et al*., 2007).

In addition, mechanical injury has a cumulative effect, i.e., seeds subjected to sustained injury become increasingly sensitive to the applied force (ANDRADE *et al*., 1999; PAIVA; MEDEIROS FILHO; FRAGA, 2000).

Several studies have characterized the mechanical properties of plant products at different moisture concentrations, including soybean (RIBEIRO *et al*., 2007), pistachio (GALEDAR *et al*., 2009), rice (RESENDE *et al*., 2013), and wheat (FERNANDES *et al*., 2014). However, to the best of our knowledge, few studies to date evaluated the mechanical properties of seeds of *Raphanus sativus*.

Among the mechanical properties, the deformation modulus allows comparing the relative strength of different materials. Total deformation can be determined after separating this variable into two components: elastic and plastic. The analysis of the strength curves as a function of deformation during the application of forces to the product and considering total deformity allows calculating the total deformation modulus of the product (RESENDE *et al*., 2007).

Considering the limited data on the mechanical properties of plant products and the need to develop efficient equipment, the objective of this study is to determine the effect of moisture content on the maximum compressive strength for fixed deformations, rupture strength, and proportional deformation modulus of seeds of *Raphanus sativus*.

MATERIAL AND METHODS

The seeds of *Raphanus sativus* L. cultivar CATI AL 1000 were cultivated in the Experimental Station of the Federal Institute of Education, Science, and Technology of Goiás, Rio Verde campus, located in Rio Verde, Goiás, Brazil, at 17º 47’ 53’’ latitude (S) and 51º 55’ 53’’ longitude (W). The study was conducted at the Post-Harvest Laboratory of Plant Products and Physical Properties and Quality of Agricultural Products of the National Storage Training Center (Centro Nacional de Treinamento em Armazenagem–CENTERINAR) affiliated to the Federal University of Viçosa (Universidade Federal de Viçosa-UFV), Viçosa, Minas Gerais, Brazil.

Seeds were harvested manually. The moisture content of 0.31 decimal d.b. was determined by gravimetry using the oven method at 105 ± 3 °C for 24 hours in two replications according to the Seed Analysis Guidelines (BRASIL, 2009).

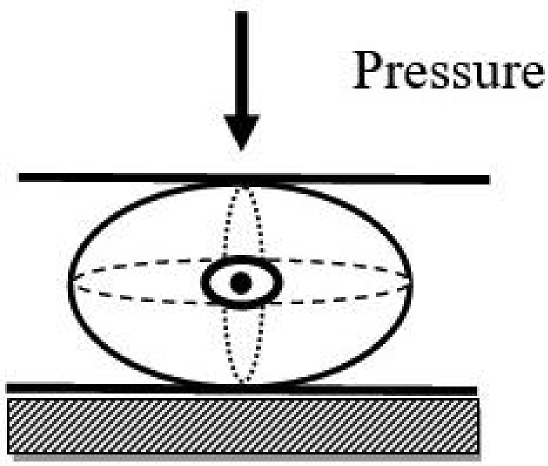
Different moisture concentrations were obtained by drying the seeds in a forced ventilation oven at a constant temperature of 40 ºC. The decrease in moisture levels during drying was monitored using the gravimetric method (loss of mass) and an analytical scale with a resolution of 0.01 g, knowing the baseline moisture concentration of the product, until the moisture content reached 0.05 decimal d.b.

For each moisture concentration (0.31, 0.18, 0.12, 0.08, and 0.05 decimal d.b.), the samples were homogenized and subjected to compression at a constant temperature of 40 ºC.

The seed compression tests were conducted individually in a TA Hdi Texture Analyzer universal test machine using a 500 N load cell.

Ten seeds oriented in the natural resting position were subjected to uniaxial compressive loading between two parallel plates at an application rate of 0.001 m s^{-1} (Figure 1).

Figure 1 - Orientation of the seeds of *Raphanus sativus* in the natural resting position during the compression test



After obtaining the force vs. deformation curves of the seeds, the strength and deformation values that provided the "bioyield point" were obtained. This point is defined as the position on the curve where there is an increase in the deformation associated with a decrease in the compressive strength (ASAE, 1974).

The proportional deformation modulus of the seeds of *Raphanus sativus* (Ep) was determined using Equation 1 and was obtained for deformations of 0.4 × 10^{-3}, 0.8 × 10^{-3}, 1.2 × 10^{-3}, 1.6 × 10^{-3}, and 2.0 × 10^{-3} m, adapted from the deformation values used by Batista *et al*. (2003).

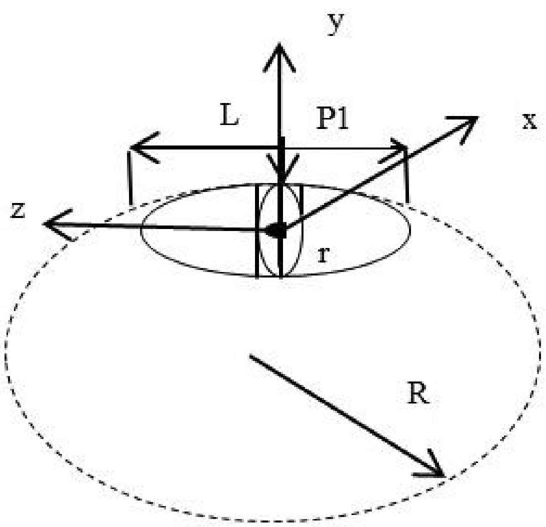
$$Ep = \frac{E}{\left(1-\mu^2\right)} = \frac{0,531 \times F}{D^{3/2}} \cdot \left[2 \cdot \left(\frac{1}{r} + \frac{1}{R}\right)^{1/3}\right]^{3/2} \quad (1)$$

where: *Ep* is the proportional modulus of elasticity, Pa; E is the modulus of elasticity, Pa; *F* is the compression force, N; *μ* is the Poisson coefficient, which varies from 0.2 to 0.5 for agricultural products; *D* is the total deformity (sum of elastic and plastic deformity), m; and *r* and *R* are the curvature radius of the seed at the points of contact, m.

The values of the curvature radius (*r* and *R*) of the seeds at the points of contact were obtained by adjusting the circumference to the body curvature according to the coordinates relevant to the compression position, as detailed by Couto *et al*. (2002) (Figure 2).

The mean curvature radius (*r* and *R*) were 1.642 × 10^{-3} and 2.529 × 10^{-3} m, respectively. These values did not change as a function of the moisture content.

Figure 2 - Curvature radius of the seeds of *Raphanus sativus* in the region of contact between the seeds and the compression plate; L: length

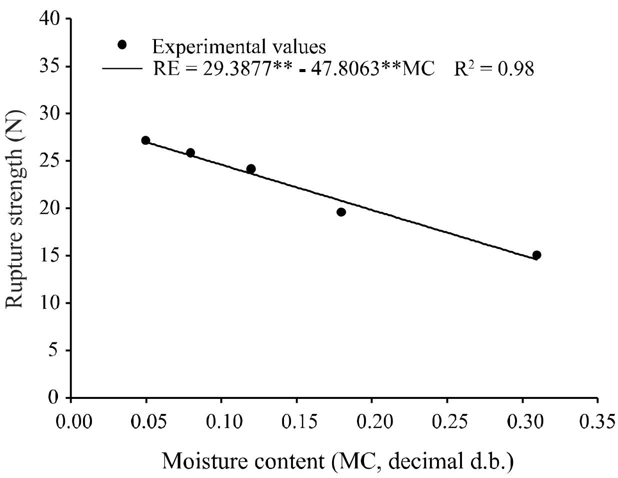


The experiment was arranged in a completely randomized 5 × 5 factorial design (five moisture concentrations and five deformations) with ten replications. Data were analyzed by analysis of variance and regression.

RESULTS AND DISCUSSION

The rupture strength of seeds of *Raphanus sativus* was increased from 15.03 to 27.08 N as the moisture content was decreased from 0.31 to 0.05 decimal d.b. (Figure 3).

Figure 3 - Experimental and estimated values of the rupture strength according to the moisture content of seeds of *Raphanus sativus*; TA: moisture content



** Significant at a level of 1% using the *t*-test

Similarly, Resende *et al*. (2013) observed that the strength required to rupture bark rice was increased from 48.0 to 79.5 as moisture concentration was reduced from 0.30 to 0.12 (decimal d.b.), and Ribeiro *et al*. (2007) found that the strength to rupture soybeans was increased from 41.9 to 127.64 N as moisture level was decreased from 0.58 to 0.093 decimal d.b. Altuntas and Yildiz (2007) and Jangi *et al*. (2011) observed that the strength required to break pigeon peas and barley was increased as the moisture concentration decreased. Tavakoli, Rajabipour, and Mohtasebi (2009) reported that the force required to rupture soybean seeds was increased from 191.09 to 270.66 N as moisture levels decreased from 0.2119 to 0.0692 decimal d.b.

These results indicate that rupture strength is highly dependent on the water concentration of the seeds and that seeds of *Raphanus sativus* subjected to compressive loading require less force to become ruptured compared to other seeds, and this difference is due to the physical and chemical structure of the evaluated seeds.

Seifi and Alimardani (2010) found differences in the rupture strength between two corn varieties (Sc 704 and Dc 370), and variety Sc 704 required less compressive strength with the increase in moisture because of its softer texture. In addition, the linear equation satisfactorily represented the rupture strength as a function of the water concentration in seeds of *Raphanus sativus* (Figure 3).

Seeds with a lower moisture content offer higher resistance to compressive loading because of the gradual increase in the integrity of the cell matrix as moisture decreased (GUPTA; DAS, 2000).

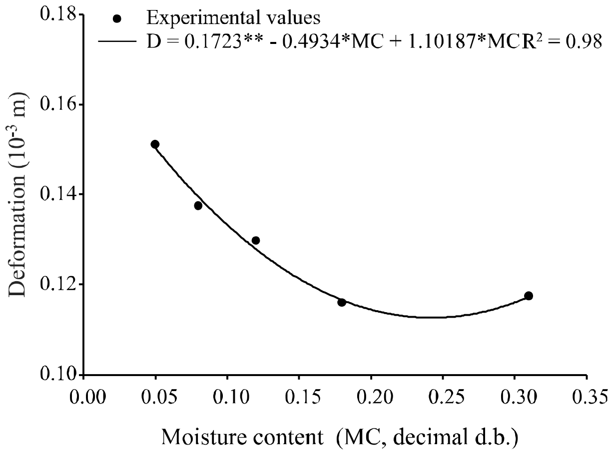
The deformation varied from 0.12×10^{-3} m to 0.15×10^{-3} m as moisture concentration varied from 0.31 to 0.05 decimal d.b. (Figure 4).

The variation in deformation as a function of the moisture concentration could be described by a quadratic equation. Similarly, Resende *et al*. (2013) observed that in shelled rice seeds, deformation varied from 0.12×10^3 to 0.15×10^3 m as moisture levels varied from 0.30 to 0.12 decimal d.b.

Galedar *et al*. (2009) reported a linear decrease in deformation with the increase in moisture levels for pistachio almond. In contrast, Fadavi, Hassan-Beygi and Karimi (2013) found that deformation was not affected by the decrease in moisture concentration from 0.18 to 0.04 decimal d.b.

In different experimental conditions, there were significant differences in the analyzed variables and in the interactions between moisture content and deformation (Table 1).

Figure 4 - Experimental values of deformation as a function of the moisture concentration of the seeds of *Raphanus sativus*



** Significant at 1%; * Significant at 5% by the *t*-test

The maximum compressive strength necessary to rupture the seeds of *Raphanus sativus* was increased as moisture concentration decreased (Figure 5). The rupture strength necessary for deformation varied from 25.68 to 0.17 N, and the quadratic regression satisfactorily represented the increase in maximum strength with the loss of moisture in seeds of *Raphanus sativus* in all analyzed deformations.

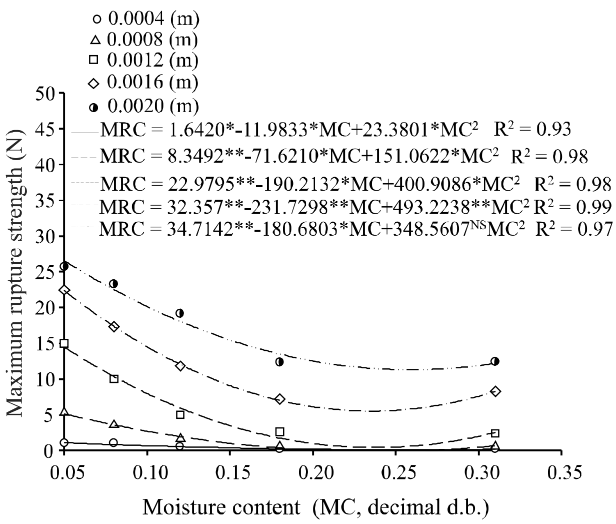
Fernandes *et al*. (2014) observed that the rupture strength of wheat increased from 21.4 to 139.8 as moisture levels decreased from 0.25 to 0.14 decimal d.b. Resende *et al*. (2007) reported that the mean rupture strength for bean seeds varied from 22.3 to 551.7 N, 10.5 to 253.1 N, and 11.6 to 143 N at three seed positions. Ribeiro *et al*. (2007) examined soybean seeds and observed that rupture strength varied from 2.72 to 72.5 N, 41.19 to 127.64 N, and 21.72 to 110.86 N for a reduction in moisture

Table 1 - Analysis of variance of the maximum rupture strength (MRS) and the proportional deformation modulus (Ep) of seeds of *Raphanus sativus* at different moisture concentrations (0,31, 0,18, 0,12, 0,26, 0.08, and 0.05 decimal d.b.) and deformations (0.0004, 0.0008, 0.0012, 0.0016, and 0.002 m)

SV	DF	MRS	Ep
		QM	
Moisture content	4	244.876406 **	2.57423 × 1014 **
Deformation	4	855.738528 **	1.308235 × 1014 **
Moisture content x deformation	16	23.123837 **	7.80169 × 1012 **
Error	50	0.77635684 × 10-17	-1.95312 × 105
CV (%)		0.34	0.34

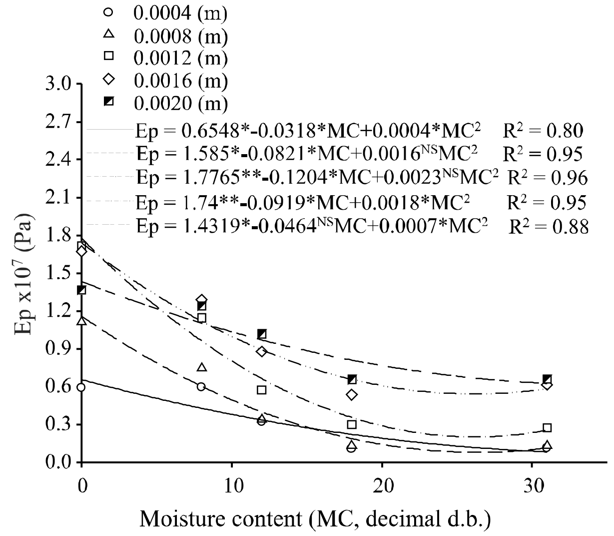
** Significant at 1% by the F-test

Figure 5 - Experimental values of the maximum rupture strength in seeds of *Raphanus sativus* as a function of the moisture content for deformations of 0.0004, 0.0008, 0.0012, 0.0016, and 0.0020 m



** Significant at 1%; * Significant at 5%; NS Not significant by the *t*-test

Figure 6. Experimental and estimated values of the proportional deformation modulus as a function of the moisture concentration of the seeds of *Raphanus sativus*



** Significant at 1%; * Significant at 5%; NS Not significant by the *t*-test

concentration from 0.58 to 0.09 decimal d.b. at three seed positions.

The quadratic regression satisfactorily represented the increase in maximum strength with the loss of moisture of seeds of *Raphanus sativus* in all analyzed deformations. The maximum rupture strength values in this study were smaller than those of other studies, and this may be because of the physical and chemical characteristics of the seeds of *Raphanus sativus*, i.e., the presence of high concentrations of lipids and a thinner tegumentary layer, which facilitates the release of moisture during drying.

Gupta and Das (2000) found that the lower was the moisture content, the higher was the compressive strength. This result is probably due to a gradual increase in the integrity of the cell matrix as moisture concentration was increased.

The proportional deformation modulus was obtained from the compressive strength data (Figure 6). The values of the proportional deformation modulus were increased as moisture levels decreased, with a variation from 0.11×10^{10} to 1.72×10^{10} Pa.

Batista *et al*. (2003) reported that the high deformation modulus indicated that a higher force should be applied to the product to obtain a specific deformation. The obtained values are higher than those obtained by Fernandes *et al*. (2014) for wheat grains, wherein deformation varied from 8.9×10^7 and 51.2×10^7 Pa as moisture content decreased from 0.26 to 0.14 decimal d.b.

Corrêa *et al*. (2008) reported values from 4.1×10^7 to 71.3×10^7 Pa for moisture concentrations from 0.136 to 0.423 decimal d.b. in bean seeds.

CONCLUSIONS

1. The rupture strength of seeds of *Raphanus sativus* is increased as the moisture content decreased;
2. Deformation is increased as moisture concentration is decreased;
3. The maximum rupture strength and proportional deformation modulus in fixed deformations of the seeds of *Raphanus sativus* increased as moisture levels were reduced.

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