Available online at www.sciencedirect.com
SCIENCE DIRECT®

Journal of Food Engineering 72 (2006) 134–140

JOURNAL OF FOOD ENGINEERING

www.elsevier.com/locate/jfoodeng

Moisture dependent physical and compression properties of safflower seed

Erica Baümler [a], Adela Cuniberti [b], Susana M. Nolasco [a,*], Isabel C. Riccobene [a,*]

[a] *Grupo de Investigación TECSE, Departamento de Ingeniería Química, Facultad de Ingeniería, UNCPBA, Av. del Valle 5737, Olavarría, Buenos Aires B7400JWI, Argentina*
[b] *Instituto de Física de Materiales Tandil, UNCPBA, Tandil, Argentina, Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina*

Received 4 May 2004; accepted 11 November 2004
Available online 5 January 2005

Abstract

The objective of this study was to investigate the effect of moisture content on some physical properties and fracture resistance of the safflower seeds typically cultivated in Argentina. The safflower seeds have an oil content of 43 ± 3.6% dry basis (d.b.), 37% (d.b.) hull contents and the initial moisture content of the safflower seeds was 6.9% (d.b.).

The results obtained show that the modifications of moisture content of safflower seed caused a little variation in its size, its hull thickness being the most affected. The volume and weight of the seed, the expansion coefficient, the equivalent diameter and the sphericity increased lineally with the increase in the seed moisture content. The true density varied nonlinearly in the considered range of moisture content. At the same time, an increase in moisture content yields a decrease in bulk density trend and an increased linearly for the porosity of the bed of grain. Under compression, the seeds rupture force is in the range of 40 N–20 N for vertical and horizontal loading orientation, the seeds are more flexible in the horizontal loading direction, and the rupture under vertical loading direction requires less energy than under horizontal loading.

Keywords: Safflower; Compression; Physical properties; Fracture resistance

1. Introduction

The safflower (*Carthamus tinctorius* L.), which belongs to the Compositae family, is cultivated in several parts of the world due to its adaptability to different environmental conditions. Safflower has been introduced in Argentina with promising results (Giayetto, Fernandez, Asnal, Cerioni, & Cholasky, 1999). This species was cultivated for more than two thousand years as a dye, carthamin, obtained from its flowers. However, safflower has lately gained importance because the seed oil has an important food-value, with a high linoleic acid content.

The physical properties of safflower seeds, like those of other grains, are essential for the design of equipment for handling, harvesting, aeration, drying, storing, dehulling and processing. These properties are affected by numerous factors such as size, form, superficial characteristics and moisture content of the grain. Moreover, knowledge of fracture characteristics of the seed hull is imperative for a rational design of efficient dehulling systems, as well as the optimization of the process and product parameters.

Research on physical and engineering properties are reported for different types of seeds, like as soybeans (Deshpande, Bal, & Ojha, 1993; Paulsen, 1978); oilbean (Oje & Ugbor, 1991); canola and wheat (Bargale,

* Corresponding authors. Tel./fax: +54 2284 451055/56.
E-mail addresses: snolasco@fio.unicen.edu.ar (S.M. Nolasco), iriccobe@fio.unicen.edu.ar (I.C. Riccobene).

0260-8774/$ - see front matter
doi:10.1016/j.jfoodeng.2004.11.029

Nomenclature

M	moisture content (% d.b.)	V_g^0	volume of dry seed. The dry seed was considered as the grain after dried during 8 h into vacuum over at 100 °C
L	length of the seed (mm)	ψ	volumetric expansion coefficient
W	width of the seed (mm)	D_e	equivalent diameter (mm)
T	thickness of the seed (mm)	φ	sphericity
ρ_b	bulk density (g/cm^3)	P_g	mass and volume of individual grain (g)
ρ_t	true density (g/cm^3)	F	rupture force (N)
ε	porosity (%)	d	rupture deformation (mm)
m	unit mass of the seed (g) determined from samples used to calculate the true density		
V_g	volume of seeds (mm^3)		

Irudayaraj, & Marquis, 1995); lentil (Çarman, 1996); cumin (Singh & Goswami, 1996); sunflower (Gupta & Das, 1997; Gupta & Das, 2000); karingda (Suthar & Das, 1997); black pepper (Murthy & Bhattacharya, 1998); legume (Laskowski & Lysiak, 1999); locust bean (Ogunjimi, Aviara, & Aregbesola, 2002); pigeon pea (Baryeh & Mangope, 2002); cotton (Özarslan, 2002); chick pea (Konak, Çarman, & Aydin, 2002); calabash nutmeg (Omobuwajo, Omobuwajo, & Sanni, 2003).

Limited research has been conducted on the physical properties and fracture resistance of safflower seed. Gupta and Prakash (1992) reported some of those properties for safflower JSF-1-type seeds. However, volumetric expansion coefficient, equivalent diameter and fracture characteristics of safflower seed and their variations at various levels of moisture content have not been investigated.

The objective of this study was to investigate the effect of moisture content on some physical properties and fracture resistance of the safflower seeds typically cultivated in Argentina. The parameters measured at different moisture content (3.7–15.6% in dry base) were size, true density, bulk density, porosity, volume and weight, volumetric expansion coefficient, equivalent diameter, sphericity, and rupture force, deformation and absorbed energy.

2. Materials and methods

The safflower seeds used in the present study were obtained from a crop grown during 1999 in Salta (25° south and 65.5° west), Argentina. The seeds were manually cleaned to remove all foreign matter, broken or immature seeds. The safflower seeds have an oil content of 43 ± 3.6% dry basis (d.b.) and it is an important component of the hull (37% d.b.). The initial moisture content of the seeds was determined by the vacuum oven method moisture (Official Method 14003, AOAC, 1980). The initial moisture content of the safflower seeds was 6.9% (d.b.).

The seeds with the desired moisture content were obtained by drying (convection air oven at 40–45 °C) or adding calculated amounts of distilled water, thoroughly mixing and sealing them in separate polyethylene bags. The samples were kept at 5 °C in a refrigerator for at least a week to allow uniformity of moisture distribution. Before starting a test, the required quantity of the seeds was taken out of the refrigerator and allowed to warm up to room temperature. All the physical properties of the seeds were obtained for six moisture contents in the range 3.7–15.6% (d.b.). The tests were carried out with three replications for each moisture content.

The coefficients of determination between the properties evaluated and the moisture content were determined using the software Sigma Plot for Windows Version 4.01 (1997 SPSS Inc.).

To determine the average size of the seed, a sample of 30 seeds was randomly selected. The three linear dimensions of the seeds, namely length (L), width (W) and thickness (T) and hull thickness were measured using a micrometer reading to 0.01 mm (Fig. 1).

The bulk density (ρ_b) considered as the ratio of the mass of a sample of the seeds to its total volume was determined using a weight per hectoliter tester (250 mL

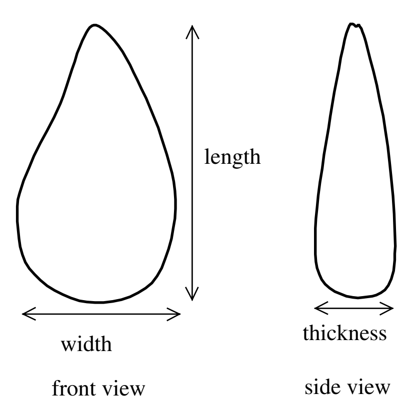

Fig. 1. Characteristic dimensions of safflower seed front view and side view.

of total volume). The true density (ρ_t) defined as the ratio of the mass of the sample of the seed to the solid volume occupied by the sample, was determined using an electronic balance reading to 0.001 g and a pycnometer (liquid displacement method).

The porosity (ε) of the bulk seed was defined as the fractions of the space in the bulk grain that is not occupied by the grain. The percent porosity was calculated from the following relationship (Mohsenin, 1986):

$$\varepsilon = (1 - \rho_b/\rho_t) * 100 \quad (1)$$

The volume (V_g) of seeds (mm^3) was determined from the following relationship (Özarslan, 2002):

$$V_g = (m/\rho_t)10^3 \quad (2)$$

where m is the unit mass of the seed (in g) determined from samples used to calculate the true density.

The volumetric expansion coefficient (ψ) was calculated using the following relationship:

$$\psi = V_g/V_g^0 \quad (3)$$

where V_g^0 is the volume of dry seed. The dry seed weight was determined after drying for 8 h in a vacuum at 100 °C.

The equivalent diameter (D_e) and sphericity (φ) were determined using the following expressions:

$$D_e = (6V_g/\pi)^{1/3} \quad (4)$$

$$\varphi = D_e/L \quad (5)$$

where L and V_g are length and volume of grain, respectively.

Safflower seeds were subject to compression up to hull failure in order to determine the force–deformation behavior at different moisture contents and orientation of loading. The dimensions of each seed were determined prior to loading. The three principal dimensions namely length, width and thickness (Fig. 1) were measured using a micrometer reading to 0.01 mm. These measurements were used to calculate the volume of the individual seeds by assuming the seeds were ellipsoid in shape. Seeds were further visually examined, discarding those with visible cracks in the hull. A universal testing machine (Shimadzu Autograph DSS-10T-S) equipped with a 1 kN load cell was used for the compression of the safflower seeds. The seeds were compressed between two flat parallel plates, at a crosshead speed of 1 mm/min. The force–deformation curves were recorded with an analog recorder, and stored for further processing using a high-speed data acquisition system. The measurement accuracy was ±0.5 N in force and 0.001 mm in deformation.

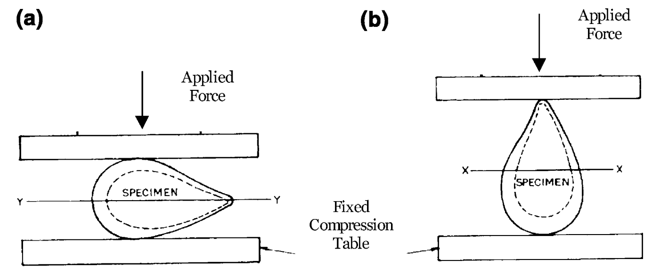

Fig. 2. Compression test of safflower seeds under different orientations of loading (not to scale). (a) Horizontal orientation and (b) vertical orientation.

To determine the effect of loading orientations on rupture, the samples were tested in horizontal and vertical orientations as shown in Fig. 2. At least 15 seeds were tested in each orientation and moisture content, adding more seeds until the average error was lower than 15%.

3. Results and discussion

The variation of the seed length, width, thickness and hull thickness with seed moisture content is shown in Table 1.

The seed drying causes little variations in its size (variation coefficient 1.6–2.9%), the hull thickness being the most affected (variation coefficient 14%). This behavior differs from that observed in safflower JSF-1 seeds by Gupta and Prakash (1992), with a direct and linear relationship between size (expressed according to Mohsenin, 1986) and moisture content (from 7.5% to 31.6%).

The variation of true density and bulk density of safflower seed with moisture content is shown in Fig. 3.

Table 1
Variation of principal dimensions and hull thickness with seed moisture content

Moisture content (% d.b.)	Range of the seed length (mm)	Average dimension			
		Length (mm)	Width (mm)	Thickness (mm)	Hull thickness (mm)
15.6	6.500–8.610	7.344 ± 0.477	3.673 ± 0.279	3.024 ± 0.260	0.407 ± 0.084
10.8	6.761–7.987	7.390 ± 0.356	3.688 ± 0.239	3.068 ± 0.215	0.365 ± 0.101
6.9	6.667–8.686	7.631 ± 0.523	3.833 ± 0.298	3.255 ± 0.215	0.372 ± 0.083
6.0	6.547–8.446	7.591 ± 0.415	3.792 ± 0.402	3.203 ± 0.299	0.285 ± 0.062
5.2	6.500–8.435	7.442 ± 0.479	3.812 ± 0.271	3.235 ± 0.275	0.313 ± 0.069
3.7	6.860–8.515	7.509 ± 0.445	3.773 ± 0.240	3.229 ± 0.228	0.282 ± 0.070

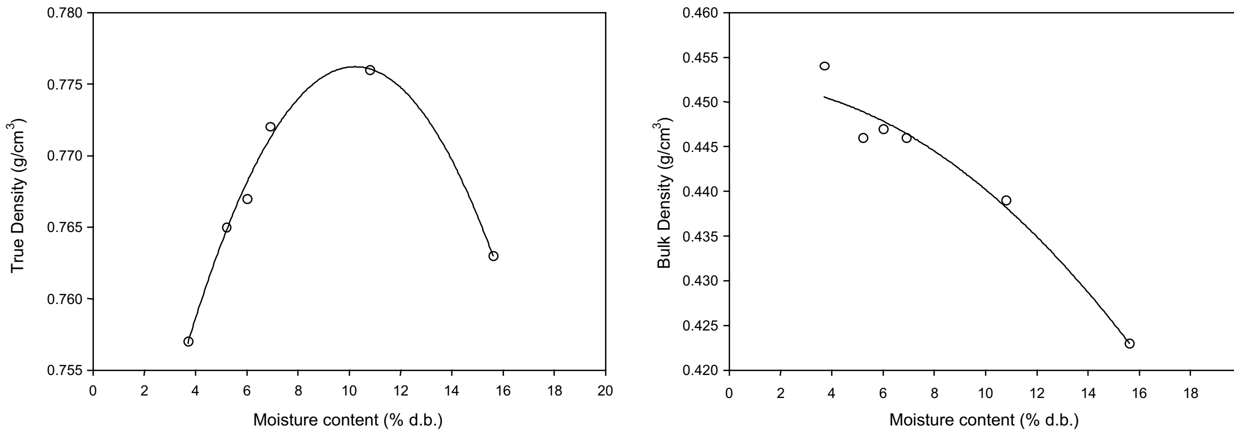

Fig. 3. Variations of true density and bulk density with moisture content.

The experimental data showed a nonlinear trend with the moisture content (M in % d.b.) in the range of moisture evaluated (3.7–15.6% d.b.), and can be expressed by the following correlation:

$$\rho_t = 0.7887 + 0.298 \times 10^{-3}M - 4.551 \times 10^{-4}M^2,$$
$$R^2 = 0.991,$$
$$P = 0.0008.$$

An increase in true density with an increase in moisture content was reported for cumin seeds (Singh & Goswami, 1996), sunflower (Gupta & Das, 1997) and pigeon pea (Baryeh & Mangope, 2002). These seeds have a higher weight increase in comparison with their volume expansion on moisture gain. However, Deshpande et al. (1993), Özarslan (2002) and Konak et al. (2002) have found that the true density of soybeans, cottonseed and chickpea seed respectively decreases as the seed moisture content increases. Gupta and Prakash (1992) found a similar trend for the specific gravity of the safflower JSF-1 seed when the moisture level increased from 7.5% to 31.6%. It is important to highlight that the range of seed moisture content studied differs of that used by Gupta and Prakash (1992) for JSF-1 safflower seeds. The explanation for these discrepancies could be found in the cell structure and the volume and mass increase characteristics of the seeds as seed moisture content increases.

The bulk density of the safflower seeds decreased from 0.450 to 0.427 with increase in moisture content (Fig. 3). This represents approximately a variation of 10% in the range of moisture content evaluated. The relationship obtained from the experimental data was

$$\rho_b = 0.4522 - 1.197 \times 10^{-4}M^2,$$
$$R^2 = 0.961,$$
$$P = 0.0006.$$

Thus, it appears that the increase in net volume was slightly highly when compared with the net increase in mass of the bulk seed. A similar behavior was reported by Gupta and Prakash (1992) for safflower JSF-1 seed and by Gupta and Das (1997) for sunflower seed and kernel.

The porosity was evaluated for safflower seed using Eq. (1). The relationship between porosity and moisture content for seed derived from the data was

$$\varepsilon = 39.53 + 0.342M,$$
$$R^2 = 0.933,$$
$$P = 0.0017.$$

The porosity of safflower seed was found to increase linearly from 41.6% to 44.6% as the moisture content increased from 3.7% to 15.6% (d.b.). A similar trend was reported for sunflower seed (Gupta & Das, 1997), lentil seeds (Çarman, 1996) and pigeon pea (Baryeh & Mangope, 2002), but different to that reported for soybean (Deshpande et al., 1993; Sreenarayanan, Subramamian, & Visvanathan, 1985) pumpkin seeds (Joshi, Das, & Mukherji, 1993) and safflower JSF-1 (Gupta & Prakash, 1992). Porosity is the property of grain that depends on its bulk and true density and this dependence is different for every seed.

Volume and weight of individual seeds increased linearly with moisture content, but the increase in volume is slightly higher as compared with the net increase in mass of grain (Fig. 4). Gupta and Prakash (1992) report a similar trend for JSF-1 safflower seeds.

The volumetric expansion coefficient (Fig. 5) was calculated using Eq. (3). It decreased with moisture content and was similar to that reported for sunflower and corn (Pagano & Crozza, 2001). The experimentally observed data on the volumetric expansion coefficient and moisture content can be represented by the following regression equation:

$$\psi = 0.9546 + 0.01638M,$$
$$R^2 = 0.969,$$
$$P = 0.0004.$$

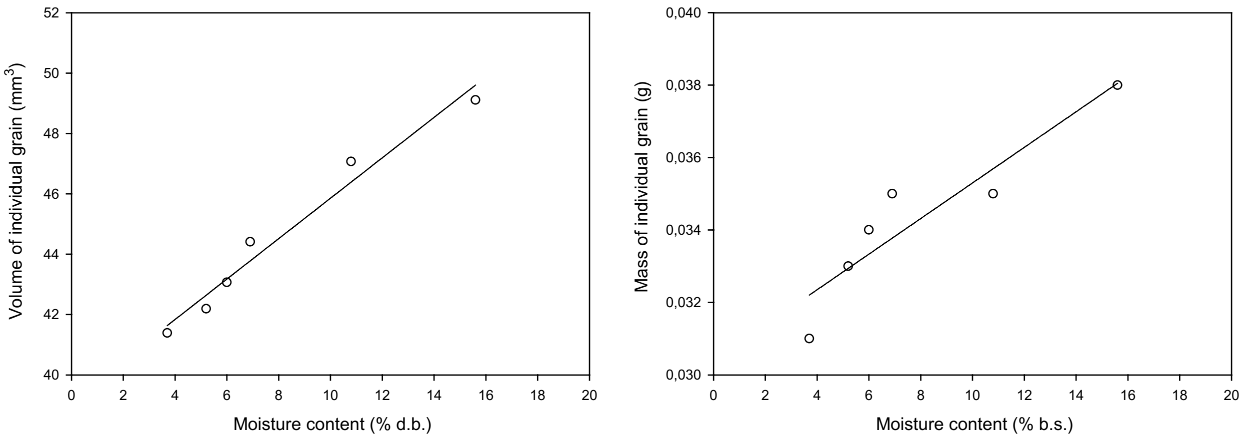

Fig. 4. Variations of mass and volume of individual grain with moisture content. $P_g = 0.03039 + 0.00049\,M$; $R^2 = 0.858$; $P = 0.0079$ and; $V_g = 39.16 + 0.6695\,M$; $R^2 = 0.969$; $P = 0.0004$, respectively, where M is moisture content (% d.b.); P_g (g) and V_g (mm^3) mass and volume of individual grain.

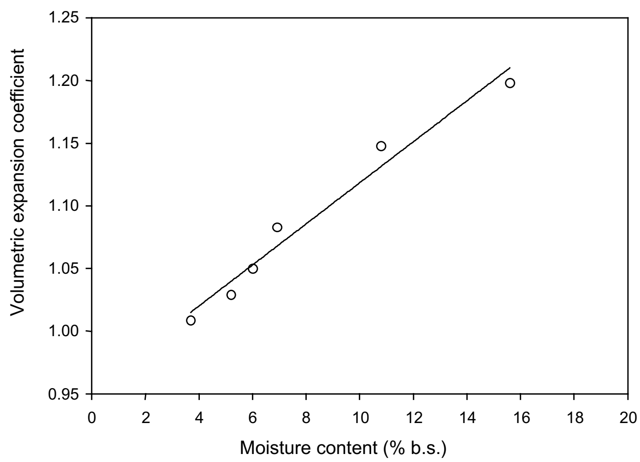

Fig. 5. Variations of volumetric expansion coefficient with moisture content.

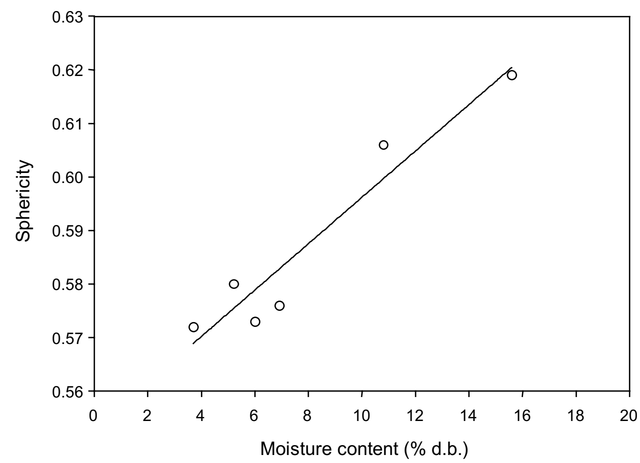

Fig. 6. Variations of sphericity with moisture content.

The equivalent diameter (D_e, Eq. (4)) of safflower seeds (ranging from 4.319 to 4.543 mm; average: 4.423 mm) was found close to sunflower seeds. A linear trend appears with the moisture content M in % d.b. ($D_e = 0.0217M + 4.222$; $R^2 = 0.964$; $P = 0.0005$).

The sphericity is the shape character of the solid relative to that of a sphere of the same volume. The sphericity of the safflower seeds (Eq. (5)) increased linearly from 0.58 to 0.62 with moisture content in the range of moisture evaluated (3.7–15.6% d.b.), Fig. 6. The relationship obtained from the data was

$$\varphi = 0.5529 + 0.0043M,$$
$$R^2 = 0.922,$$
$$P = 0.0023.$$

However, Gupta and Prakash (1992) did not find any specific trend between the sphericity and seed moisture content.

A typical compression curve is shown in Fig. 7. At all moisture contents and loading orientations, an increase of deformation with an increase in applied forces was

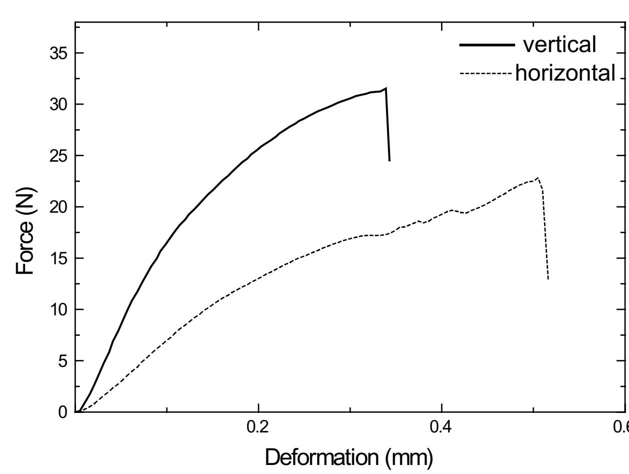

Fig. 7. Typical compression curve (6.5% d.b.).

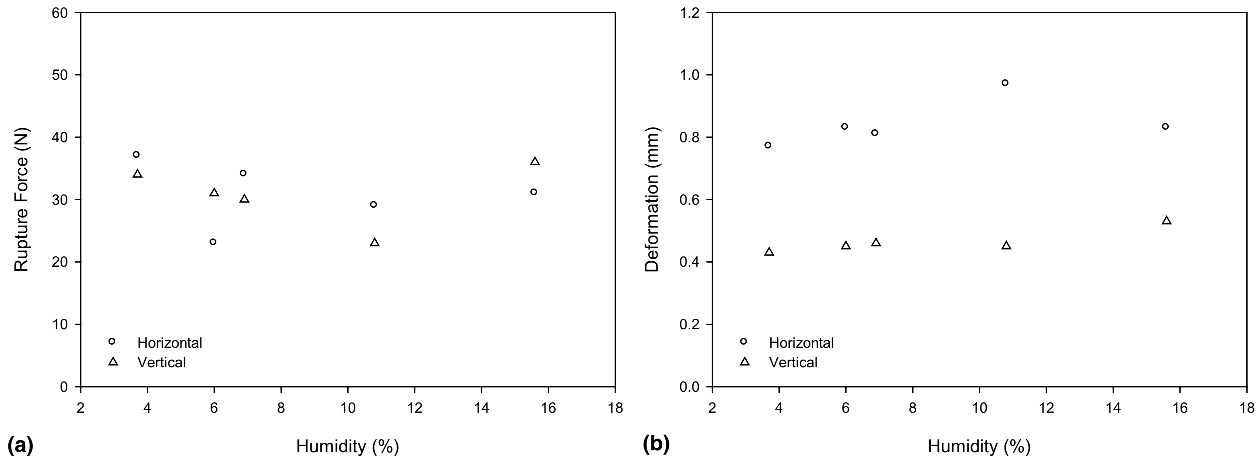

Fig. 8. (a) Force rupture and (b) rupture deformation for safflower seeds.

observed. The hull rupture is marked by an audible "click", and a sudden decrease of the force occurs.

The point marked by the abrupt force decrease is often called the bio-yield point, and the loading was stopped once this point was reached. The measured parameters were the rupture force, when the seed hull undergoes failure during compression, the deformation up to the rupture point, and the rupture energy. The rupture energy is the energy needed for the cracking of the hull, determined from the area under the curve up to the point of rupture, and it can be considered as the minimum energy for dehulling.

The effect of moisture content and orientation of loading on the rupture force (F) and the rupture deformation (d) of the hull is presented in Fig. 8(a) and (b), respectively. No important difference in F between both loading orientations is measured. The force required for the hull rupture decreases as the moisture content increased, and it attained a minimum value at around 11% (d.b.), followed by an increasing trend with further increase in moisture content. Paulsen (1978) for soybeans seedcoat and Gupta and Das (2000) for sunflower hull reported a decrease in rupture force as moisture content increased. The hull mechanical strength in our case could be determined by two competing factors: the mechanical softening of the cellulosic fibres at higher moisture content, leading to a decrease in F, and the increase of the hull thickness with the moisture content increase (Table 1), leading to an F increase.

A weak increase of the deformation values (d) with the moisture content increase was obtained for both the vertical and horizontal positions. The deformation values up to hull failure in the horizontal position were always higher than those for the vertical position for the entire range of moisture contents. A higher rupture deformation increase with the moisture content increase occurs in sunflower seeds, and with a contrary trend to safflower, sunflower seeds are more flexible in the vertical loading direction (Gupta & Das, 2000). It could be related to the differences in the geometry between both types of seeds.

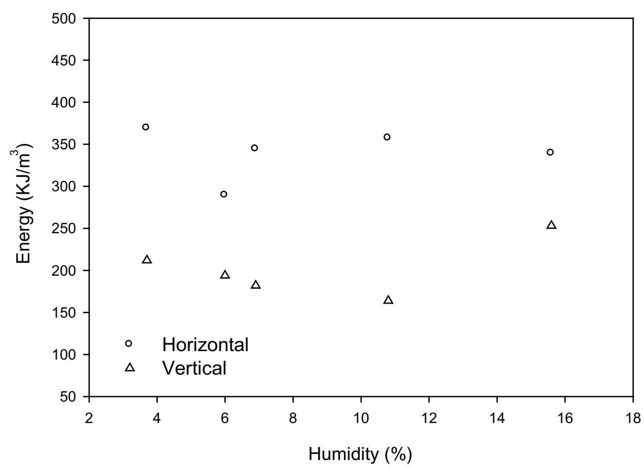

Fig. 9. Effect of moisture content on energy absorbed per unit volume at rupture for safflower seed under horizontal and vertical loading orientations.

Fig. 9 shows the energy required for safflower hull rupture for different moisture content values and load position. The energy absorbed at rupture per unit volume of seeds for the horizontal position was always higher than that for the vertical position. This suggests that the dehulling resistance is particularly influenced by the higher flexibility of seeds loaded in the horizontal position. The rupture energy shows a smooth decrease with moisture increase for the horizontal load position, while it attains a minimum at around 11% of moisture content for the vertical one.

4. Conclusions

Several properties of Argentina cultivated safflower seeds were investigated in the range of moisture contents from 3.7% at 15.6% (d.b.). The results obtained show that the modifications of moisture content of safflower seed caused a little variation in its size, with its hull thickness being the most affected. The volume and weight of the seed, the expansion coefficient, the equivalent diameter and the sphericity increased lineally with the increase of the seed moisture content. The true density varied nonlinearly in the considered range of moisture content. At the same time, an increase in moisture content gives a decrease in bulk density and a linearly increase in porosity of a bed of grain. Under compression, the seeds rupture force is in the range of 40 N–20 N for vertical and horizontal loading orientation, the seeds being more flexible in the horizontal loading direction, and the rupture under vertical loading requiring less energy than under horizontal loading.

References

AOAC (1980). Association of the official analytical chemists, method 14.003. In: W. Howitz, Ph.D. (Ed.), *Official Methods of Analysis of the Association of the Official Analytical Chemists* (13th ed.). Washington DC, USA.

Bargale, P. C., Irudayaraj, J., & Marquis, B. (1995). Studies on Rheological behaviour of canola and wheat. *Journal of Agricultural Engineering Research, 61*, 267–274.

Baryeh, E. A., & Mangope, B. K. (2002). Some physical properties of QP-38 variety pigeon pea. *Journal of Food Engineering, 56*, 59–65.

Çarman, K. (1996). Some physical properties of lentil seeds. *Journal of Agricultural Engineering Research, 63*, 87–92.

Deshpande, S. D., Bal, S., & Ojha, T. P. (1993). Physical properties of soybean. *Journal of Food Engineering Research, 56*(2), 89–98.

Giayetto, O., Fernandez, E. M., Asnal, W. E., Cerioni, G. A., & Cholasky, L. (1999). Behaviour of safflower (*carthasmus tinctorius*, L.) cultivars in Rio IV, Córdoba, Argentina. *Investigation of Agricultural Products and Protection of Vegetation, 14*(1–2), 203–215.

Gupta, R. K., & Das, S. K. (1997). Physical properties of sunflower seeds. *Journal of Agricultural Engineering Research, 66*, 1–8.

Gupta, R. K., & Das, S. K. (2000). Fracture resistance of sunflower seed and kernel to compressive loading. *Journal of Food Engineering, 46*, 1–8.

Gupta, R. K., & Prakash, S. (1992). The effect of seed moisture content on the physical properties of JSF-1 safflower. *Journal of Oilseeds Research, 9*(2), 209–216.

Joshi, D. C., Das, S. K., & Mukherji, R. K. (1993). Physical properties of pumpkin. *Journal of Agricultural Engineering Research, 54*, 219–229.

Konak, M., Çarman, K., & Aydin, C. (2002). Physical properties of chick pea seeds. *Biosystems Engineering, 82*, 73–78.

Laskowski, J., & Lysiak, G. (1999). Use of compression behaviour of legume seeds in view of impact grinding prediction. *Powder Technology, 105*, 83–88.

Mohsenin, N. N. (1986). *Physical properties of plant and animal materials* (3rd ed.). New York: Gordon and Breach.

Murthy, C. T., & Bhattacharya, S. (1998). Moisture dependant physical an uniaxial compression properties of black pepper. *Journal of Food Engineering, 37*, 193–205.

Ogunjimi, L. A. O., Aviara, N. A., & Aregbesola, O. A. (2002). Some engineering properties of locust bean seed. *Journal of Food Engineering, 55*, 95–99.

Oje, K., & Ugbor, E. C. (1991). Some physical properties of oilbean seed. *Journal of Agricultural Engineering Research, 50*, 305–313.

Omobuwajo, T. O., Omobuwajo, O. R., & Sanni, L. A. (2003). Physical properties of calabasch nutmeg (*Monodora myristica*) seeds. *Journal of Food Engineering, 57*, 375–381.

Özarslan, C. (2002). Physical properties of cotton seed. *Biosystems Engineering, 83*, 169–174.

Pagano, A. M., & Crozza, D. E. (2001). Modelling of expansion during adsortion for two oleaginous. *Tercer Congreso Iberoamericano de Ingeniería de Alimentos*. Valencia, España.

Paulsen, M. R. (1978). Fracture resistance of soybeans to compressive loading. *Transactions of ASAE*, 1210–1216.

Singh, K. K., & Goswami, T. K. (1996). Physical properties of cumin seed. *Journal of Agricultural Engineering Research, 64*, 93–98.

Sreenarayanan, V. V., Subramamian, V., & Visvanathan, R. (1985). Physical and thermal properties of soybean. *Proceedings of Indian Society of Agricultural Engineers, 3*, 161–169.

Suthar, S. H., & Das, S. (1997). Fracture resistance of Karingda (*Citrusllus lanatus* (Thumb) Mansf) seeds to compressive loading. *Journal of Food Engineering, 34*, 77–90.