Relation between mechanical properties and structural changes during osmotic dehydration of pumpkin

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Abstract

This work presents the changes in the mechanical properties of pumpkin (Cucurbita pepo L.) fruits when submitted to osmotic dehydration processes. Cylinders of the parenchymatic tissue were dehydrated with sucrose solutions, varying the concentration (30–60% w/w) and temperature (12–38 °C) of the osmotic solution and process time (0–9 h). As an opposite process to dehydration, water soaking of some cylinders was also performed. Samples were submitted to uniaxial compression until rupture, and four parameters were analyzed: apparent modulus of elasticity, true stress at failure, Hencky strain at failure and failure work (toughness). Values of these mechanical properties for fresh material ranged from 0.96 to 2.53 MPa for apparent modulus of elasticity, 250–630 kPa for failure stress, 0.42–0.71 for failure strain and 85–285 kJ/m³ for toughness. Mechanical properties of osmodehydrated samples showed no dependence on concentration of the osmotic solution and process temperature, whereas they were found to be dependent on moisture content: apparent elastic modulus decreased and failure strain increased during dehydration; toughness and failure stress initially decreased with moisture content, and increased at advanced stages of the process. Water soaked samples showed a decrease in failure strain, failure stress and toughness, but the apparent elastic modulus increased. Simultaneous structural observation during compression showed that the material fails in the contact zones of its fibres. This fact and the observed structural profiles during dehydration could explain the changes in the failure properties (strain, stress, toughness) along the studied processes. Changes in the apparent modulus of elasticity were likely related with the changes in the turgor pressure of cells.

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1. Introduction

Dehydration is a widely used process for the conservation of foods. Water content decrease in the material leads to a decrease in its water activity, making difficult the microbial development. In the last decades there has been an increasing interest by a type of dewatering process called osmotic dehydration. In this treatment, the material is submerged in an osmotic solution of low water activity, allowing the water transfer from the material to the osmotic solution and the transfer of solids from the osmotic solution to the material (Hawkes & Flink, 1978). This process has been used in the dehydration of different types of food materials, such as meat (Gerelt, Ikeuchi, & Suzuki, 2000) and fish (Andrés, Rodríguez-Barona, Barat, & Fito, 2002), but is mostly employed in the dehydration of fruits and vegetables (Raoult-Wack, 1994; Torreggiani, 1993).

Dehydration processes lead to changes in the chemical properties of the material, such as changes in nutritional components (Khraisheh, McMinn, & Magee, 2004), and in some physical properties, like colour (Maskan, 2001), density, porosity (Lozano, Rotstein, & Urbicain, 1983),
and mechanical properties. The changes in the mechanical properties are important because they are related with the textural and sensorial characteristics of the food, and consequently with the quality and acceptance of the product by the consumer. Besides, the knowledge of the mechanical-rheological properties of foods is useful in the design of food processes and equipment (Rao & Quintero, 2005).

The mechanical properties of cellular food materials, such as vegetables and fruits, have been associated with the different levels of structure existing in the material (Waldron, Smith, Parr, Ng, & Parker, 1997). At micro-structural level, some elements can be pointed as relevant to the texture: structure and chemistry of the polymers that make up the plant cell wall, cell wall thickness, turgor pressure of cells and strength and nature of the cell to cell adhesion. At higher structural levels can be cited the structure of the tissue (cellular orientation, quantity of intercellular spaces/porosity), and the different types of tissues or organs that make up the vegetable product.

Several authors have studied the changes in the mechanical properties of food materials during convective drying. In a general way, during drying the soft product (fresh) transforms into a rigid product (dried) or change from a predominantly plastic to a more elastic behaviour, whereas an accentuated viscoelastic behaviour occurs in the intermediate moisture content (Telis, Telis-Romero, & Gabas, 2005). Lewicki and Jakubczyk (2004) found that the decrease in water content during convective drying caused an increase of the force needed to compress apples slices up to a constant deformation of 20%. Krokida, Karathanos, and Maroulis (2000a), during drying of several vegetables (apple, banana carrot and potato), observed a similar behaviour in all the materials during compression tests: failure strain increased during drying, whereas failure stress initially decreased up to a certain moisture content and after that increased up to the end of the dehydration process. The authors attributed this fact to the crystallization of the cellulose cell wall components at that critical moisture content, making difficult the failure of the material.

Lewicki and Wolf (1995) studied the rheological properties of raisins stored at different water activities. They observed that at low water activity (and low moisture content), the rheological properties of raisins changed dramatically and behaved as brittle bodies, more resistant to compression than fresh ones but easily breakable. They suggested that the transition from the rubbery to a glassy state of the concentrated liquid phase (rich in sugars) at low water activities was the cause of this behaviour. Other structural changes affecting the mechanical properties of convective dried products may be the changes in the density and tissue alterations (cell rupture, formation of air cavities) during drying.

Some works can be found in the literature about the mechanical behaviour of foods submitted to osmotic dehydration, when used as a pre-treatment or as a single process. Krokida, Karathanos, and Maroulis (2000b) studied the rheological properties of apple and banana pre-dehydrated with glucose solutions and convective dried. Osmo-convective dried samples presented more resistance to rupture (higher values of failure stress and strain) that convective dried ones, for the same moisture content. The authors suggested that this fact was due to the plasticization of the structure and reduction of the elasticity caused by the sugar uptake during the osmotic pre-treatment. Chiralt et al. (2001) observed a cryoprotectant effect of sucrose on kiwi and mango. Fruits osmotically dehydrated with sucrose solutions and frozen presented more resistance to compression after thawing than the other non-pre-treated frozen samples. In the same work, the authors observed a decrease in the apparent modulus of elasticity (initial slope of the stress-strain compression curve) in osmotically dehydrated kiwifruit and mango, compared with fresh products. Failure stress during compression also decreased for kiwi and mango osmodehydrated samples.

In spite of these works, the literature data on mechanical properties of foods submitted to osmotic dehydration is relatively scarce, and more work with different food products is needed to understand the effect of osmotic dehydration.
on textural characteristics of food materials. These studies can be done after complete equilibration of the structural and compositional profiles in the material (Gerschenson, Rojas, & Marangoni, 2001), or in short time treated and non-equilibrated samples (Chiralt et al., 2001; Del Valle, Aranguiz, & Leon, 1998). The last approach, common when osmotic dehydration is used as a pre-treatment, is important to understand the physical changes that occurs during the process, as well as to evaluate the physical properties of the osmotically treated material, which can be quickly submitted to other treatments such as convective drying (Riva, Campolongo, Leva, Maestrelli, & Torreggiani, 2005), freezing (Tregunno & Goff, 1996) or thermal treatment.

Pumpkin is a seasonal crop that has been traditionally used as human feed. The flesh of the fruit is eaten fresh, or processed in different ways for human consumption, such as fried, frozen, dried, candied or pickled (Teotia, 1992). The development of new processed products based on this fruit can be interesting for the consumers. Specifically, the application of an osmotic treatment on pumpkin fruits may make the vegetable tissue softer and improve its taste, making it more attractive from an organoleptic point of view. Further processing can be also done as commented before.

The aim of this work was to study the changes in the mechanical properties of pumpkin fruits subjected to osmotic dehydration. This study was performed immediately after processing, without storage of samples, in order to assess the effect of the structural profiles formed during dehydration on these properties. For comparison purposes, mechanical properties of pumpkin soaked in water (as an “opposite” process to dehydration) were also studied. The relations between the structure of the vegetable tissue and the mechanical properties were evaluated by observation of the tissue structure in fresh and processed samples before and during the compression tests.

2. Materials and methods

2.1. Material

Pumpkin fruits (Cucurbita pepo L.) were purchased from a local producer, and stored at 15–20°C in a chamber until processing. Pumpkins with similar initial moisture content (95–97 kg water/100 kg product) and soluble solids (2–4 Brix) were selected for the experiments. Cylinders (25 mm length, 15 mm diameter) from the parenchymatic tissue were obtained employing a metallic cork borer and a cutter. These cylinders were used in the different studied processes.

2.2. Processes

Osmotic dehydration experiments were done using sucrose as osmotic agent. Osmotic solutions were prepared with commercial sucrose and distilled water. The levels of sucrose were prepared as osmotic agent. Osmotic solutions were prepared with commercial sucrose and distilled water. The levels of sucrose were

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where $m$, $w$ and $M$ are sample mass, mass of water and moisture content; the subscript 0 refers to fresh material.

For textural measurements, 15–20 cylinders were removed from the stirred vessels, blotted with paper tissue and then they were weighed and dried in a vacuum oven (pressure less than $10^4$ Pa) at 70°C until constant weight, in order to determine their solids content. Normalized moisture content (NMC) (kg water/kg wet product), was obtained by means of Eq. (1)

$$\text{NMC} = \frac{M}{M_0} = \frac{w \cdot m_0}{w_0 \cdot m}$$

(1)

temperature (12–38°C), and sucrose concentration (30–60 kg Sucrose/100 kg Solution) were selected using a Uniform Shell Design (Doehlert, 1970) as outlined in Table 1. The cylinders were put in baskets, which were introduced in stirred vessels containing the osmotic solution. The weight ratio solution to pumpkin cylinders was 20:1, allowing solution to maintain a constant sucrose concentration during the dehydration process. Agitation was produced using a variable speed magnetic stirrer; the speed was varied for each solution so as to have for all of them a constant Reynolds number (c.a. 3000). Thermoregulation was obtained by means of a thermostatic bath (±0.2°C). Two runs were performed for each process condition.

Soaking of pumpkin cylinders was performed in distilled water at 25°C, in the same stirred vessels as those used in the osmotic treatments. Two runs were also performed in this treatment.

2.3. Experimental determinations

At different process times (0, 0.5, 1, 3, 6 and 9 h), four cylinders were removed from the treatment, blotted with paper tissue and then they were weighed and dried in a vacuum oven (pressure less than $10^4$ Pa) at 70°C until constant weight, in order to determine their solids content. Normalized moisture content (NMC) (kg water/kg wet product), was obtained by means of Eq. (1)
in a TA.XT2 texture analyzer (Texture Technologies Corp., USA), with a flat-end cylindrical probe (35 mm diameter). The probe was lubricated to avoid the effects of the plate-sample friction during compression. Compression tests were done at 0.5 mm s\(^{-1}\) deformation rate until 90% of sample deformation. From the force-deformation data, it was possible to calculate Hencky strain (Eq. (2)) and true stress (Eq. (3)) (Calzada & Peleg, 1978).

\[
\varepsilon = \int_{L_0}^{L} \frac{dL}{L} = \ln \frac{L}{L_0} \tag{2}
\]

\[
\sigma = \frac{F}{A(t)} \tag{3}
\]

where \(L\) and \(L_0\) are the height of the cylinder at a time of compression \(t\) and \(t = 0\), respectively, \(F\) is the compression force and \(A(t)\) is the contact area of compression at a time \(t\). Contact area at each time was obtained from the measured diameter of the cylinder before compression and the height at each time, assuming constancy of sample volume during compression.

Apparent modulus of elasticity (\(E_{ap}\)) was calculated from the slope of the initial linear zone (values of Hencky strain less than 0.15, equivalent to 13.9% deformation) of the stress–strain curve. Stress–strain curves show in principle an initiating effect resulting from a non-ideal flat surface of samples, due to the manual incision. This initiating effect corresponded on average to 3% of the failure strain (always lower than 5%) and was considered negligible for the calculation of the mechanical parameters at failure. \(E_{ap}\) was taken from the slope of the curve after this initiating effect (Keetels, Visser, van Vliet, Jurgens, & Walstra, 1996). Failure stress (\(\sigma_F\)) and failure strain (\(\varepsilon_F\)) were determined from the first peak of the stress–strain curve. The work at rupture or toughness (\(W\)), defined as the energy absorbed by the material up to the rupture point per unit of volume of the cylinder, was obtained from the area of the stress–strain curve until the rupture point, as described by Eq. (4):

\[
W = \int_{\varepsilon_0}^{\varepsilon_F} \sigma \cdot \varepsilon \cdot d\varepsilon \tag{4}
\]

Since texture is not uniform among fruits, values of the four parameters presented above were normalized as the ratio between values for treated cylinders and the fresh counterparts (Rodrigues, Cunha, & Hubinger, 2003).

At the same sampling times of the textural measurements, two samples were removed from the stirred vessels for structural observation. One rectangular slab with ca. 1 mm of thickness was gently cut parallel to the major axis of each cylinder and in its middle length with a razor blade (Fig. 1a). The slabs were stained with an aqueous solution of methylene blue 0.1% during 15 s (Mayor, Silva, & Sereno, 2005). Images of fresh and processed samples at different process times were obtained using a stereomicroscope (Olympus SZ-11, Tokyo, Japan). A digital colour video-camera (SONY Exwavehd, Tokyo, Japan) was attached to the microscope and connected to a TV monitor and a personal computer. Image acquisition was done with an interface (PCTV videocard, Pinnacle Systems GmbH, Munich, Germany). Images were calibrated with a stage micrometer of 2 mm length and divisions of 0.01 mm interval (Leitz Wetzlar, Germany). Treatment of the images was carried out using Microsoft Photo Editor 3.0 (Microsoft Corporation) software.

For the simultaneous structural observation/compression tests, two samples were removed from the stirred vessels at the same sampling times of the textural measurements. Samples were cut in the same way as in the textural measurements, but after that another cut was done parallel to the sample height with a depth ca. 20% of the cylinder diameter, as described in Fig. 1c. This modification was done in order to have a flat surface that allows the visualization of the structural changes during compression with a stereomicroscope, hence solving its focal limitations. The flat lateral surface of the sample was stained in the same-way as in the structural analysis.

The experimental set-up shown in Fig. 2 was used for the simultaneous structural observation/compression experiments. A sample (a) was compressed in the texture analyzer (b). During the compression test, a stereomicroscope (c) attached to a video-camera (d) monitored the changes of the tissue structure during the compression. Both texture analyzer and video camera were connected to a personal computer (e), for further combined simultaneous analysis of force, structure images and compression time. Although the force distribution during compression is strictly different between the samples used for compression tests and those used in simultaneous structural observation/compression test, in both cases the shape of curves was the same and the mechanical parameters obtained from the curves were very similar.

From the digital video files some images at selected times were obtained using Microsoft Windows Movie Maker 5.1 software (Microsoft Corporation), and were related with the corresponding force–strain curve.
3. Results and discussion

3.1. Dehydration kinetics

Fig. 3 shows values of normalized moisture content (wet basis), versus time for the studied processes.

For water soaked samples moisture content slightly increases along the process due to the entrance of water into the material. Due to the high initial value of moisture content, the increase after 9 h of water soaking is not high, attaining a value of NMC = 1.005; the samples gained water around 14% of their initial weight to attain this final moisture. The quantity of solids in the material did not show changes, assuming negligible transfer of soluble solids from the material to the surrounding water.

In the osmotic dehydration treatments the behaviour for all the tested conditions is very similar. Initially (up to 3 h), the values of moisture content decreased considerably, due to the combined effect of the removal of water and the gain of sucrose from the osmotic solution. From three to nine hours the water and sucrose fluxes were less fast, and moisture content decreased in a less accentuated way up to the end of the process. Values of normalized moisture content at 9 h ranged from 0.802 (for 30% sucrose, 25°C) to 0.624 (for 52% sucrose, 38°C). Within the osmotic treatments the final values (at 9 h of process) of moisture content decreased with the increase of the concentration of the osmotic solution, for the same process temperature. The higher the concentration the higher the difference between osmotic potential of the material and the osmotic solution, and so the higher the driving force for the process, leading products with lower moisture content; this behaviour has been reported for different materials and different osmotic agents (Hawkes & Flink, 1978; Sereno, Moreira, & Martínez, 2001). For treatments with the same concentration of the osmotic solution, more dehydrated samples at 9 hours of process were obtained with higher temperatures. The increase of temperature enhances water and sugar fluxes (Sereno et al., 2001), obtaining products with lower moisture content comparing with lower temperatures. Diffusivities of the transferring components, metabolic processes and membrane permeability may be influenced by the changes in process temperature.

3.2. Mechanical properties and structure

3.2.1. Fresh material

Fig. 4 shows a typical compression–decompression force–strain curve for fresh pumpkin. Initially, it can be observed a linear force–strain relationship, followed by a nonlinear region where is also observed an increase of force with the strain, up to a critical point (the failure point).
where the force reach a maximum value and starts to decrease. This behaviour has been observed in several vegetables, such as apples (Rebouillat & Peleg, 1988), kiwifruit and strawberries (Chiralt et al., 2001) and potatoes (Luscher, Schlüter, & Knorr, 2005). Fig. 5b shows a photograph of the section of a fresh pumpkin cylinder. It can be observed a fibre oriented structure of the tissue. These fibres are formed by sclerenchymatic cells (more lignified) in the centre and parenchymatic cells around them, constituting a circular arrangement. The sclerenchymatic fibrous centre acts as support of the fruit structure (Raven, Evert, & Eichhorn, 1999). Around this centre, the parenchymatic tissue is compacted with few intercellular spaces; in the limits of the fibre-unit the parenchyma cells are less compacted, with more intercellular spaces and likely with a less efficient middle lamella, delimiting the fibre dimensions.

Previous experiments showed no dependence of the fibre orientation (perpendicular or parallel to the compression axis) on the mechanical properties (apparent elastic modulus, failure stress and strain, toughness), and compression was performed perpendicular to the fibres during all the tests. In Fig. 4, are also shown online-photographs taken during the compression test. Point A corresponds to the linear region of the compression curve, where compression of the intercellular spaces and cells without irreversible changes can be observed. Point B corresponds to the non-linear region before rupture. In this region it is considered that the changes occurring in the material are irreversible; it can be observed the incipient release of water out of the tissue due to compression, probably due to the fracture of cells or coming from intercellular spaces. Although microfractures occurred in the tissue, these were not enough to cause a failure of the structure but the linearity initially observed changes to a curve. In point C water release and compression of fibres were more accentuated. After the failure point (point D), pumpkin tissue failed by the zone of adhesion of the fibres. After compression (point F), the tissue was partially separated in its fibres.

Several factors may influence the values of the mechanical properties, such as density and composition of the material, turgor pressure of cells, cell adhesion and mode of fracture (Waldron et al., 1997). Vegetable tissue can fail in two modes: cell wall rupture and/or cell–cell debonding through the middle lamella (Edwards, 1999), the thin layer composed by pectin polysaccharides which surrounds the cell wall and acts as cement among cells. In the case of pumpkin tissue, these two failure modes can exist, but there is a preferential failure pathway for the rupture: the
connection zones among the fibres of the material. In these zones, parenchymatic tissue is less compacted (Fig. 5b), with more intercellular spaces and likely with a less efficient middle lamella, delimiting the fibre dimensions. It can be said that the failure mode for fresh pumpkin is “fibre debonding”.

For the strain–stress curves, the values of apparent modulus of elasticity, Hencky strain at failure, true stress at failure and toughness were obtained. These values ranged 0.96–2.53 MPa for apparent elastic modulus, 0.42–0.71 for failure strain, 250–630 kPa for failure stress and 83–285 kJ/m³ for toughness in fresh pumpkin. The variability of these values was mainly due to the variability among fruits, since coefficients of variation for these parameters were always less than 15% within the same fruit. Table 2 shows the values of apparent modulus of elasticity, failure stress and failure strain for fresh pumpkin of this work and for other vegetable products found in the literature. Although a strict comparison can not be done because the compression experiments were performed with different conditions in all these works (deformation rate, lubrication), the results are different enough to establish a comparison among these vegetable products. From the values of this table, pumpkin tissue shows an elastic behaviour (high values of elastic modulus) similar to apples and higher than mango and kiwifruit. It also presents a high ability to resist force during compression (high values of failure stress) similar to potatoes but bigger than those showed by apple, mango, kiwifruit and cherry. It can also be considered a deformable product (high values of failure strain).

3.2.2. Osmotically dehydrated samples

As an example of osmotic treatment, Fig. 6a shows the stress–strain curves of pumpkin samples osmotically dehydrated with 60% sucrose solutions at 25 °C. As can be observed, the slope of the initial linear zone of the curves decreases with moisture content, and consequently the apparent modulus of elasticity also decreases. Chiralt et al. (2001) observed a decrease in the apparent modulus after osmotic dehydration with sucrose solutions of kiwifruit, strawberries and mango. In dehydration processes, water loss in the material can lead to the collapse and deformation of the cell walls, the decrease of turgor pressure in the cells and even plasmolysis (Mauro, Tavares, & Menegalli, 2002). Some authors have reported a decrease in turgor pressure with the decrease of the apparent
modulus of elasticity, as observed by Scanlon, Pang, and Biliaderis (1996) during the immersion of potato tissue in mannitol solutions. Others (Lin & Pitt, 1986), during the equilibration of apples and potatoes with the same type of solutions, observed a decrease in initial modulus with increasing turgor when the dominant mode of failure was cell rupture, whereas the trend was reversed in the range where cell debonding was dominant.

Hencky strain at failure increases with the decrease in moisture content. This increase of strain at failure after osmotic dehydration was also observed for kiwifruit (Chiralt et al., 2001) and mango (Torres, Talens, Escriche, & Chiralt, 2006). Failure stress initially decreases during dehydration, but at certain moisture content failure stress starts to increase with the decrease of moisture content until the end of the process.

Fig. 5 shows the structure of fresh, water soaked and osmotically dehydrated (60% sucrose, 25 °C) cylinders at different process times. Initially, the fresh tissue (Fig. 5b) shows a homogeneous and fibre-oriented structure. The high values observed for the apparent initial modulus during compression (Fig. 6a, NMC = 1), can be associated to the natural turgor pressure of the cells. The material fails at a certain stress and strain by the contact zone of its fibres, as observed in Fig. 4.

At 9 h of dehydration process, the structure of the sample has changed considerably (Fig. 5f); the volume has decreased as a consequence of the loss of water, and the delimitation of the fibres is not so clearly observed, likely because they are more compacted. Fig. 6a (NMC = 0.640) shows the compression curve of a sample osmotically dehydrated during 9 h (60% sucrose, 25 °C). It is observed a dramatic decrease of the initial modulus, probably due to the decrease of the turgor pressure in the cells. However, the material shows more ability to resist the failure (failure stress slightly decreases but failure strain increases considerably) compared to fresh material; this fact can be due to the compacting of the fibres during dehydration. At microscopic level, an increase in failure strain and a decrease in initial modulus and failure stress may be an indicative of a prevailing cell-debonding mechanism during failure in the dehydrated samples at 9 h, since a decrease of turgor pressure can reduce the contact area between the cells and consequently intercellular bond strength (Lin & Pitt, 1986).

Between these two situations, a monotonic evolution in the mechanical properties from the fresh to the more dehydrated product should be expected. In Fig. 6a, this behaviour is observed for the apparent elastic modulus (continuous decrease) and failure Hencky strain (continuous increase), but not for failure stress, which shows a
minimum around NMC = 0.82. The existence of different structural profiles in the samples during dehydration can explain this behaviour. It can be observed, along the dehydration process, two zones with different structure in the material: a dehydration front, where dehydration process occurs, which penetrates in the tissue during the treatment; and a solid core, with the same physical, chemical and structural characteristics as the fresh material, which decreases along the osmotic treatment. The advance of the dehydration front and decrease of the solid core can be observed in Fig. 5. For the sample osmotically dehydrated during one hour (Fig. 5c) the dehydration front is observed in the outer region of the cylinder, whereas the solid core is observed in the inner of the sample. At nine hours (Fig. 5f), the material seems to be dehydrated in all the zones and the solid core is practically inexistent. The dehydration front, where the cells have lost their turgor pressure and the fibres are more compacted, probably has similar mechanical characteristics than the material dehydrated at 9 h: lower apparent elastic modulus, similar failure stress and higher failure strain when compared with the fresh material. However, the solid core has the mechanical characteristics of the fresh material: elastic, hard, and brittle.

When a sample showing these structural profiles is submitted to a compression test, initially the dehydration front is compressed, and at a certain strain the solid core starts also to be compressed. Since the soft (low apparent elastic modulus) and deformable dehydration front penetrates in the sample during dehydration, $E_{ap}$ decreases and Hencky strain increases with the decrease in moisture content. The compression, at a certain strain value, attains the solid core, and the material fails in this more brittle zone. Since the solid core decreases during dehydration, the failure stress decreases. The lowest value of failure stress is observed for NMC = 0.82 (55% of the value for fresh material). From this moisture content, the solid core has decreased considerably, the failure properties start to be more influenced by the dehydration front and the material tends to be more similar to the dehydrated samples at 9 h: the failure stress starts to increase up to the end of the process which attains a value of 80% of the value for fresh material.

Fig. 7 shows online photographs taken during the compression test of an osmotically dehydrated (60% sucrose, 25 °C) pumpkin cylinder during 3 h. It was observed an intense release of water during compression, probably...
due to the plasmolysis of cells in the osmotic process, as observed in all the photographs. Initially (point A), a minimal compression force is needed due to the turgor pressure loss. After this (point B), the force increases linearly up to the failure point (immediately before point C). As can be seen (point C), the material fails in the central zone of the cylinder, where the less deformable solid core is found. This failure in the solid core was verified in all the samples that showed structural profiles, at different process times.

No significant influence of solution concentration and process temperature on mechanical parameters was observed, and in a general way the behaviour during dehydration can be explained as a function of the changes in moisture content. The changes of the studied mechanical properties with moisture content, for osmotically dehydrated samples, are shown in Fig. 8. The average variation coefficients were 15%, (ranging 0.5–35%) for apparent elastic modulus, 36% (17–56%) for normalized failure strain, 22% (14–33%) for normalized failure stress and 34% (22–55%) for normalized toughness. This dispersion of data is acceptable considering the high number of replicates; each point is the average of 30–40 samples (two runs each one with 15–20 samples).

Apparent modulus of elasticity decreased with moisture content up to NMC = 0.8, then the modulus attained a residual value and remained practically constant. Failure strain increased with the decrease of moisture content, until three times its initial value at the lowest moisture content achieved (NMC = 0.62). Failure stress and toughness initially decreased with moisture content until a critical moisture content (somewhere between NMC = 0.8–0.85), reaching 50% of their initial values; then increased up to the end of the process until attaining, for NMC = 0.62, the 75% and 90% of the initial value for failure stress and toughness, respectively.

The polynomial equation showed in Eq. (5) was fitted to experimental data on apparent elastic modulus, failure strain, failure stress and toughness and the fitted parameters are presented in Table 3. The selection of the polynomial order was performed by a backward elimination procedure using the statistical software STATISTICA 6.0 (Statsoft Inc., USA). For the apparent elastic modulus (cubic polynomial) was obtained a very good fit, whereas
for failure strain (quadratic), failure stress (cubic) and toughness (quadratic) the fit was less satisfactory

\[
Y = a_0 + a_1(NMC) + a_2(NMC)^2 + \cdots + a_n(NMC)^n
\]  

(5)

Although this equation has no physical meaning, it can be very useful from a practical point of view, if some model is used to relate the process conditions (concentration of the osmotic solution, temperature and time) with the normalized moisture content during dehydration. Then, it will be possible to relate the mechanical properties of the material with the process conditions. The knowledge of the mechanical properties may be important when a treatment after osmotic dehydration is carried out, such as drying or freezing.

3.2.3. Water soaked samples

Fig. 6b shows the typical compression curves for fresh and water-soaked pumpkin cylinders after 9 h soaking, and Fig. 9 shows the average values of the analyzed compression parameters. As can be observed, soaked samples have higher apparent elastic modulus (more accentuated initial slope), and are less hard (lower failure stress) and less deformable (lower failure strain) than fresh samples. Apparent elastic modulus increased 40%, failure strain and failure stress decreased 20% and toughness decreased 30% compared with fresh material.

Fig. 5a shows images of a water soaked cylinder during 9 h. It is observed the swelling of the tissue due to the entrance of water in cells and intercellular spaces. As a consequence, turgor pressure of cells increases, and probably the internal stresses in the tissue. The increase of the apparent elastic modulus in water soaked samples can be attributed to the increase of turgor pressure in cells. It is also observed that the spaces of connection of fibres are more stained, suggesting that the methylene blue solution easily entered among the fibres, as a consequence of the separation among them caused by the uptake of water, resulting in an less compacted structure than in the fresh material. The decrease of failure strain and failure stress can be associated to this separation of fibres.

Fig. 10 shows a compression profile of a water soaked cylinder and online photographs of the compression test. In the initial linear zone of the curve, it is observed the compression of fibres and cells (point A). At higher deformations (points B and C) some water release starts to appear, and after that (between points C and D) it is observed the rupture of the material by the zone of adhesion of the fibres, as in fresh and osmotically dehydrated pumpkin. The rupture pathway is clearly observed in points E and F. All these changes lead to a more elastic, weak and more brittle product compared with fresh tissue.

4. Conclusion

Osmotic dehydration and water soaking produced important changes in the mechanical properties of pumpkin tissue. Fresh tissue was elastic, hard and brittle, but after dehydration the tissue lost its elasticity, keeping its strength but became more deformable. When tissue was soaked in water its elastic behaviour increased, but became less resistant to compression, decreasing failure stress and failure strain.

The mechanical properties seem to be related with different levels of structure. At small deformations, the resistance to compression is controlled by the turgor pressure of cells. The increase in turgor pressure (water soaked samples) led to the increase of the apparent elastic modulus, whereas during osmotic dehydration cellular turgor pressure decreased, and consequently the apparent elastic modulus in pumpkin tissue. At higher deformations, and near of the failure point, the properties were more influenced by the strength of the adhesion among the fibres that compose the pumpkin parenchyma. In water soaked samples the fibres looks like more separated due to the entrance of water in the intercellular spaces; as a consequence the material fails at lower deformation and stress. For low moisture content dehydrated samples the fibres are more compacted and tissue fails at similar stress than fresh material but at higher strain. Next experimental work will be oriented to study the relations.
mechanical properties/structure of osmotically dehydrated samples after equilibration (long time of osmotic treatment or cold storage after dehydration).

Empirical polynomial models were successfully used to relate the changes in the studied mechanical properties with moisture content during osmotic dehydration. Future work is needed to develop more fundamental models relating textural properties with composition and structure of fresh and dehydrated vegetable products.

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