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Journal of Food Engineering 69 (2005) 307–316
JOURNAL OF FOOD ENGINEERING
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Influence of osmotic dehydration conditions on apple air-drying kinetics and their quality characteristics

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Received 24 May 2004; accepted 13 August 2004

Abstract

The influence of different osmotic pre-treatments on apple air-drying kinetics and their physical characteristics during drying were investigated. Apple samples were immersed in glucose or sucrose solutions of 30%, 45% (w/w) at different times. Sugar gain (SG) and water loss (WL) were calculated and an immersion time of 12 h was selected. Samples were further air-dried and the experimental data were fitted successfully using the Page model: $MR = \exp(-kt^n)$. Porosity, compressive fracture stress and colour were measured. Apples osmosed in glucose showed a large moisture decline in the early drying periods and similar drying rates to untreated samples for the same moisture change. Osmosed apples in sucrose showed lower drying rates ascribed to sugars concentration on the outer layers of apple tissue and their crystallization during drying. Samples pre-treated in 45% sugar solutions had greater porosity and better colour retention during drying. In glucose osmosed samples a greater texture hardening rate was observed, in sucrose just the opposite occurred.

Keywords: Apple; Osmosis; Sugar solutions; Air-drying; Physical properties

1. Introduction

Dried fruits are widely used as components in many food formulations such as pastry, confectionery products, ice cream, frozen desserts and yogurt. Among them, dried apples are a significant raw material for many food products.

A widely used unit operation in the dried food process industry is hot air-drying, which could be considered as a simultaneous heat and mass transfer process, accompanied by phase change (Barbanti, Mastrocola, & Severini, 1994).

Fruit drying is a well-known preservation method, mainly because water removal and water activity lowering reduce the risk of microbial development. Moreover, dried fruit can be stored and transported at a relatively low cost. However, water removal using high temperatures and long drying times may cause serious decreases in the nutritive and sensorial values, damaging mainly the flavour, the colour and the nutrients of dried products (Lenart, 1996; Lin, Durance, & Scaman, 1998).

One way of producing dried fruits of good quality is to use a pre-drying treatment, such as osmotic dehydration, able to reduce energy consumption and improve food quality (Torreggiani, 1993; Sereno, Moreira, & Martinez, 2001). Osmotic dehydration, also termed as 'Dewatering and Impregnation Soaking Process' (DISP), is a useful technique for the concentration of fruit and vegetables, realized by placing the solid food, whole or in pieces, in aqueous solutions of sugars or

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doi:10.1016/j.jfoodeng.2004.08.021

Nomenclature

a	redness (CIELab tristimulus colour values)
b	yellowness (CIELab tristimulus colour values)
L	lightness (CIELab tristimulus colour values)
ΔC	colour change during drying time
ΔL	lightness change during drying time
Δa	redness change during drying time
Δb	yellowness change during time
A_0	original area of apple sample (cm^2)
A_t	circular area of apple cylinder at drying time t (cm^2)
F_f	force under compression at fracture point (N)
σ_f	stress at fracture (Pa)
H_0	initial height of the apple tube (mm)
H_t	height of the tube after compression at time t (mm)
M	moisture content at time t (g H_2O/g dry solids)
M_0	initial moisture content (g H_2O/g dry solids)
M_∞	equilibrium moisture content (g H_2O/g dry solids)
MR	moisture ratio
$\Delta M/\Delta T$	drying rate, moisture change versus respective time change (g H_2O/g dry solids · min)
k	drying constant of Page's model $(min^{-1})^n$
n	drying constant of Page's model
t	time (min)
V_b	bulk volume of apples (cm^3)
V_S	solids volume of apples (cm^3)
ε	porosity
SG	sugar gain (g/g fresh product)
WL	water loss (g/g fresh product)
ws_0	weight of solids initially present in the fruit (g/g fresh product in dry basis)
ws_t	weight of the solids in the fruit at the end of the treatment (g/g fresh product in dry basis)
w_t	weight of the fruit at the end of the treatment (g/g fresh product in dry basis)
ww_0	weight of water (g/g fresh product in dry basis)

salts of high osmotic pressure. It gives rise to, at least, two major simultaneous counter-current flows: an important water flow out of the food into the solution and a simultaneous transfer of solute from the solution into the food, that both occur due to the water and solute activity gradients across the cell's membrane (Rault-Wack, 1994; Torreggiani, 1993).

In addition osmotic dehydration is effective at ambient temperature with minimal damaging effect on food quality, achieving product stability, retention of nutrients and improvement of food flavour and texture. It results also in less discoloration of fruits by enzymatic oxidative browning, it satisfies consumers' demand for minimally processed products while additionally facilitates the industrial processes requiring reduced drying times (Kim & Toledo, 1987; Lerici, Pinnavaia, Dalla Rosa, & Bartolucci, 1985; Rault-Wack, 1994; Torreggiani, 1993; Velić, Planinić, Tomas, & Bilić, 2004). However, because it is a time consuming process, supplementary ways to increase the mass transfer are needed without affecting the product quality (Rastogi, Raghavarao, Niranjan, & Knorr, 2002).

Air-drying following osmotic dehydration was proposed for fruits and vegetables by many authors (Ertekin & Cakaloz, 1996; Kim & Toledo, 1987; Lenart & Lewicki, 1988b, 1988a; Lerici, Mastrocolla, & Nicoli, 1988; Lerici, Pinnavaia, Dalla Rosa, & Mastrocola, 1983; Torreggiani, 1993). Especially for apples the use of air-drying after osmotic pre-treatment is referred to Lenart (1996), Monsalve-Gonzalez, Gustavo, Barbosa-Cánovas, and Cavalieri (1993), Nieto, Salvatori, Castro, and Alzamora (1998), Reppa, Mandala, Kostaropoulos, and Saravacos (1999), Sereno et al. (2001) and Simal, Deyá, and Roselló (1997).

Mass transfer during osmosis depends on operating variables such as concentration and solute type of the dehydration solution. Therefore, the solute molecular weight can be a determinant factor influencing solute uptake during osmosis (Monsalve-Gonzalez et al., 1993; Rault-Wack, 1994; Rastogi & Raghavarao, 1995; Rastogi et al., 2002; Saurel, Raoult-Wack, Rios, & Guilbert, 1994).

In recent years there has been increased interest in the investigation of the physical characteristics of fruits, and especially of apples, after osmotic pre-treatment and drying.

Osmotic pre-treatment had a beneficial effect on the firmness of the rehydrated apples that had been air-dried at 50 °C. In addition osmotic dehydration before microwave-assisted air-drying increased the final overall quality of the product, but a negative correlation between apple texture and sugar diffusion was observed by Monsalve-Gonzalez et al. (1993) and Prothon et al. (2001).

Porosity can be related to the degree of water loss and solid gain in osmotic dehydration, to the immersion time during osmosis, to the fruit moisture content or to the microstructure changes of the tissue during drying. Moreover, changes in fruit porosity result in changes of its texture, influencing its firmness (Andrés, Bilbao,

& Fito, 2004; Nieto, Salvatori, Castro, & Alzamora, 2004; Reppa et al., 1999).

The purpose of this work was to study osmotic dehydration in combination with air-drying of apple (Red Delicious) and to evaluate the influence of different osmotic dehydration in relation to the solute type and its concentration in the solution on drying kinetics and physical properties (texture, porosity and colour) of dried apples.

2. Materials and methods

2.1. Materials

Apples, Red Delicious variety, were used as a raw material for osmotic dehydration. Samples were stored at 0 °C and RH 90% for a month. No considerable water loss during this period of storage had been noticed.

2.2. Osmotic dehydration treatment

Samples were cut with a cork borer in a cylindrical shape of 20 mm diameter and 11 mm height. They were weighed and placed into 250 mL beakers, containing the osmotic solutions at a temperature of 40 °C. The rate of mass exchanges increases with temperature, but above 45 °C enzymatic browning and flavour deterioration begin to take place (Torreggiani, 1993).

Two different sugar solutions were chosen: glucose (Merck, Darmstadt, Germany) and sucrose (Serva, Heidelberg, Germany) in two different concentrations: 30% and 45% w/w. The osmotic solutions were prepared by blending the sugar with distilled water on a weight-to-weight basis and the agitation level was chosen in order to make the surface mass transfer resistance negligible. The ratio fruit/syrup was 1.5 by weight, preventing significant alteration of syrup concentration during osmotic drying. The samples were taken out of the osmotic medium at times of 3, 12 and 18 h.

Each time five samples were removed, shaken manually, put on plotting paper to eliminate superficial syrup and weighed.

Water loss WL (g/g fresh product in dry basis), and SG (g/g fresh product in dry basis) were calculated based on the following equations (Giangiacomo, Torreggiani, & Abbo, 1987):

$$\mathrm{WL} = \frac{(\mathrm{ww}_0) - (w_t - \mathrm{ws}_t)}{(\mathrm{ws}_0 + \mathrm{ww}_0)} \times 100 \tag{1}$$

$$\mathrm{SG} = \frac{(\mathrm{ws}_t - \mathrm{ws}_0)}{(\mathrm{ws}_0 + \mathrm{ww}_0)} \times 100 \tag{2}$$

where ww_0 is the weight of water and ws_0 is the weight of solids initially present in the fruit, since w_t and ws_t are the weight of the fruit and the weight of the solids at the end of the treatment, respectively.

2.3. Air-drying experiments and drying kinetics modelling

The apple samples, either osmotically pre-treated or untreated were placed in an air oven at 55 °C with an air velocity of 2 m/s. The weight of the samples during drying was monitored at different time intervals by a precision balance (±0.0001 g). For each measurement four different samples were used. Their moisture content was gravimetrically determined from the sample initial moisture content (after osmosis) by vacuum drying at 70 °C for 48 h. All moisture content values were expressed on a dry basis.

The moisture at equilibrium was measured when the sample weight became constant as a dynamic equilibrium between the sample moisture content and drying air humidity was achieved, after around 8 h of drying.

The drying data were fitted into the Page model (Page, 1949), which is an empirical modification of the simple exponential model. A nonlinear regression procedure was performed by using a mathematical package Microcal™Origin™5.0 (Microcal Software, Inc. USA) and the equation used was as follows:

$$\text{Moisture ratio (MR)} = \frac{M - M_\infty}{M_0 - M_\infty} = \exp(-kt^n) \tag{3}$$

where MR is defined as the ratio of the free water still to be removed at time t to the total free water initially available.

The criteria for characterising the fitting efficiency of the model was the coefficient of multiple determination or the multiple correlation coefficient squared (R^2), the chi-square values (χ^2), and a measure of total variation: the total sum of squares (SST).

$$R^2 = \frac{\sum_{i=1}^{N}(\mathrm{MR}_{\mathrm{pre},i} - \overline{\mathrm{MR}})^2}{\sum_{i-1}^{N}(\mathrm{MR}_{\mathrm{exp},i} - \overline{\mathrm{MR}})^2} \tag{4}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(\mathrm{MR}_{\mathrm{exp},i} - \mathrm{MR}_{\mathrm{pre},i})^2}{N - n} \tag{5}$$

$$\mathrm{SST} = \sum_{i=1}^{N}(\mathrm{MR}_{\mathrm{exp},i} - \overline{\mathrm{MR}})^2 \tag{6}$$

where $\mathrm{MR}_{\mathrm{exp},i}$ stands for the experimental moisture ratio found in any measurement, $\mathrm{MR}_{\mathrm{pre},i}$ is the predicted moisture ratio for each measurement and $\overline{\mathrm{MR}}$ is the mean of all the observations. N and n are the number of observations and the number of constants respectively (Toğrul & Pehlivan, 2003).

2.4. Characteristics measured during drying

At different drying times the following characteristics were measured: the porosity, the fracture stress under

compression and the colour of the samples. Experimental values presented here concerned the first two hours of drying and 5–6 different samples were used for each measurement. For each heating time different samples were also used.

2.5. Porosity

For porosity measurements, samples were taken at different time intervals and the volume of their solids (V_S, cm^3) was measured by a gas pycnometer (Stereopycnometer SPY-3, Quantachrome, Syosset) using helium as a displacement fluid. The bulk volume (V_b, cm^3) was also found from the outside geometric dimensions of the sample, using a micrometer and measuring the diameter of the apple cylinders at three different locations, in the middle and near the opposite edges of the samples. In some cases of a greater shrinkage, the bulk volume was determined by liquid displacement method using water as the displacement medium. A bottle of a known volume with stopper was filled with water and was weighed. A weighed sample was immersed in the bottle resulting in displacing the excess water. From the remained weight, the displaced volume of water was calculated and the bulk volume of the sample was found. Porosity can be described as the ratio between the volume of the pores ($V_b - V_S$) and the total volume of the product (V_b) and it is given by the equation:

$$\varepsilon = 1 - \frac{V_S}{V_b} \tag{7}$$

2.6. Fracture stress

Apple cylinders, treated and untreated were removed from the air-oven at different times intervals (15, 30, 45, 60, 80 and 120 min) and were left to stand 2–3 min for cooling at room temperature. Thereafter they were uniaxially compressed in an Instron Universal Machine (Instron 1011, Massachusetts, USA). A cylindrical probe of 40 mm diameter was used, a cross head speed of 2 mm/min, and samples were deformed to 60% of their original height. The initial dimensions of the apples cylinders were selected so as to avoid any slipping during compression (Khan & Vincent, 1993).

Stress at fracture (σ_f) was determined from the peak force values of the force–deformation curves. The stress at fracture indicates a total failure and macroscopic collapse of apple tissue and it was calculated from the equation:

$$\sigma_f = \frac{F_f}{A_t} \tag{8}$$

where A_t is equal to $A_t = A_0H_0/H_t$ assuming that apples are incompressible. H_t/H_0 is also known as apparent or Cauchy strain.

The assumption of incompressibility is not completely right for dried samples with a more rubbery texture, especially at greater heating times, where shrinkage was also more evident. However, differences between true and apparent volume were found to be small and it was considered that the volume of all samples remained constant during compression. Furthermore data are comparable and errors in calculations of strain are repeated in all samples.

Since texture was not uniform among fruits, fracture stress values were normalized as the ratio between values for treated samples to their fresh counterparts (σ_f) and their ratio was calculated for each drying time.

2.7. Colour

The colour of apples was measured using a Minolta tristimulus colorimeter (Minolta, CR-200, Tokyo, Japan) and L (lightness), a (redness), and b (yellowness) parameters were calculated.

Samples were placed vertically and measurements were made directly on the top (upper) surface, which was always steady, of cylindrical samples. A standard white colour was used as a reference.

Total colour difference was calculated according to Hunter (1975) as:

$$\Delta C = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \tag{9}$$

This was calculated using the treated or untreated apple before the drying process as the source of L_0, a_0 and b_0.

2.8. Statistical analysis

Statistical analysis was performed using the Statgraphics Statistical Graphics System, Version 2.1 (Statgraphics, Rockville, MD, USA). Fisher's LSD was used to determine significant differences between samples. A p-value of less than 0.05 was considered significant.

3. Results and discussion

3.1. Osmotic dehydration

The water loss, WL (a) and sugar gain, SG (b) of apple samples, as a function of the time immersed in two different concentrations of glucose and sucrose solutions at 40 °C, is presented in Fig. 1.

The sugar gain in glucose solutions was higher than in sucrose at both concentrations (30% w/w and 45% w/w). This occurred, because low molar mass sugars, such as glucose, favour the sugar uptake. Due to the high velocity of penetration of the molecules, a solid

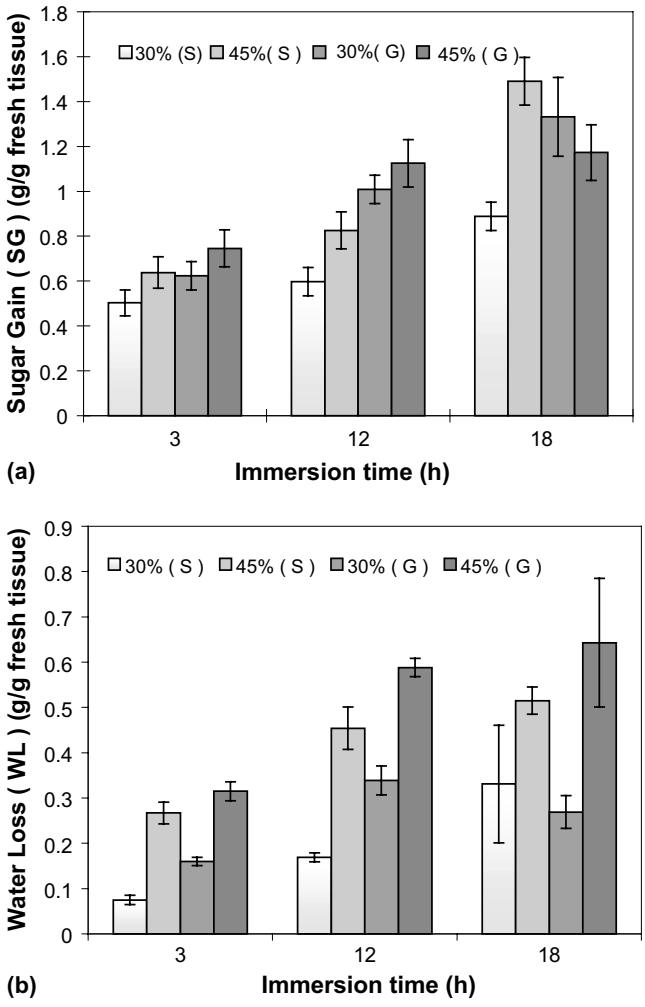

Fig. 1. Sugar gain (a) and water loss (b) as a function of immersion time in sucrose (S) and glucose (G) solutions in two concentrations (30% w/w, 45% w/w). Temperature of solutions: 40 °C.

enrichment instead of dehydration occurred as the main effect of the process (Torreggiani, 1993). However, as the glucose solution concentration increased, the osmotic pressure in the apple also increased. This resulted in a higher water mobility followed by cell dehydration (Reppa et al., 1999). According to literature data (Lenart & Lewicki, 1990; Marcotte, Toupin, & Le Maguer, 1991) the WL and SG increase with sugar solute concentration and immersion time. At low immersion time (3 h) WL was relatively low, because osmotic dehydration was not completed. This was especially evident in samples immersed in 30% sucrose solution (Fig. 1(b)). On the other hand at high immersion times (18 h), WL and SG were high. However, this immersion time was considered as inappropriate for further experiments for two reasons: (a) in samples immersed in sucrose solution a macroscopic cell rupture was observed due to the high size of macromoleculates penetrating and causing cell tissue destruction (b) in some cases, glucose (G) 30%, WL was reduced, or SG was very high (sucrose (S) 45%). This may influence negatively the drying time and rate during further air-drying. Therefore, the time of 12 h was considered more appropriate for the osmotic dehydration process.

3.2. Drying kinetics

After dehydration the moisture content of osmosed samples was 20–55% of that of the untreated samples. The samples immersed in glucose or sucrose of 30% (w/w) had greater moisture content values. For comparison reasons the dimensionless moisture content (MR) was calculated, and its change during drying is presented (Fig. 2). In this figure the experimental data and the mathematical modelling of the drying kinetics experimental data using Eq. (1) for fresh and osmosed apple samples immersed at two different sugars and concentrations are also shown.

The physical and chemical changes in apple samples during osmosis caused differences in moisture change during air-drying compared with the fresh samples. Fresh samples showed a rapid moisture ratio (MR) decline. However, at higher moisture content in the initial stages of drying, osmosed samples showed also a rapid moisture decrease. Specifically, samples osmosed in glucose solutions independently of the concentration used, showed a fast moisture decline the first $1\frac{1}{2}$h, than that of untreated samples, but after this time the rate of moisture change decreased. Apples osmosed in sucrose also showed a rapid moisture reduction initially (around the first 40–50 min), close to that of the control samples, but thereafter a considerably lower moisture decrease was noticed.

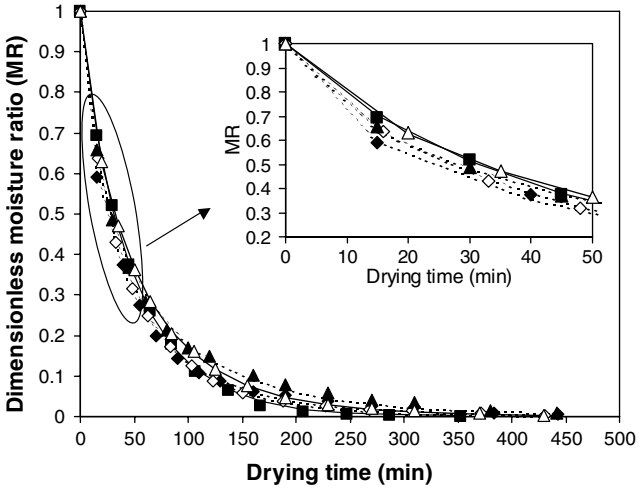

Fig. 2. Drying curves of osmotically dehydrated apples in (▲) sucrose (S) and (♦) glucose (G) solutions (40 °C, 12 h immersion time), and of (■) untreated apple samples. Open symbols: sugar concentration: 30% w/w, close symbols: 45% w/w. Lines: predicted curves using Page model/solid line: fresh sample.

From the above observations, it is clear that the increased internal resistance to mass transfer during drying due to the solute uptake in the osmotic process noticed by Rahman and Lamb (1991) and Nieto et al. (1998) was not observed in the early stages of drying for osmosed samples, but only after a certain time. Perhaps, it was the free water that was removed during the first drying period, resulting in similar behaviour to the untreated samples. Free water here could be a part of the water excluded from the plasmalemma of the cells due to the osmosis process remaining near the surface outside of the cells. According to Andrés et al. (2004) free water has probably a higher diffusion coefficient value compared with the water included in the tissue cells, inducing a higher drying rate.

Samples osmosed in sucrose, especially those pretreated in 45% solution, showed a greater mass transfer resistance during air-drying from the beginning of drying. According to the osmosis results, samples immersed in 45% sucrose solution had a great dehydration efficiency index (WL/SG), indicating a high efficiency of water removal with minimal sugar uptake. Therefore a considerable amount of water was already removed during osmosis and a further water removal during drying was more difficult. Furthermore sugar surface impregnation during osmosis favours sugar crystallization in some parts of the outer layers of apple tissue during drying (Prothon et al., 2001; Rault-Wack, 1994). This fact resulted in water transfering hindered and was especially evident in higher molar mass sugars (here sucrose), causing a lower moisture decline after a short drying period.

Table 1 shows Page's parameters for the above samples. Page's equation gives a very good fit to the experimental data, as expected, better than that of the simple model (data not shown here). Therefore it was considered more appropriate for further interpretation. The parameter k represents the water diffusion velocity in the material (El-Aouar, Azoubel, & Murr, 2003) and the higher its value, the higher the moisture ratio change during time. However, this is not true in cases when n values of the model differ. Combining the two values, untreated samples presented the steeper moisture ratio descent during time, followed by samples osmosed in low sugar concentrations. As mentioned above, the samples osmosed in high sucrose concentration had the lowest moisture ratio change during drying.

Table 1
Page's equation parameters for drying kinetics of fresh and osmosed samples

Treatment	k (×10) $(1/\text{min})^n$	n	R^2	χ^2 (×10^4)	SST (×10^4)
Untreated	0.29^a	0.92^a	0.9996	0.40	4.42
Osmosed samples					
G30%	0.50^c	0.80^b	0.9998	0.32	4.14
G45%	0.75^e	0.71^c	0.9987	1.05	13.6
S30%	0.39^b	0.83^b	0.9999	0.10	1.35
S45%	0.66^d	0.71^c	0.9982	1.55	2.02

G: glucose.
S: sucrose.
Samples in same column with different letter differ significantly at $p < 0.05$.

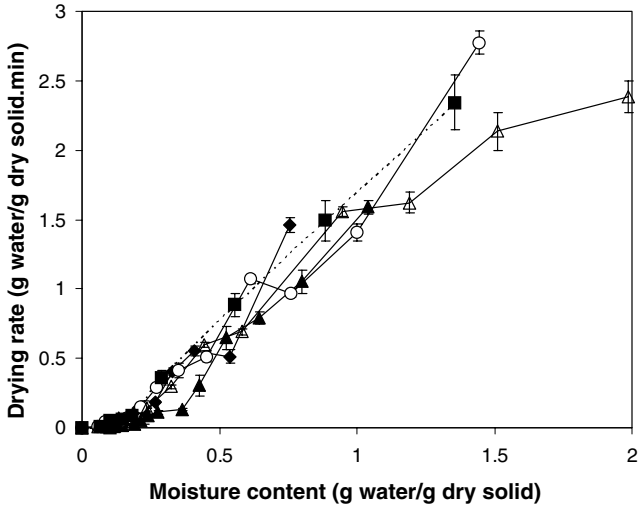

Fig. 3. Drying rate ($\Delta M/\Delta T$) of osmotically dehydrated and untreated apple samples as a function of moisture content during air-drying. Dashed line: fresh sample. Symbols as in Fig. 2.

In all samples the drying rate was higher, as was expected, at higher sample moisture content (Fig. 3), but even the fresh samples did not show an initial constant drying rate period at the beginning of air-drying (data not shown here for clarity reasons in comparisons with osmosed samples). This behaviour is typical in case of fruits (Babalis & Belessiotis, 2004) and it was also observed in papaya (El-Aouar et al., 2003) and in apricots (Toğrul & Pehlivan, 2003). This suggests that diffusion is the dominant physical mechanism governing moisture movement. Untreated samples and samples immersed in glucose followed similar drying rate/moisture content curves. After the first falling drying rate period observed in Fig. 3, a second slower one started at a moisture content around 0.18 g/g dry solid for these samples. In samples pre-treated in 45% sucrose, a change in drying rate was observed at greater moisture content, i.e. 0.36 g/g dry solid. After this value, these samples showed also the lowest drying rate.

3.3. Physical characteristics of apples during drying

Fresh apples had porosity values in the range of 0.25–0.33 with an average value of 0.29. At the beginning of the drying all samples except those osmosed in 45% glucose presented low porosity (ε) values mainly because the vacuum spaces were filled with sugars (Fig. 4). Water loss resulted in vacuum space increase in plant tissue and the porosity increased during air-drying. Additionally

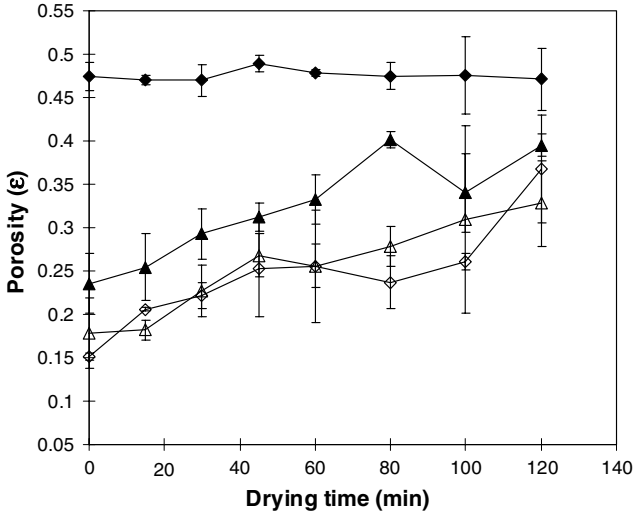

Fig. 4. Porosity versus drying time of osmotically treated apple samples in sucrose and glucose solutions. Symbols as detailed in Fig. 2.

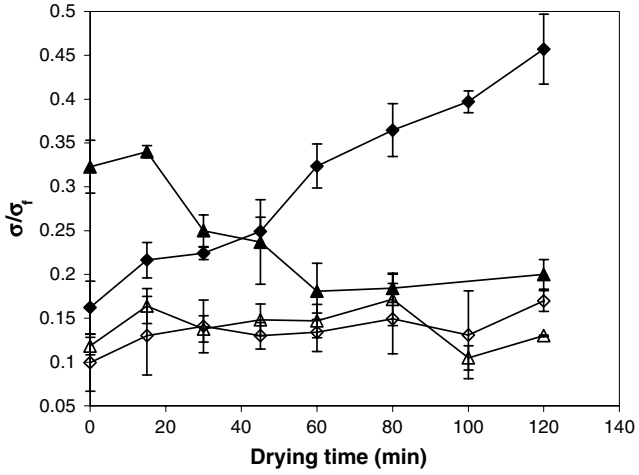

Fig. 5. Stress ratio (treated/fresh) at fracture point versus drying time of osmotically treated apple samples in sucrose and glucose solutions. Symbols as detailed in Fig. 2.

the porosity of the osmosed samples and especially of those that have been immersed in sucrose solutions increased during air-drying, with the increase of sucrose concentration. At higher concentrations, a higher WL was observed during osmosis. At the same time the samples gained sugars, but WL was greater than the sugar gain (Reppa et al., 1999). Due to this fact, sugars were not able to cover the vacuum spaces. Furthermore, higher porosity values during drying can be attributed to the higher viscosity of tissue matrix as the air-drying process was extended and the corresponding absence of collapse (Lozano, Rotstein, & Urbicain, 1983). Porosity of osmosed samples immersed in 30% sucrose solution was higher than that pre-treated in 30% of glucose solution due to the space that plasmolysis created during osmosis (Marcotte & Le Maguer, 1991).

The fracture stress of osmosed samples in comparison to that of fresh ones during air-drying is presented in Fig. 5. Osmosed samples were considerably softer that untreated samples. For example the fracture stress in 30% sugar pre-treated samples was 10% of that of fresh samples. The loss of cell turgor and the degradation of the middle lamellae during osmosis could result in this softening (Poovaiah, 1986). After drying all the samples had semi-chewy characteristics indicating a rubbery texture.

During air-drying the fracture stress of samples immersed in glucose 45% at 40 °C increased. The increased solids content of these samples, which can crystallize during heating, in combination with the water loss during drying led to this great texture hardening rate. Osmosed samples in both glucose and sucrose of 30% had a low fracture stress, which was almost constant during drying. Samples immersed in sucrose of 30% had lower SG and WL than the respective samples immersed in glucose. As these samples lose more water during drying, one would expect to observe greater fracture stress values during drying, closer to those of the control samples. However, these samples had low porosity (Fig. 4). Since SG was not so high for assuming that the vacuum spaces were filled with sugars, one can conclude that a more severe shrinkage than that of the respective samples immersed in glucose took place. According to the volume measurements before and after 2 h of drying the volume reduction of samples osmosed in 30% sucrose was 45% and 30% that of the samples immersed in glucose. Shrinkage can cause internal stresses that can disrupt cell walls, create cavities and result in general loosening of the tissue structure, which can reduce significantly the resistance to compression in apples (Lewicki & Jakubczyk, 2004). This indicates that these samples were influenced severely by the drying process resulting in a soft texture similar to that of the respective glucose osmosed samples. Furthermore, as was noted above, the cell tissue of samples immersed in sucrose was more damaged that that in glucose during osmosis.

Finally, samples pre-treated in 45% sucrose solution had also a high SG during osmosis resulting in greater firmness initially. However, during drying a large porosity increase was observed (Fig. 4) resulting in texture softening.

Hunter "L", "a" and "b" values of apples after osmosis and air-drying are given in Table 2. After air-drying "L"-values were higher in osmosed samples than in untreated samples (significant differences at $p < 0.05$). This increase in "L" values indicated a slight lightening in colour. The 45% sucrose osmosed samples showed a higher "L" value representing less darkening compared to all other osmosed samples, which had similar "L" values after air-drying.

The colour parameter "a" increased in osmosed samples during air-drying (significant differences in most cases at $p < 0.05$) but it remained in the greenness ($-a$)

Table 2
Colour parameters of fresh apples and samples after osmosis or air-drying process

Treatment	L	a	b
Untreated (raw)	81.93 (0.88)^{ab}	−4.73 (0.95)^{a}	22.65 (1.43)^{a}
Untreated air-dried (8 h)	68.99 (2.99)^{e}	5.68 (1.75)^{d}	27.20 (1.50)^{b}
Osmosed samples			
G30%	75.58 (0.68)^{d}	−4.75 (0.19)^{a}	22.80 (0.76)^{a}
G45%	79.65 (2.32)^{c}	−4.94 (1.33)^{a}	26.65 (2.74)^{b}
S30%	74.80 (1.17)^{d}	−5.04 (0.50)^{a}	23.98 (1.57)^{a}
S45%	79.22 (1.44)^{c}	−4.29 (0.48)^{ab}	24.19 (1.21)^{a}
Osmosed and air-dried samples			
G30%	79.59 (2.06)^{c}	−2.21 (1.41)^{c}	33.79 (2.61)^{c}
G45%	80.38 (1.80)^{bc}	−2.20 (0.96)^{c}	34.84 (2.76)^{c}
S30%	79.31 (0.60)^{c}	−1.82 (0.68)^{c}	38.10 (1.87)^{d}
S45%	82.16 (0.94)^{a}	−3.41 (0.59)^{b}	34.62 (1.34)^{c}

Standard deviation values in parentheses.
Samples in same column with different letter differ significantly at $p < 0.05$.

area. On the other hand, the untreated samples were in the redness (+a) area after drying. Furthermore, the "b" values were significantly ($p < 0.05$) higher in osmosed than in non-osmosed samples.

Sugar impregnation seemed to maintain lightness, resulting in a final product close to that of the fresh fruit. Generally, as is well known, the colour parameters "L" and "a" are well correlated to colour changes in fruit tissues (darkening) due to enzymatic browning (Mastrocola & Lerici, 1991). As browning increases, "L"-values decrease and "a" values increase. The increase in redness and yellowness was clear and seemed to be a result of solids uptake during osmosis pre-treatment.

The colour difference (ΔC) was higher for untreated samples compared to the osmosed samples during air-drying (Fig. 6). This occurred due to the solute uptake, which resulted in lower O_2 being transferred to the surface. All these resulted in less discoloration of the osmosed samples by enzymatic browning (Kim, 1990). Moreover, the use of low temperature (55 °C) during air-drying was justified by the great co-action of temperature on reactions Maillard of surface sugars.

The greatest changes in ΔC of osmosed samples in 45% sugar solutions occurred during the first two hours of air-drying because of non enzymatic browning and then the ΔC remained practically unchanged. These samples had lower moisture content after osmosis and this could inhibit the oxidant enzymes action. In these latter samples the ΔC was lower, in contrast with samples that were treated in 30% sucrose solution and had greater ΔC. Osmosed samples in 45% glucose solution were found to be slightly better than those that were pre-treated in 45% sucrose solution in colour retention during drying.

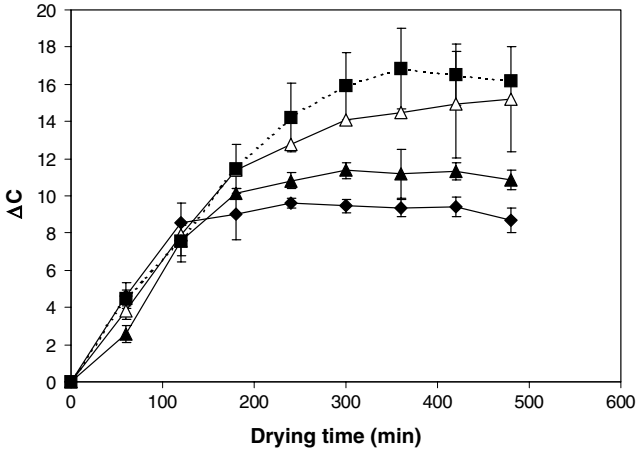

Fig. 6. Colour change versus drying time of fresh and osmotically treated apple samples in sucrose and glucose solutions. Symbols as detailed in Fig. 2. Dashed line: fresh samples.

4. Conclusions

The SG and WL values of osmosed apples depended on immersion time, sugar concentration and sugar type. Greater dehydration efficiency index (WL/SG) was observed in osmosed samples immersed in high concentration sugars. During drying, osmosed samples presented a major moisture decline during the initial period of drying, but at greater times a moisture ratio decrease was noticed. However, drying rate for the same moisture change was similar in untreated and samples osmosed in glucose solutions. Drying kinetics could be well fitted by using the Page equation, but interpretation of the constants obtained should be made with caution.

Samples osmosed in 45% glucose showed the greatest porosity value and the greatest firmness increase during drying, since samples of lower sugar concentration had both reduced porosity and firmness values. Firmness increase could be ascribed in the high total solids amount of these samples. A relative high moisture loss rate during drying contributed to their crystallization and consequently to hardening. However, other factors such as the extent of tissue destruction in both osmosis and drying could influence firmness values.

All osmosed samples had improved lightness "L' and relatively low "a" values because browning was considerably hindered during drying. Osmosed samples in 45% glucose solution showed the greatest colour retention during drying.

In conclusion, samples osmosed in high sugar concentration had better physical characteristics than those treated at lower concentrations. Among them, osmosed samples in glucose had even better characteristics and additionally had a higher drying rate. The only disadvantage of these samples was the firmness increase during drying. However, after two hours of drying, fracture stress was less than the 50% of that of the fresh samples.

Acknowledgement

The authors gratefully acknowledge Prof. Kostaropoulos for technical advice and suggestions.

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