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INFLUENCE OF DRYING METHOD ON KINETICS AND REHYDRATION CAPACITY OF APRICOT AND APPLE

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ABSTRACT

This study aims to determine the influence of microwave application on air drying of apricot and apple in terms of the rehydration rate and capacity of dried samples. The microwave power level was 0.4 W/g for apricot and 0.5 W/g for apple samples. Furthermore, the effect of air temperature (50 and 30 ºC) and vacuum impregnation pre-treatment (with a commercial isotonic juice) was examined. The sample mass change, water gain and soluble solids loss, was obtained before sample rehydration (in distilled water at 20 ºC for 8 h). Peleg's model was used to assess the effect of process conditions on rehydration kinetics, with a good fitting of experimental data. Taking into account the lower $k_{1(i)}$ *and*

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$k_{2(i)}$ values, the vacuum impregnation pre-treatment and microwave application to air drying allow us to obtain a dried product with a better rehydration capacity, promoting the rate and capacity of water gain and solute loss, although the structure of product remains with a lower liquid phase retention capacity. A less relevant influence of air temperature on water gain kinetics was observed, improving the rehydration ratio only for non vacuum impregnated samples.

PRACTICAL APPLICATIONS

Dehydration is widely applied to food preservation in stable and safe conditions. Dried and rehydrated fruits are key ingredients in pastries, dairy products, breakfast cereals, dietetics and traditional foods. Rehydration product behavior must be known when a total or partial reconstitution is required. This work provides information on the influence of microwave assisted air drying method and vacuum impregnation pre-treatment on the rehydration capacity and kinetic analysis of dried apricot and apple. The study aims to determine the appropriate drying conditions to ensure that the properties of rehydrated foods are in accordance with the requirements in further processing and consumer expectations.

KEYWORDS

Dried fruit, rehydration ratio, Peleg’s model, rehydration index, retention capacity, air drying, microwave drying.

NOMENCLATURE

AD	Air drying
$k_{1(i)}$	Peleg's constant 1 (h g^{-1}) relative to component *i*. Kinetic rate parameter
$k_{2(i)}$	Peleg's constant 2 (g^{-1}) relative to component *i*. Parameter associated to maximum mass change capacity
LPRC	Liquid phase retention capacity, equal to WRC+SRC (g/g dry matter)
M	Sample mass (g)
m	Rehydrating solution mass (g)
m_{LP}	Liquid phase weight after rehydrated sample centrifugation (g)
MWAD	Microwave-assisted air drying
RR	Rehydration ratio (g rehydrated sample/ g dehydrated sample)
SRC	Solute retention capacity (g/g dry matter)
t	time (h)
VI	Vacuum impregnation
WRC	Water retention capacity (g/g dry matter)
x_i	Mass fraction relative to component *i* expressed in wet basis (g/g sample)
y_s	Soluble solids mass fraction in the rehydrating solution (g /g solution)
z_s	Soluble solids mass fraction in the sample liquid phase, equal to ºBrix/100 (g /g liquid phase)
ΔM	Global sample mass change, equal to $\Delta M_w+\Delta M_s$ (g)
ΔM_i	Sample mass change (g) relative to component *i*
Δm_i	Rehydration solution mass change (g) relative to component *i*
ΔL_i	Rehydration losses during sample handling (g) relative to component *i*

$\Delta m_{(S+RS)}$	Difference between the sample plus rehydration solution mass in two successive controls (g)

Superscripts

f for raw fruit, *o* for dried sample (initial reference composition when rehydration time equals zero), *rh* for rehydrated sample, *t* at rehydration time t, *e* at equilibrium state.

Subscript

i= *w* (water) or *i*= *s* (soluble solids)

INTRODUCTION

Dried fruits are widely consumed as dehydrated products (powders or snacks) or as semi-moist ingredients in prepared foods and may also be rehydrated for other purposes. The advantage of dried fruits is that they are versatile foods and are available year-round. They also have longer preservation times than fresh fruit and are easier to consume. However, depending on their distinct uses, a previous rehydration step is sometimes required.

The rehydration process and quality of rehydrated fruits is highly dependent on structural and compositional changes occurred in plant tissues and cells during processing. It is generally accepted that the degree of rehydration is dependent on the degree of cellular and structural disruption (Cunningham *et al*. 2008). Rehydration is a complex process which aims to restore fresh product properties when the dried material is in contact with the rehydration solution. Pre-drying treatments, subsequent drying and rehydration *per se* induce many changes in structure and composition of plant tissue and thus result in impaired reconstitution properties (Lewicki 1998). Hence, rehydration can be considered as a measure of the degree of alterations to the material caused by drying and pre-dehydration treatments.

Several authors suggest applying pre-treatments such as vacuum impregnation and/or osmotic dehydration prior to drying in order to help preserve colour and texture (Alvarez *et al*. 1995; Contreras *et al*. 2007; Contreras *et al*. 2008). A combined air-microwave drying technique is useful to shorten drying times and to improve the final quality of the dried products (Feng and Tang 1998; Gunasekaran 1999; Xu *et al*. 2004; Zhang and Xu 2003; Lewicki 2006; Contreras *et al*. 2008).

However, little has been published regarding the effect of this drying method on the sample rehydration behavior. In this context, rehydration capacity and kinetic analysis are crucial parameters to be considered when selecting the best drying conditions. The aim of this research was to determine how drying technology (convective air drying or microwave-air drying) and sample pre-treatment by vacuum impregnation affect the rehydration characteristics of dried apricot and apple samples.

MATERIALS AND METHODS

Raw Material

Fruits were purchased in a local market. The apricots (var. Galta Roja) were 0.87±0.02 g water/g sample, 0.097±0.003 g soluble solids/g sample and water activity: 0.983±0.003 and the apples (var. Granny Smith) were 0.86±0.02 g water/g sample, 0.121±0.004 g soluble solids/g sample and water activity: 0.991±0.004. The reported water content value was measured by vacuum drying at 60 ºC to constant weight (AOAC 1980); soluble solids were measured with a refractometer (ABBE ATAGO 89553 of Zeiss) at 20 ºC; water activity was determined at 25-30 ºC using a dew point hygrometer (Decagón, CX-1, sensitivity 0.001).

Sample Preparation

Apricots were cut longitudinally into two halves, each apple was cut perpendicular to the axis and three central slices (7 mm thick) were obtained; they were not peeled, but the core was taken out with a cylindrical core borer (20 mm in diameter). Apple experiments were carried out using fresh and vacuum-impregnated (VI) samples. The VI samples were prepared by immersing the slices in a commercial isotonic apple juice whose water activity was the same as fresh apple and then applying vacuum to reduce the pressure to 50 mbar for 5 min. The atmospheric pressure was then restored and the apple samples were kept in the same solution for 10 additional minutes. The water content, soluble solids content, water activity and sample weights were measured after the vacuum impregnation pre-treatment. Vacuum impregnation of apple with the isotonic solution did not significantly change these properties ($P>0.05$). Nevertheless, the presence of liquid phase instead of air in the pores of the structure occurred because of vacuum impregnation, seems to favor the generation of an additional compact cell matrix during drying, enhancing the mechanical resistance of dried samples (Contreras et al. 2008). This could be related with a different behavior of the samples during rehydration.

Drying Treatments

The samples of apricots, pre-treated apples and untreated apples were subjected to air drying and microwave-assisted air drying (MWAS), using a modified household microwave oven, so that air temperature, air velocity and microwave power could be controlled (Contreras *et al*. 2008). The microwave power level (0.4 W/g for apricot and 0.5 W/g for both apple samples), determined with an intelligent energy controller (IEC-test), was selected to prevent the sample from burning during drying. The air temperature (50 ºC) was chosen to favor the rate process while protecting the samples from heat damage. However, as notable thermal damage was observed in the VI samples dried with MWAD (VI-MWAD), a second lower temperature, 30 ºC, was also used in apple experiments. The process conditions employed and the sample codes assigned are summarized in Table 1. Air velocity was kept at a constant value of 2.5 m/s inside the oven and relative humidity ranged between 35-45 %. Samples were dried till the moisture content reached 10 % (w.b), which was controlled by continuously monitoring the sample weight (recorded at 3 min intervals) and taking into account the initial moisture content. Each drying treatment was repeated three times.

Rehydration Experiments

Dehydrated samples obtained from each drying experiments were rehydrated by immersion in distilled water at 20 ºC for 8 h. Sample:water ratio was 1:7 and 1:12 (w/w) for apricot and apple, respectively. This ratio was established ensuring the maximal amount of water that ensures enough sensitivity in the measurements of compositional changes (ºBrix) of the solution during process. To obtain the sample mass change (Eq. 1 to 6), at the different times (between 0 and 480 min), the weight of the samples was controlled as well as the ºBrix of the rehydrating solution (Giraldo *et al.* 2006). The global mass change, ΔM, was indicated as ΔM_w plus ΔM_s.

$$\Delta M_w = \Delta m_w - \Delta L_w \qquad (1)$$

$$\Delta M_s = \Delta m_s - \Delta L_s \qquad (2)$$

$$\Delta m_w = \frac{m^t * (1 - y_s^t) - m^o}{M^f} \qquad (3)$$

$$\Delta L_w = \sum_{t=0}^{t} \frac{\Delta m_{(S+RS)}^t * (1 - y_s^t)}{M^f} \qquad (4)$$

$$\Delta m_s = \frac{m^t * y_s^t - m^o}{M^f} \qquad (5)$$

$$\Delta L_s = \sum_{t=0}^{t} \frac{\Delta m_{(S+RS)}^t * y_s^t}{M^f} \qquad (6)$$

Modelling Data and Rehydration Indexes

The model proposed by Peleg (1988) was used to fit the mass changes obtained. It is an empirical model with two parameters, initially developed to describe curves that approach equilibrium asymptotically (Kowalska *et al*. 2008). Peleg's equation can be applied to model the sample mass change (Eq. 7) throughout rehydration time (Giraldo *et al*. 2006). If the time of rehydration is long enough ($t \rightarrow \infty$), the equilibrium mass change is given by $1/k_{2(i)}$.

$$\Delta M_i^t = \Delta M_i^o + \frac{t}{k_{1(i)} + k_{2(i)} * t} \qquad (7)$$

The rehydration ratio was considered as a simple index to compare rehydration capacity. The RR defines the ratio between the weight of rehydrated samples at the end of process and that of the dehydrated samples (Lewicki 1998; Giri and Prasad 2007). Additionally, the samples were centrifuged (10 min at 4000 rpm) to obtain the liquid phase weight not retained by the sample as well as the soluble solid mass fraction. Then water retention capacity (Eq. 8) and solute retention capacity (Eq. 9) were both calculated. These retention capacity indexes refer to initial fresh samples. The liquid phase retention capacity was considered as WRC plus SRC.

$$\mathrm{WRC} = \frac{M^{rh} * x_w^{\;rh} - m_{LP} * (1 - z_s)}{M^f * (1 - x_w^{\;f})} \tag{8}$$

$$\mathrm{SRC} = \frac{M^{rh} * x_s^{\;rh} - m_{LP} * z_s}{M^f * (1 - x_w^{\;f})} \tag{9}$$

Analyses of variance (ANOVA) were done using Statgraphics Plus software version 5.1 to evaluate the effects of process variables on the measured parameters.

RESULTS AND DISCUSSION

During the rehydration process, the samples recovered the “identity” of the fresh raw material without any fruit pieces disintegrating into the rehydrating solution. Figure 1 shows, as a case in point, the water and solutes mass variation curves for dried apple samples obtained under certain process conditions. Similar behavior was observed for the other testing conditions. All samples showed an initial increase in water absorption followed by a decrease in the rehydration rate (decline in curve’s slope). This asymptotic behavior is related to the decrease in driving force for water transfer as rehydration progresses and the system is close to equilibrium (Moreira *et al.* 2008). The solute loss follows the inverse trend, indicating that during rehydration, together with water intake, soluble compounds may be leached to the external water. Total mass changes throughout the rehydration process are illustrated for all the studied samples in Fig. 2.

Mass balances were verified by comparing experimental weight gain with the water gain and solute loss as provided by the mass balance equations. A close fit was obtained in all cases between experimental and predicted values, which validate the procedure used during experimental work. Peleg's equation can be expressed in a linearized form and the water gain or the soluble solids loss data may be plotted in a $t/(\Delta M_i^t - \Delta M_i^o)$ *versus* t plot to obtain the respective $k_{1(i)}$ and $k_{2(i)}$ parameters. The estimated parameters from the linear regression analysis are presented as a function of drying conditions in Table 2. The determination coefficients were in all cases found to be very high ($R^2 \geq 0.990$). The low root mean square deviation values (Table 2) confirm the goodness of the fit between the experimental data and predicted values, as shown in Fig. 1 and Fig. 2.

The porous structure of apple tissue may be affected by the partial substitution of the air occluded in the intercellular spaces by the external isotonic solution during the VI pre-treatment, despite the non significant samples compositional changes. In this sense, the VI effect was also considered on the apple rehydration behavior together with those of temperature and microwave. Only the microwave effect was considered for apricot samples. As deduced from Eq. (7), the water absorption rate and the solute loss rate are inversely related to the respective $k_{1(i)}$ values, and likewise, the water absorption capacity and the solute loss capacity are inversely related to the $k_{2(i)}$ values. Therefore, results shown in Table 2 indicate that VI promotes the water absorption rate and water absorption capacity but it also promotes the solute loss rate and solute loss capacity. No significant effect of air drying temperature was observed except for the water absorption rate of non VI samples. In this case, the higher the drying temperature, the lower the rates for water absorption. Additionally, all air-dried samples showed higher water absorption capacity at higher air temperatures. When microwaves were applied during air drying, the values obtained for kinetic constants showed that the water absorption rate and water absorption capacity were higher for MWAD samples. From this point of view, the effect of microwave application to drying process was similar to that of VI. The solute loss rate and solute loss capacity were both accelerated by microwave application on apricot samples. Moreover, the lower $k_{1(w)}$ and $k_{1(s)}$ values indicate the faster water absorption and solute loss rate in apple samples when compared to apricot.

Table 2 shows as well the real proportion of ΔM^e achieved (see Fig. 2) at the end of the rehydration process (t = 8 h). These ratio values were over 87 % and between 48-60 % for apple and apricot samples, respectively. Thus, rehydrated apricot was far from the equilibrium state and a longer rehydration time will be required to increase the water absorption although the complete rehydration may never be achieved.

Considering the $k_{2(w)}$ values obtained, the RR values (Table 3) were significantly ($P<0.05$) higher for VI and MWAD samples. On the other hand, these samples showed significantly lower WRC and LPRC. Nevertheless, the microwave effect on SRC was not significant ($P>0.05$). These indexes were not affected by the air drying temperature. In order to compare the behavior of rehydrated samples with the raw material, the WRC and SRC were also measured using fresh apple. The values for WRC were 5.1±0.3 g/g d.m. and for SRC, 0.824±0.012 g/g d.m. As expected, rehydration capacity indexes for all rehydrated samples decrease significantly due to the structural changes induced by pre-drying and thermal treatments. In fact, taking into account the ΔM, both the VI pre-treatment and microwave application during air-drying increase the rate and capacity of mass change during the rehydration process but decrease the retention capacity of the liquid phase. The VI influence may be explained by the structural damage from pressure changes during the vacuum impregnation step. Apparently, the intercellular spaces of the VI samples would tolerate a longer liquid phase during the rehydration, the samples having a higher value for the final total mass variation than for the non pre-treated samples. On the other hand, the rapid water evaporation and the higher temperature reached in the sample during air-microwave drying create a porous structure with less shrinkage than those obtained by air drying (Bilbao *et al.* 2005; Giri and Prasad 2007), thereby providing better rehydration characteristics. In this sense the water incorporation is improved, but this porous structure has a lower capacity to retain the incorporated liquid.

CONCLUSION

Peleg's model is an adequate tool to predict the rehydration behavior of dried apple and apricot. Microwave application to air-drying process and the optional vacuum impregnation step allow us to obtain a dried product with a faster and better rehydration capacity. Nevertheless, a lower liquid phase retention capacity and a greater quantity of solids leached under these conditions occur. Rehydration rate of VI samples was not affected by air drying temperature. Nevertheless, the higher the air temperature during drying, the lower the water absorption rate of non vacuum impregnated samples. Convective dried samples increased its water absorption capacity when air temperature was increased.

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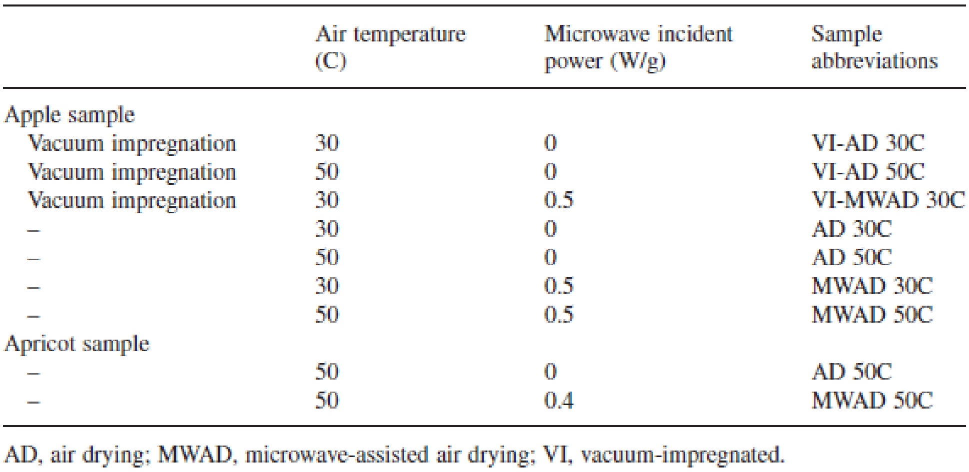
TABLE CAPTIONS

TABLE 1.

PROCESS CONDITIONS AND ASSIGNED SAMPLE'S ABBREVIATIONS ACCORDING TO DRYING METHOD



	Air temperature (C)	Microwave incident power (W/g)	Sample abbreviations
Apple sample			
Vacuum impregnation	30	0	VI-AD 30C
Vacuum impregnation	50	0	VI-AD 50C
Vacuum impregnation	30	0.5	VI-MWAD 30C
–	30	0	AD 30C
–	50	0	AD 50C
–	30	0.5	MWAD 30C
–	50	0.5	MWAD 50C
Apricot sample			
–	50	0	AD 50C
–	50	0.4	MWAD 50C

AD, air drying; MWAD, microwave-assisted air drying; VI, vacuum-impregnated.

TABLE 2.

PELEG'S EQUATION PARAMETERS, ROOT MEAN SQUARE DEVIATION (RMSD) AND PROPORTION OF EQUILIBRIUM MASS CHANGE (EMC) REACHED AT THE END OF REHYDRATION PROCESS

	Water gain		Soluble solids loss		RMSD$^{(1)}$	EMC$^{(2)}$
	$k_{1(w)}$ (h g^{-1})	$k_{2(w)}$ (g^{-1})	$\lvert k_1\rvert_{(s)}$ (h g^{-1})	$\lvert k_2\rvert_{(s)}$ (g^{-1})		(%)
Apple sample						
VI-AD 30ºC	1.16 ±0.09^{b}	1.72 ±0.03^{b}	3.8 ±0.5^{ab}	10.2 ±0.3^{a}	0.0019	95 ±5
VI-AD 50ºC	1.19 ±0.07^{b}	1.52 ±0.06^{a}	4.0 ±0.2^{b}	10.1 ±0.2^{a}	0.0016	93 ±5
VI-MWAD 30ºC	0.99 ±0.03^{a}	1.54 ±0.02^{a}	3.2 ±0.3^{a}	10.17 ±0.05^{a}	0.0029	92 ±4
AD 30ºC	1.39 ±0.04$^{c\ d}$	1.91 ±0.07^{d}	6.0 ±0.3^{c}	10.9 ±0.2^{c}	0.0017	87 ±4
AD 50ºC	1.51 ±0.04^{e}	1.71 ±0.02^{b}	5.9 ±0.4^{c}	10.6 ±0.3$^{b\ c}$	0.0033	91 ±5
MWAD 30ºC	1.28 ±0.03^{c}	1.65 ±0.03^{c}	5.5 ±0.3^{c}	10.7 ±0.3$^{b\ c}$	0.0028	91 ±5
MWAD 50ºC	1.41 ±0.05^{d}	1.67 ±0.02^{c}	5.52 ±0.05^{c}	10.2 ±0.4$^{a\ b}$	0.0027	87 ±4
Apricot samples						
AD 50 ºC	3.11 ±0.12^{b}	2.05 ±0.07^{b}	38.3 ±1.8^{b}	10.73 ±0.58^{b}	0.0019	48 ±2
MWAD 50 ºC	2.57 ±0.07^{a}	1.93 ±0.04^{a}	25.75 ±1.22^{a}	8.6 ±0.4^{a}	0.0022	60 ±3

Means in the same column with the identical letter are not significantly different (P>0.05)

$^{(1)}$ $\mathrm{RMSD} = \frac{1}{z}\sqrt{\sum_{i=1}^{z}\left(\Delta M^{t}_{\exp,i} - \Delta M^{t}_{\mathrm{pre},i}\right)^{2}}$ where $\Delta M^{t}_{\exp,i}$ is the *i*th experimental sample mass change at each control time; $\Delta M^{t}_{\mathrm{pre},i}$ is the *i*th predicted sample mass change at that time and z is the number of observations. Corresponds to the higher value, among replicates, for each drying treatment

(2) $\mathrm{EMC}=\frac{\Delta M_{(8\,h)}}{\Delta M^{e}}$

TABLE 3.

REHYDRATION RATIO (RR), WATER RETENTION CAPACITY (WRC), SOLUTE RETENTION CAPACITY (SRC) AND LIQUID PHASE RETENTION CAPACITY (LPRC) VALUES FOR THE DIFFERENT SAMPLES

	RR	WRC	SRC	LPRC
	(g/g)	(g/g dry matter.)		
Apple sample				
VI-AD 30ºC	4.11 ±0.18 ^{bc}	1.92 ±0.09 ^{b}	0.097 ±0.002 ^{ab}	2.02 ±0.09 ^{b}
VI-AD 50ºC	4.32 ±0.09 ^{c}	1.93 ±0.04 ^{b}	0.099 ±0.002 ^{b}	2.04 ±0.07 ^{b}
VI-MWAD 30ºC	4.54 ±0.08 ^{d}	1.59 ±0.10 ^{a}	0.094 ±0.003 ^{a}	1.68 ±0.08 ^{a}
AD 30ºC	3.7 ±0.12 ^{a}	2.51 ±0.16 ^{d}	0.112 ±0.003 ^{c}	2.62 ±0.10 ^{d}
AD 50ºC	4.1 ±0.06 ^{b}	2.43 ±0.05 ^{d}	0.111 ±0.002 ^{c}	2.54 ±0.12 ^{d}
MWAD 30ºC	4.34 ±0.08 ^{c}	2.19 ±0.08 ^{c}	0.106 ±0.004 ^{c}	2.32 ±0.08 ^{c}
MWAD 50ºC	4.51 ±0.09 ^{d}	2.16 ±0.09 ^{c}	0.108 ±0.004 ^{c}	2.26 ±0.09 ^{c}
Apricot sample				
AD 50ºC	4.08 ±0.12 ^{a}	1.54 ±0.08 ^{b}	0.14 ±0.003 ^{a}	1.66 ±0.08 ^{b}
MWAD 50ºC	4.44 ±0.15 ^{b}	1.25 ±0.06 ^{a}	0.12 ±0.002 ^{a}	1.36 ±0.04 ^{a}

Means in the same column with the identical letter are not significantly different (P>0.05)

FIG. 1. EXPERIMENTAL WATER MASS CHANGE AND SOLUBLE SOLIDS MASS CHANGE IN APPLE SAMPLES DRIED AT 30 ºC AS A FUNCTION OF REHYDRATION TIME (FULL SYMBOLS = AIR DRIED SAMPLES; HOLLOW SYMBOLS = MICROWAVE-AIR DRIED SAMPLES). THE POSITIVE AND NEGATIVE TRENDS REFLECT WATER GAIN AND SOLUBLE SOLIDS LOSS, RESPECTIVELY. THE DASHED LINE INDICATES THE PREDICTED CURVES.

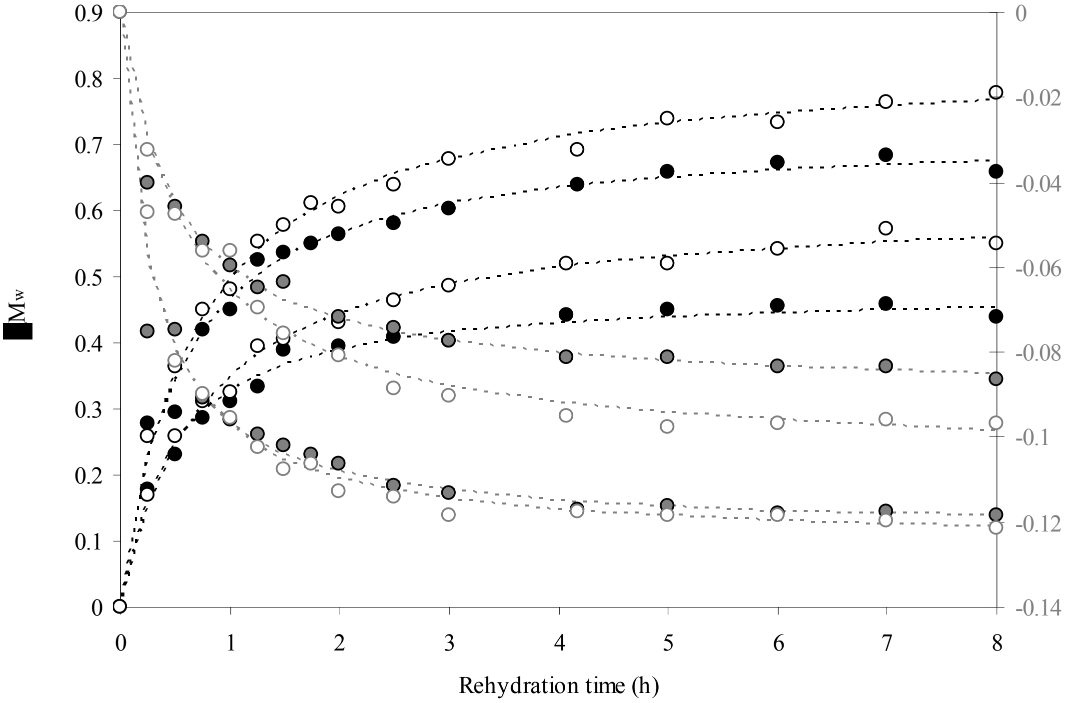


FIG. 2. EXPERIMENTAL GLOBAL MASS CHANGE DATA (INDICATED BY GEOMETRIC SYMBOLS) AND PREDICTED REHYDRATION CURVES (INDICATED BY SOLID LINES). FULL SYMBOLS ARE AIR DRIED SAMPLES AND HOLLOW SYMBOLS ARE MICROWAVE-AIR DRIED SAMPLES. THE INNER TABLE CONTAINS THE EQUILIBRIUM MASS CHANGE.