

# Moisture migration in a cereal composite food at high water activity: Effects of initial porosity and fat content

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Received 18 March 2005; received in revised form 1 July 2005; accepted 12 August 2005

## Abstract

Water sorption isotherms and effective moisture diffusivities were determined at 20 °C for sponge cakes at high water activity as a function of their initial porosity, in the range 86 and 52% (0 g/g dry basis fat content), and of their fat content, ranging between 0 and 0.30 g/g dry basis (67% initial porosity). The equilibrium moisture values were not affected by food structure and decreased with increasing fat content. The effective moisture diffusivity decreased from 7.5 to  $0.3 \times 10^{-10}$  m<sup>2</sup>/s with increasing moisture content from 0.30 to 2.20 g/g dry basis. Decreasing initial porosity from 86 to 52% decreased effective moisture diffusivity by more than four orders of magnitude. This behaviour was related to differences of water transfer mechanisms, with the contribution from liquid water diffusion in the solid matrix and from vapour water diffusion in pores. Increasing fat content of 0.30 g/g dry basis in sponge cake, independently of porosity, decreased effective moisture diffusivity by more than five orders of magnitude. A predictive mathematical model was used to simulate moisture intake in two-composite food systems: sponge cakes with varying initial porosities and fat contents and an agar gel as a model of a non-rate limiting water source. Increasing the density of the structure or addition of fat in the cereal-based phase could increase shelf life of composite foods.

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**Keywords:** Moisture migration; Sorption isotherm; Moisture diffusivity; Composite food

## 1. Introduction

The increasing consumer demand for high quality ready-to-eat foods with long shelf lives has initiated the development of

*Abbreviations:*  $a_w$ , water activity;  $\alpha$ ,  $\gamma$ ,  $r$ , parameters of the Ferro Fontan model for moisture sorption isotherm; d.b., dry basis;  $d_{\text{apparent}}$ , apparent density (kg of dry matter/m<sup>3</sup> of total material including air);  $d_{\text{true}}$ , true density (kg of dry matter/m<sup>3</sup> of total material excluding air);  $D_{\text{eff}}$ , effective moisture diffusivity (m<sup>2</sup>/s);  $D_0$ , empirical parameter of the effective moisture diffusivity law (m<sup>2</sup>/s);  $\varepsilon$ , porosity;  $n$ , empirical parameter of the effective diffusivity law;  $N$ , number of measurements for the determination of the RMSE;  $\rho_{\text{toluene}}$ , density of the toluene (kg/m<sup>3</sup>);  $p$ , number of estimated model parameters for the determination of the RMSE; RMSE, root mean square error (g/g dry basis); SC, sponge cake;  $V$ , volume (m<sup>3</sup>);  $V_p$ , volume of the pycnometer (m<sup>3</sup>); w.b., wet basis;  $W$ , Weight (kg);  $W_p$ , weight of the pycnometer (kg);  $W_{\text{total}}$ , weight of the pycnometer plus the sample and the toluene (kg);  $X$ , moisture content (g/g dry basis);  $y$ , simulated moisture content (g/g dry basis);  $y_{\text{exp}}$ , experimental moisture content (g/g dry basis).

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numerous composite foods, which consist of compartments of various textures, e.g. a sponge cake with a cream filling. Moisture migration is an important problem in these composite systems, where at least two phases with different water activity ( $a_w$ ) are adjacent. Water diffuses from the 'wet' phase to the 'dry' phase leading to irreversible changes in the organoleptic and microbiological quality of the composite food, and to a reduction of its shelf life (Labuza and Hyman, 1998; Le Meste et al., 2002). The investigation and the modelling of the equilibrium and dynamic water properties, i.e. water sorption isotherm and water migration, in each food material involved in a composite system is of great interest in the design of composite foods from an organoleptic and nutritional point of view. Models describing the relationship between water activity and moisture diffusivity in foods with respect to moisture content and/or temperature have been proposed by Guillard et al. (2003b) to allow modelling of moisture transfer in a composite food consisting of fresh filling and a cereal-based food.

Water sorption isotherms are quite easily determined using standard methods, with equilibrium attained under saturated

salts solutions (Bell and Labuza, 2000). They are also modelled successfully in the high water activity range by the Ferro Fontan equation (Baucour and Daudin, 2000; Guillard et al., 2003a; Iglesias and Chirife, 1995). Moisture sorption isotherms of composite foods represent the integrated hygroscopic properties of the individual components. Consequently, any modification in chemical composition of the food material may influence its sorption equilibrium properties irrespective of any structural modification, e.g. pore size and pore distribution (Iglesias and Chirife, 1982). Some authors have developed approaches to predict the water activity of multicomponent food systems from their initial chemical compositions (Caurie, 2005; Ross, 1975).

Unlike water sorption equilibrium, moisture migration is quite difficult to characterize in food products and numerous experimental methods are used for its determination (Zogzas et al., 1994). Water migration in food products is the consequence of a number of coexisting moisture transport mechanisms, enhanced by the complexity of the food structure (e.g. porosity) and its composition (e.g. interaction of water with the food constituents). Molecular diffusion is however the main water transport mechanism and to predict the water transfer in food materials diffusion models based on Fick's second law are used. An apparent moisture diffusion coefficient, the effective moisture diffusivity ( $D_{\text{eff}}$ ), is used to describe the overall moisture transport phenomena in the food system studied. The sensitivity of effective moisture diffusivity to water content has been widely studied (Zogzas et al., 1996). Studies have shown that effective diffusivity increases with moisture content in corn based extruded pasta (Andrieu et al., 1988), bread, biscuits and muffins (Tong and Lund, 1990) and in sponge cake (Lostie et al., 2002a,b). In porous starch mixtures and industrial sponge cakes. Karathanos et al. (1990), Marousis et al. (1989, 1991) and Guillard et al. (2003a) reported that effective moisture diffusivity increased with moisture content up to a limit value and then decreased and eventually became constant at high moisture contents. However, the differences between the results of these studies indicated that the relationship between effective diffusivity and moisture content is not well established and that moisture content is probably not the only parameter influencing effective moisture diffusivity in porous cereal foods.

Several authors have pointed out that the effective diffusivity values in cereal-based products are strongly affected by the physical structure of the product, due to the contribution of water vapour diffusion in the open-pores of the product and liquid water diffusion in the solid matrix. As liquid water diffusivity is  $10^{-4}$  orders of magnitude lower than water vapour diffusivity (Gekas, 1992), the global diffusion coefficient is enhanced by increases in porosity as observed in starch gels (Marousis et al., 1991), pasta (Waananen and Okos, 1994; Xiong et al., 1991) and in cakes (Baik and Marcotte, 2002). In addition, porosity is affected by the water content of cereal-based foods. An increase in moisture content leads to a swelling of the components and, consequently, to a decrease in porosity of the material (Guillard et al., 2003a).

The effective moisture diffusion coefficient is also affected by the fat content of food products. Palumbo et al. (1977) observed that the effective moisture diffusivity of sausages decreased slightly from  $5.7$  to  $4.7 \times 10^{-11}$  m<sup>2</sup>/s, respectively, for fat contents of 13.3 and 25.1%. Similar results were found in avocado (Alzamora and Chirife, 1980) and in an agar gel containing fat (Biquet and Guilbert, 1986). Fat, dispersed into the food material, hinders the migration of water in the solid matrix of the product, thus decreasing the effective moisture diffusivity.

The objective of the present study was to investigate the influence of initial porosity and fat content of sponge cakes on the moisture sorption equilibrium and effective moisture diffusivity in the high moisture content range ( $a_w > 0.7$ ). The composite food systems studied were sponge cakes of varying initial porosity and fat content, and an agar gel, as a model for a non-rate limiting water source. Water sorption isotherms were constructed using a controlled atmosphere microbalance by the conventional saturated salts method. Effective moisture diffusivities were calculated from a mathematical model predicting moisture transfer using experimental moisture content profiles. The impact of initial porosity and fat content in the composite foods was then evaluated from a predictive model of moisture migration and using the previously determined parameters.

## 2. Materials and methods

### 2.1. Sponge cake

Laboratory prepared sponge cake (SC) was chosen as a relevant porous cereal food of high  $a_w$ . The ingredients were: flour (flour T-45, Moulin de Sauret, Montpellier, France), sugar (Beghin Say, Thumeries, France), whole egg powder (Igreca, Seiches-sur-le-Loir, France), vegetable fat (OK 35; solid fat content at 20 °C: 82%; SIO, Saint-Laurent-Blangy, France), water and salt. Several formulations were prepared to vary the structure and/or the fat content. The formulations are listed in Table 1. The sponge cakes were prepared from a premix with whole egg powder, water and sugar warmed at 50 °C and then beaten at high speed in a Kenwood mixer (Model KM800). The beating time varied from 0 to 50 min to give sponge cakes with different densities (SC1, SC2 and SC3). Flour and salt were then incorporated into the batter at low speed and varying amounts of melted fat were added by substitution of the other ingredients to obtain sponge cakes with fat contents of 0.11 and 0.30 g/g dry basis (d.b.) (respectively, SC4 and SC5). Baking powder (3% of the total weight of the batter) was added to obtain homogeneous porosity. After moulding (moulds of 24 cm in diameter and 5 cm high) and cooking in an electrical oven for 20 min at a temperature of 180 °C, the cakes were allowed to cool at 20 °C for 1 h. They were packed in water-impermeable, polyvinylidene chloride bags (Avenir Complexage Service, St-Varent, France) and frozen at -18 °C for long-term storage (4–6 months). Before the experiments, the cakes were slowly thawed to 5 °C and kept for 7 days at 5 °C to allow

Table 1  
Composition, process parameter and characteristics of the investigated sponge cakes

		SC1	SC2	SC3	SC4	SC5
Composition (% of wet batter)	Flour	30.5	30.5	30.5	28.1	23.2
	Sugar	30.5	30.5	30.5	28.1	23.2
	Egg powder	12.2	12.2	12.2	11.2	9.2
	Water	26.4	26.4	26.4	24.3	20.1
	Vegetal fat	0	0	0	8	24
	Salt	0.4	0.4	0.4	0.3	0.3
Process parameter	Beating time (min)	0	25	50	50	50
Initial water activity and content	$a_w$	0.86	0.86	0.86	0.88	0.87
	$X$ (g/g d.b.)	0.37	0.37	0.37	0.28	0.22
Structure properties	Density (kg/m <sup>3</sup> d.b.)	625 [±9]	314 [±11]	190 [±4]	344 [±36]	343 [±9]
	Porosity (%)	52 [±5]	67 [±2]	86 [±2]	68 [±4]	65 [±3]
Fat content (g/g d.b.)		0	0	0	0.11	0.30

Numbers in brackets are the 95% confidence intervals on parameters.

moisture redistribution. The initial  $a_w$  of the sponge cake was  $0.86 \pm 0.02$ .

## 2.2. Agar gel

The agar solution was prepared by adding 3 g agar powder to 97 g water with vigorous stirring, and heating on a water bath at 1 h at 100 °C. Sodium azide (0.4 g) was then added to the solution to limit microbial growth. Cylindrical agar gel samples were prepared by pouring the warm liquid solution into plastic tubes (27 mm diam., 50 mm long). The gels were stored at 20 °C in a controlled humidity jar over pure water. The initial  $a_w$  of the agar gel was  $0.999 \pm 0.001$ .

## 2.3. Sponge cake structure characterization

### 2.3.1. True density

The true density of the sponge cakes ( $d_{\text{true}}$ ) was calculated as the ratio of the weight of the dry matter to the corresponding volume of the total material, excluding air ( $V$ ). This volume was estimated by toluene displacement in a 25 ml pycnometer. The volume ( $V_p$ ) of the pycnometer was determined using distilled water at ambient temperature. Samples of sponge cake were pre-equilibrated at 0% relative humidity in a jar containing silica gel. Six replicates of each sponge cake were prepared. Each sample was weighed precisely and transferred into a half filled pycnometer. The liquid level was then carefully adjusted with toluene. The solid volume of sponge cake samples was calculated using the following formula

$$V = V_p - \frac{W_{\text{total}} - W_p - W}{\rho_{\text{toluene}}} \quad (1)$$

where  $V_p$  and  $W_p$  are, respectively, the volume (m<sup>3</sup>) and the weight (kg) of the pycnometer,  $V$  and  $W$  the volume (m<sup>3</sup>) and the weight (kg) of the sponge cake sample,  $W_{\text{total}}$  the weight of the pycnometer plus the sample and toluene (kg) and  $\rho_{\text{toluene}}$  the density of the toluene (kg/m<sup>3</sup>).

### 2.3.2. Apparent density

The apparent density of the sponge cakes ( $d_{\text{apparent}}$ ) was calculated from the ratio of the weight of dry matter (determined by drying in an oven at 103 °C for 24 h) to the corresponding volume of total material including air (determined by measuring the height and diameter of the cylinders of sponge cakes with a micrometer vernier). The apparent density was expressed in kilogram of dry matter per cubic meter of product. Five replicates were performed.

### 2.3.3. Initial porosity

The initial porosity of the sponge cakes ( $\varepsilon$ ) was calculated using the following equation

$$\varepsilon = \left(1 - \frac{d_{\text{apparent}}}{d_{\text{true}}}\right) \times 100 \quad (2)$$

where  $d_{\text{apparent}}$  is the apparent density (kg of dry matter/m<sup>3</sup> of total material including air) and  $d_{\text{true}}$  the true density of the sponge cakes (kg of dry matter/m<sup>3</sup> of total material excluding air).

Initial porosity values for the different sponge cakes are presented in Table 1. Sponge cakes with initial porosity ranges falling into three groups, SC3 > SC2 ≈ SC4 ≈ SC5 > SC1, were investigated.

## 2.4. Sorption isotherm

### 2.4.1. Experimental determination

The experimental water sorption isotherm of the sponge cakes was determined at 20 °C over the range  $0.70 < a_w < 0.95$  using a controlled atmosphere microbalance (Dynamic Vapour Sorption (DVS) apparatus; Surface Measurement System Ltd, London, UK). The measurement of water sorption isotherm for cereal-based products using the DVS apparatus was thoroughly described by Roman-Gutierrez et al. (2002). Samples of average weight 0.5 g were pre-equilibrated at 0% relative humidity in a controlled relative

humidity jar containing P<sub>2</sub>O<sub>5</sub> for 7 days and then loaded into the microbalance and equilibrated at the respective relative humidities. For each kind of sponge cake, three adsorption experiments were conducted. These data for  $a_w > 0.90$  were obtained using the conventional method based on equilibrium over standard saturated salt solutions (Iglesias and Chirife, 1982). Five samples of 1 g of sponge cake were placed into tightly closed jars over pure water to adjust their water activity to 1. Sodium azide solution (400 ppm) was sprayed on the surface of the samples to inhibit microbial development. After allowing one month to reach equilibrium, the water content of sponge cakes was determined by weighing before and after complete desiccation (24 h at 103 °C). The experimental water sorption isotherms were plotted from the equilibrium moisture contents for each water activity.

#### 2.4.2. Modelling the sorption isotherm

The Ferro Fontan equation (Eq. (3)) was used to model the sorption isotherm curve

$$X = \left[ \frac{1}{\alpha} \ln \left( \frac{\gamma}{a_w} \right) \right]^{-1/r} \quad (3)$$

where  $X$  is the moisture content (g/g d.b.),  $a_w$  the water activity and  $\alpha$ ,  $\gamma$  and  $r$  are empirical parameters. The model for sorption isotherm was simulated using Matlab<sup>®</sup> software (The Mathworks, Inc., Natick, MA, USA) and the equation parameters identified using the Levenberg–Marquardt method (Gill et al., 1981), by minimizing the root mean square of the deviations between simulated and experimental results. To estimate the quality of the simulation fitting, the root mean square error (RMSE) was calculated as follows

$$\text{RMSE} = \sqrt{\frac{(y - y_{\text{exp}})^2}{(N - p)}} \quad (4)$$

where  $y$  and  $y_{\text{exp}}$  are, respectively, the simulated and the experimental moisture content (g/g d.b.),  $N$  is the number of moisture content measurements and  $p$  the number of estimated model parameters.

### 2.5. Effective moisture diffusivity

#### 2.5.1. Migration experiments

The two-component food was composed of a cylinder of agar gel and a cylinder of sponge cake, taken from the centre of the cake after removal of the crust. The cylindrical compartments were placed in contact in a hermetically sealed, glass diffusion cell described by Guillard et al. (2003b). The system was kept at constant temperature ( $20 \pm 0.1$  °C) for 1, 6, 20 and 30 days. The sponge cake compartment was placed above the agar gel compartment to avoid gravimetric moisture transfer. Experimental moisture content profiles were obtained by slicing each compartment into 2 mm thick discs, using an adapted microtome for the purpose (Sercom, Montpellier, France). Moisture content of each slice was determined by

weighing before and after complete desiccation (24 h at 103 °C).

#### 2.5.2. Modelling the moisture diffusivity profiles

The effective moisture diffusivity values in the sponge cakes were determined by adjusting simulated moisture distribution profiles to experimental profiles using the Levenberg–Marquardt optimisation procedure previously described. Moisture content profiles as a function of time were predicted for a two-component food using the model described by Guillard et al. (2003b) and developed with Matlab<sup>®</sup> software (The Mathworks, Inc., Natick, MA, USA). This model is based on a numerical solution of Fick's second law. The model assumes that the food system is composed of two finite plane sheets placed side by side, the wet compartment is non-rate limiting and at the interface between wet and dry compartments, water activity equilibrium is reached instantaneously. Initial parameters for simulations are, for each compartment, the three parameters of Ferro Fontan model for sorption isotherm, the effective moisture diffusivity, initial moisture content and density. These parameters are given in the literature for agar gels (Guillard et al., 2003b) and were evaluated for all the sponge cake formulations. The effective moisture diffusivity variations with moisture content were modelled using the empirical equation

$$D_{\text{eff}}(X) = D_0 \times X^n \quad (5)$$

where  $D_{\text{eff}}(X)$  is the effective moisture diffusivity (m<sup>2</sup>/s),  $X$  is the moisture content (g/g d.b.) and  $D_0$  (m<sup>2</sup>/s) and  $n$  are empirical parameters.

The parameters of the effective diffusivity law were identified by minimizing the root mean square of the deviations between predicted and experimental moisture contents. In order to estimate the quality of the simulation fitting, the root mean square error (RMSE) was calculated.

### 2.6. Moisture migration simulations

Moisture transfer in a two-component food was simulated using the mathematical model described in Section 2.5.2. The simulated composite food consisted of sponge cake with varying porosity and/or fat content in contact with contact with an agar gel with  $a_w$  of, respectively, 0.85 and 0.99. The moisture intake in the sponge cake compartment was predicted and water activity as a function of time was plotted according to the sorption isotherm models. Moisture transfer in sponge cakes with two initial porosity values, 67% (SC2) and 52% (SC1), and two amounts of fat, 0 (SC2) and 0.30 g/g d.b. (SC5) was simulated using the evaluated parameters in this study.

### 2.7. Presentation of the moisture distribution profiles

Although the moisture contents and parameters in Eq. (3), Eq. (5) and in the mathematical model were in g/g dry basis, the experimental and predicted moisture content results (local moisture distribution profiles as function of the distance from

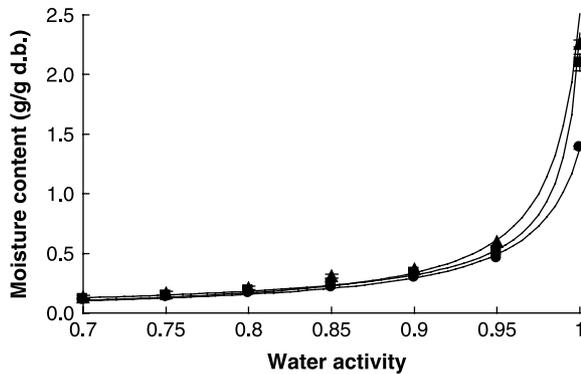


Fig. 1. Moisture sorption isotherm at 20 °C of sponge cakes with different fat contents: experimental data (▲: 0; ■: 0.11; ●: 0.30 g/g d.b. fat content) and predicted values with the Ferro Fontan model (lines).

the interface) are presented in wet basis moisture content units (g/100 g wet basis, w.b.).

### 2.8. Statistical analysis

The statistical significance of the experimental results was assessed using a single-factor analysis of variance (ANOVA). Multiple comparisons were performed by calculating the least significant difference. All tests were conducted at the 5% significance level.

## 3. Results and discussion

### 3.1. Sorption isotherm

The experimental moisture sorption equilibrium values for sponge cakes of varying initial porosity or fat content were determined at 20 °C on the range of water activities from 0.70 to 1. The resulting experimental moisture sorption isotherms are presented in Fig. 1. The moisture intake of non-fat sponge cakes suddenly increased for very high  $a_w$  ( $>0.90$ ), according to their hygroscopic nature: the maximal experimental moisture content near saturation reached 2.20 g/g d.b. This value is close to the saturation values of 2.30 and 2.33 g/g d.b. obtained, respectively, by Guillard et al. (2003a) and by Guinot and Mathlouthi (1990) at 20 °C on industrial sponge cakes using a Cahn microbalance and/or the standard saturated salts method.

Water sorption isotherms determined for sponge cakes with initial porosities of 86, 67 and 52% (0 g/g d.b. fat content) were not significantly different ( $p > 0.05$ ; not presented). Structure and particle-size distribution of the food usually does not influence the sorption isotherm. Xiong et al. (1991) obtained

similar results for extruded mixtures of starch and gluten with varying pore structure and porosities of 6 and 27%, respectively. In contrast to porosity, which had a negligible effect on sorption equilibrium, adding fat to sponge cake significantly decreased the equilibrium moisture contents at high  $a_w$  ( $a_w > 0.9$ ) ( $p < 0.05$ ). For example, equilibrium moisture content near saturation decreased from 2.2 to 1.4 g/g d.b., for a fat content ranging from 0 to 0.30 g/g d.b. (Fig. 1). Similar results were observed by Kim et al. (1999) for dry biscuits using the standard saturated salts method: the equilibrium moisture contents were higher for crackers than for cookies, which had 10 times higher amount of margarine. As the moisture sorption isotherm of a food product is the sum of the hygroscopic properties of its individual components, any modification in chemical composition, such as increasing the amount of hydrophobic constituents, may in turn influence the sorption isotherm.

The Ferro Fontan equation was successfully used to model the sorption isotherms at 20 °C for sponge cakes containing 0 (one curve for sponge cakes of varying porosity: SC1, SC2 and SC3), 0.11 (SC4) and 0.30 g/g d.b. (SC5) of fat content. The resulting fitted curves are shown in Fig. 1. The parameters of the Ferro Fontan model and the RMSE (g/g d.b.) are given in Table 2. RMSE values ranging from 0.05 to 0.08 are in the same order of magnitude as the experimental error, varying between 0.01 and 0.20 g/g d.b., proving the adequacy of the Ferro Fontan equation to model water sorption isotherms of sponge cakes at high  $a_w$ . This model gave accurate values of the equilibrium moisture contents and was used to predict moisture migration in composite foods.

### 3.2. Effective moisture diffusivity

Simulated and experimental local moisture distribution profiles as a function of the distance to the interface were determined after 1, 6, 20 and 30 days storage and compared for each sponge cake characteristic (porosity and fat content). An example of experimental local moisture distribution profiles for a sponge cake with 0 g/g d.b. fat content and 86% initial porosity (SC3) is given in Fig. 2. Simulated moisture contents were obtained using the model as follows: optimisation was performed on the two parameters of the effective moisture diffusivity law while the others fixed parameters are given in Table 1 (sponge cake initial moisture content and density) and Table 2 (parameters of water sorption isotherm equation). The parameters of sponge cake water diffusivity law were adjusted to give the best fit to the experimental data. The resulting effective moisture diffusivities for sponge cakes of varying porosity (SC1, SC2 and SC3) and of varying fat content

Table 2

Parameters and RMSE (g/g d.b.) of the Ferro Fontan model for sponge cakes with fat contents 0, 0.11 and 0.30 g/g d.b.

Product name	Fat content	$\gamma$	$\alpha$	$r$	RMSE
SC1, SC2, SC3	0 g/g d.b.	1.0176 [1.0129; 1.0223]	0.0427 [0.0364; 0.0490]	0.9730 [0.8666; -1.1090]	0.06
SC4	0.11 g/g d.b.	1.0385 [1.0170; 1.0600]	0.0650 [0.0408; 0.0893]	0.7406 [0.5640; 1.0782]	0.06
SC5	0.30 g/g d.b.	1.0762 [0.9618; 1.1907]	0.0895 [0.0205; 0.1994]	0.5843 [0.2854; 12.3457]	0.05

Numbers in brackets are the 95% confidence intervals on parameters.

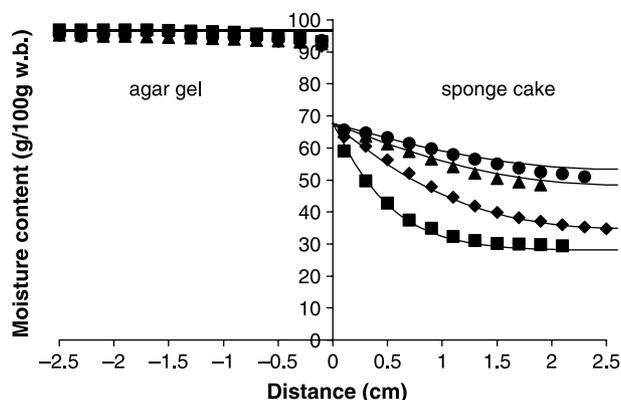


Fig. 2. Moisture distribution profiles at 20 °C in a two-compartment food system made of fat-free sponge cake with 86% initial porosity (SC1) and an agar gel for experimental data after 1 (■), 6 (◆), 20 (▲) and 30 (●) days of contact and the respective modelled profiles (lines).

(SC2, SC4 and SC5) are presented in Fig. 3. Optimised parameters of the effective moisture diffusivity law and RMSE in g/g d.b. are given in Table 3.

The mean experimental error, the average of 95% confidence intervals obtained for all the profiles, was 0.02 g/g d.b. regardless initial porosity and fat content of the sponge cake (Table 3). A good fit between experimental and calculated values was observed for all the moisture transfer experiments as shown, for example, in Fig. 2. RMSE were mostly less than experimental errors for all the experiments. Whatever the

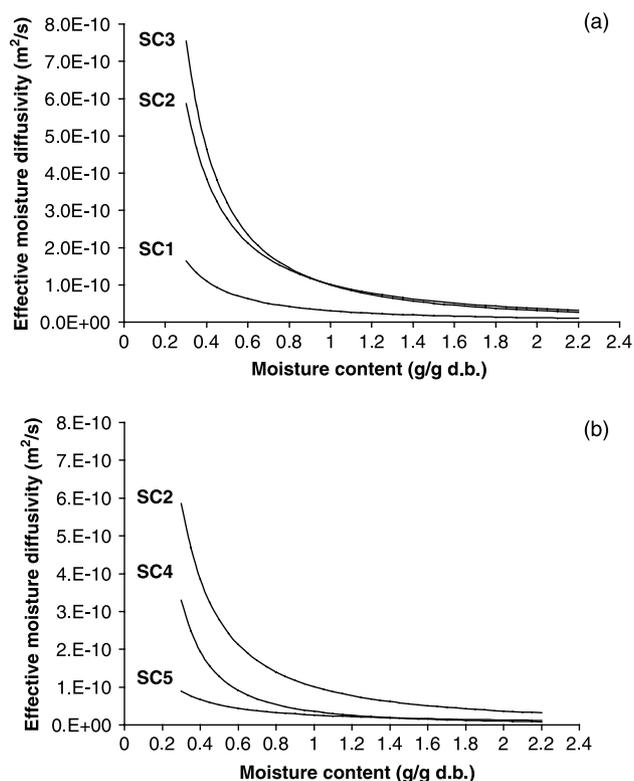


Fig. 3. Effective moisture diffusivity as a function of moisture content for sponge cakes of: (a) 86% (SC3), 67% (SC2) and 52% (SC1) initial porosity (0 g/g d.b. fat content). (b) 0 (SC2), 0.11 (SC4) and 0.30 g/g d.b. (SC5) fat content (67% average initial porosity).

structure and the composition of sponge cakes, the effective moisture diffusivities decreased with moisture content as already observed for high water activity porous cereal products, e.g. porous starch gels by Maroulis et al. (1989, 1991) and industrial sponge cake by Guillard et al. (2003a). As shown in Fig. 3, for the no fat sponge cake and 86% initial porosity (SC3), effective moisture diffusivity decreased from  $7.5$  to  $0.3 \times 10^{-10}$  m<sup>2</sup>/s for moisture content varying from 0.30 to 2.20 g/g d.b. These values are in the range or slightly lower than those reported in the literature for similar products. Saravacos and Maroulis (2001) reported effective moisture diffusivity in baked cereal products varying from  $3.97 \times 10^{-12}$  to  $5.00 \times 10^{-8}$  m<sup>2</sup>/s, with higher values of moisture diffusivity in porous food materials. For example, Guillard et al. (2003b) reported moisture diffusivity in sponge cake varying from 1 to  $11 \times 10^{-10}$  in the moisture range of 0.01 to 1.00 g/g d.b. Tong and Lund (1990) reported moisture diffusivity in muffins varying from 8.5 to  $12 \times 10^{-10}$  m<sup>2</sup>/s in the moisture range of 0.10–0.80 g/g d.b.

The effective moisture diffusivity of sponge cake significantly decreased ( $p < 0.05$ ) with decreasing initial porosity: for example, at a moisture content of 0.30 g/g d.b., effective diffusivity is, respectively, 4.6 and  $0.8 \times 10^{-10}$  m<sup>2</sup>/s for initial porosities of 86% (SC3) and 52% (SC1). Similar decreases in effective moisture diffusivity with decreasing porosity has been reported (Baik and Marcotte, 2002) with diffusivities varying from 0.04 to  $0.35 \times 10^{-10}$  m<sup>2</sup>/s across a porosity range of 10–90%. Increasing the amount of fat in sponge cakes independently of the initial porosity significantly decreased the effective moisture diffusivity ( $p < 0.05$ ): for example, at a moisture content of 0.30 g/g d.b., water diffusivity is 5.9 and  $0.9 \times 10^{-10}$  m<sup>2</sup>/s for sponge cakes with 0 and 0.30 g/g d.b. of fat content with the same porosity (respectively, SC2 and SC5). Similar results were observed by Biquet and Guilbert (1986) for agar gels containing fat and by Palumbo et al. (1977) for sausages.

For moisture contents in sponge cake higher than 1 g/g d.b., the effective moisture diffusivity slightly varied with moisture content, initial porosity and fat content. Minimal values of effective moisture diffusivity at saturation (moisture contents above 1.50 g/g d.b.) were different according to the initial porosity and fat content of the sponge cake. These variations in effective moisture diffusivity of the sponge cakes near saturation could reflect contributions from liquid diffusion in the solid matrix of the food and vapour diffusion in pores, which have diffusivity values differing by several orders of magnitude. Typical values are  $10^{-9}$  and  $10^{-5}$  m<sup>2</sup>/s for liquid and vapour-phase diffusion, respectively (Saravacos and Maroulis, 2001). Water migration in porous sponge cakes (SC2 and SC3) would occur preferentially in the gaseous phase by vapour diffusion. For the sponge cake with lower initial porosity (SC1), which is less anisotropic than porous sponge cake, water transport would occur mainly in the liquid phase through the wet solid matrix, leading to lower values of effective moisture diffusivity: at saturation effective moisture diffusivities for dense (SC1) and porous (SC2 and SC3) sponge cakes reached, respectively, 0.1 and  $0.3 \times 10^{-10}$  m<sup>2</sup>/s.

Table 3  
Parameters of effective moisture diffusivity laws a function of moisture content and RMSE (g/g d.b.) for sponge cakes of varying initial porosity and fat content

Product name	Initial porosity (%) and fat content (g/g d.b.)	$D_0$	$D_X$	RMSE	Experimental error
SC1	52%; 0 g/g d.b.	$3.05 \times 10^{-11}$	-1.40	0.01	0.02
SC2	67%; 0 g/g d.b.	$10.10 \times 10^{-11}$	-1.46	0.02	0.02
SC3	86%; 0 g/g d.b.	$9.97 \times 10^{-11}$	-1.68	0.01	0.02
SC4	68%; 0.11 g/g d.b.	$4.23 \times 10^{-11}$	-1.60	0.02	0.02
SC5	65%; 0.30 g/g d.b.	$2.62 \times 10^{-11}$	-1.02	0.02	0.02

Moreover, for high moisture contents, the effective diffusivity of the porous sponge cakes would decrease according to the swelling of the solid matrix, which leads to collapse of the pores. The effective moisture diffusivity for sponge cakes with 0.11 and 0.30 g/g d.b. fat content near saturation reached  $0.2 \times 10^{-10} \text{ m}^2/\text{s}$  and was lower than the value for a sponge cake with no fat and the same porosity (SC2). This difference could be explained by the presence of hydrophobic constituents in the solid matrix, constituting an obstacle to water migration through the solid matrix but also at the surfaces of the pores. Nevertheless, as the initial porosity of fatty sponge cakes was in the range of 65–68%, moisture would preferentially migrate through the gaseous phase of the product. Therefore, despite the high fat content of sponge cakes SC4 and SC5, effective moisture diffusivity values of these materials at saturation were higher than for fat-free dense sponge cakes (SC1).

### 3.3. Moisture migration simulations in a composite food: effect of varying porosity and fat content of the sponge cake compartment

The effect of increase in density or fat content on shelf life of the cereal compartment in a composite food (sponge cake/agar gel with an  $a_w$  gradient 0.85/0.99) was evaluated using a moisture migration simulation. Two values of initial porosity, 67% (SC2) and 52% (SC1), and two amounts of fat, 0 (SC2) and 0.30 g/g d.b. (SC5), were compared. The resulting simulated time-course  $a_w$  of the investigated sponge cakes are presented in Fig. 4.

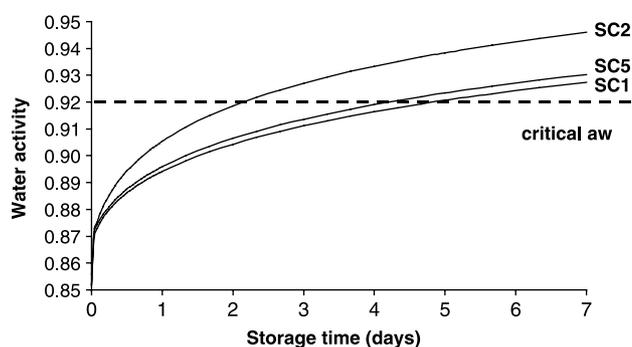


Fig. 4. Simulated water activity profiles as a function of time of sponge cakes of varying initial porosity and fat content in contact with an agar gel (initial water activity = 0.999). Black lines: simulated water activity. (SC2) control: initial porosity 67% and fat content 0 g/g d.b.; (SC1) initial porosity 52% and fat content 0 g/g d.b.; (SC5) initial porosity 65% and fat content 0.30 g/g d.b. Dotted lines: critical water activity (0.92).

When comparing the re-moistening of sponge cakes, densification of the structure (SC1) or addition of fat (SC5) the moisture intake was reduced significantly as compared with sponge cake with high initial porosity and zero fat content (SC2). With regard to the sorption isotherm of sponge cake materials, moisture intake increased mainly in the high water activity region. For  $a_w > 0.92$ , water condenses in the gaseous phase of the porous food (Labuza et al., 1970) leading to unacceptable organoleptic changes for consumers. Considering this  $a_w$  of 0.92 as a critical value for the texture of sponge cake, the shelf life of a 67% porosity fat-free sponge cake was 2.2 days and increased to 4.2 and 4.7 days, respectively, for a 65% initial porosity sponge cake with 0.30 g/g d.b. fat content (SC5) and a 52% initial porosity fat-free sponge cake (SC1).

Adding large amounts of fat to a cereal-based product would produce a food with poor nutritional qualities and change the porosity, an important organoleptic parameter which cannot be easily modified. If there is a requirement to balance the target shelf life and the nutritional and textural quality of the cereal food then slight increases in fat content and densification may be an acceptable solution. Moreover, moisture intake simulations have been done for a composite food composed of a wet filling with a very high  $a_w$  value of 0.99, leading to an extreme  $a_w$  gradient. Moisture transfer in composite foods could also be reduced by adding humectants such as mineral salts (NaCl) or carbohydrates (Guilbert, 1984) or using lipid barriers at the interface between the phases (Debeaufort et al., 1999; Guillard et al., 2003c). The impact of such strategies on composite food shelf life will be investigated and compared with the effect of the fat content of the cereal-based compartment.

### Acknowledgements

We gratefully acknowledge ANRT (Association Nationale de la Recherche Technique), Ministère Français de l'Enseignement Supérieur et de la Recherche and Industries for financial support of this work that takes part of the national French program CANAL 'Conception Assistée d'Aliments Composites'.

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