Effect of milk fat and total solids concentration on the kinetics of moisture uptake by ready-to-eat breakfast cereal

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Summary When immersed in milk, breakfast cereal easily take up moisture, lose their brittle texture and become soggy. Earlier comparative analysis of the moisture sorption by breakfast cereal immersed in water and milk indicated that milk solids might play an important role on the sorption kinetics. In this work, the moisture uptake by ready-to-eat corn breakfast cereal immersed in milk solutions, reconstituted from whole and skimmed milk powder, was measured under isothermal conditions at 5, 30 and 55 °C. Dilutions between 0.25 and 1.5 were tested, with the factor of dilution 1 corresponding to the standard recommended by the milk powder manufacturer. The Weibull probabilistic model adequately fitted the experimental data by appropriate choice of its variable parameters. The dependence of the model parameters on temperature and total solids concentration was assessed for both skimmed and whole milk. Fat was found to play a major role on the process mechanism, which was attributed to the deposition of a fat layer at the solid matrix surface, hindering water and solids uptake. Yet, for short times, moisture uptake proceeded at a similar rate both in skimmed and whole milk.

Keywords Extruded cereal, kinetic modelling, microstructural analysis, pH, viscosity, Weibull probabilistic model.

Introduction

Ready-to-eat breakfast cereal are expanded and dried during manufacturing to develop a brittle texture and a cellular structure, which is supported by a series of struts and walls made primarily of starch. Loss of textural properties occurs upon gain of moisture from the environment and this can be detrimental to the product quality, being a major cause of rejection by consumers. Loss of bowl life occurs as the cereal gains moisture from the milk, loses its brittle texture and becomes soggy (Nelson & Labuza, 1993). Moisture uptake depends on temperature, on the immersion medium and on the cereal composition and structure. When soaked in milk, cereal with similar dry peak forces or crispness may exhibit undesirable textural changes or remain crispy (Loh & Mannell, 1990). Cereal cooking conditions are known to affect the quality of the final product: high-shear and low-moisture extrusion causes severe dextrinization of starch molecules and results in a product that gains moisture quickly (Miller, 1994). A sugar (with some fat) coating is often added to breakfast cereal in order to retard moisture sorption in the bowl.

Food rehydration has found extensive interest, particularly in the case of legumes (Quast & Silva, 1977; Hsu, 1983; Hsu *et al.*, 1983; Singh & Kulshrestha, 1987; García-Reverter *et al.*, 1994), cereal grains (Zhang *et al.*, 1984; Sopade *et al.*, 1992; Lu *et al.*, 1994), dried fruits (Ilincanu *et al.*,

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1995) and extruded cereal products (Duce & Hall, 1995; Hills *et al.*, 1996; Machado *et al.*, 1997). In relation to breakfast cereal, most of the studies reported focus on the moisture uptake when the cereal is exposed to air. Recently, work developed by Machado *et al.* (1997) brought some insight into the kinetics of moisture sorption by breakfast cereal immersed in liquid media. Different kinetic models were tested, but the best process description was obtained with the probabilistic Weibull model (Hahn & Shapiro, 1967):

$$M_t=M_0+(M_\infty-M_0)\times\left[1-\exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right]\right] \quad (1)$$

where M_t is the moisture content at time t, M_0 is the initial moisture content, M_∞ is the equilibrium moisture content, β is a scale parameter and α a shape parameter. The scale parameter defines the rate of the moisture uptake process and represents the time needed to accomplish approximately 63% ($1-e^{-1}$ or 1 log cycle) of the moisture uptake process. The shape parameter is a behaviour index, which depends on the process mechanism. This is a quite simple and flexible model because different α values lead to very different moisture uptake curves: (i) the higher its value, the slower the process at short times, (ii) if α equals one, the Weibull model reduces to a first order growth, and (iii) for greater values, the model predicts a lag phase. This model was found to yield good results in the description of rehydration of a variety of dried foods (Misra & Brooker, 1980; Lu *et al.*, 1994; Ilincanu *et al.*, 1995). Cunha *et al.* (1998) showed that the Weibull model adequately describes rehydration processes controlled by different physical mechanisms. The comparative analysis of moisture uptake by breakfast cereal, either immersed in water or low-fat milk, indicated that milk solids might play an important role on the sorption process (Machado *et al.*, 1997). The objective of this work was to assess further the effect of the immersion medium on the mechanism and rate of moisture uptake by ready-to-eat breakfast cereal. Milk solutions with different dilution factors and fat content were tested, so that the effect of total solids, fat content, viscosity and pH could be studied.

Materials and methods

Breakfast cereal and milk powder

Commercial puffed corn (Kellogg's Corn Pops) breakfast cereal and whole (Nestlé's Nido) and skimmed (Nestlé's Molico Sveltess) milk powders were obtained from local supermarkets.

The main ingredients of the puffed corn cereal were, according to the manufacturer, corn, wheat and oat flours, sugar, glucose and honey. Total sugar and protein from breakfast cereal were measured, respectively, by the standard Lane Einon and Kjeldahl methods. Lipids were extracted using a Soxhlet apparatus and fibre was determined by the Weende method implemented in a Fibertec system (AN 01/78, 1978). Two replicates were analysed. The values obtained were, respectively (% w/w): total sugars, 65.8 ± 0.27; proteins, 6.4 ± 0.014; lipids, 1.4 ± 0.0012; fibres, 0.6 ± 0.17.

For powder milk, total protein was determined by the Kjeldahl method according to NP 1986 (1991) using a Kjeltec apparatus. Lactose content was measured according to FIL-IDF 28 (1974). Calcium was determined according to PIE.AA.01 (1993) and total fat according to FIL-IDF, 126A (1989) with a Soxhlet apparatus. Total solids were obtained according to NP 475 (1983). Table 1 shows the composition of the milk powders.

Preparation of milk solutions

Milk powder was reconstituted in deionized water at room temperature and the solutions were stirred continuously for 30 min. Milk solutions will be referred to in terms of both the dilution factor and total solids content. The recommendation of the powder manufacturer, 130 g of whole milk powder and 100 g of skimmed milk powder to reconstitute 1 litre of milk, was taken as dilu-

Table 1 Composition of milk powder

Composition	Skimmed milk	Whole milk
Total solids (% w/w)	95.1 ± 0.071	97.2 ± 0.064
Total fat (% w/w)	0.3 ± 0.071	25.5 ± 0.43
Protein (% w/w)	34.2 ± 0.042	26.3 ± 0.027
Calcium (mg/100 g)	1189 ± 4.2	895 ± 2.5
Lactose (g monohydrated lactose/100 g)	45.2 ± 0.47	32.8 ± 0.31

tion factor 1. Other dilution factors used were 0.25, 0.5, 0.75, 1.25 and 1.5 (see Table 2).

Measurement of the moisture uptake and soluble-solids loss/uptake

Cereal samples were selected in terms of weight (≈1 g), size (10.6 ± 0.2 mm) and geometry (spheres) and stored in airtight glass containers with food grade desiccants (Dydra Déshydratant, Saint-Mames, France). Four samples were selected for each run, weighed in a Sartorius 210S balance (± 0.0001 g), placed in covered wire baskets and immediately immersed in a beaker containing 1000 ml of milk, pre-heated/cooled to the required temperature. The beaker was immersed in a thermostatic bath set at a pre-defined constant temperature of 5, 30 or 55 °C. For the lowest temperature (5 °C), a cooling bath (Julabo HC-FP40, Seelbach, Germany) was used. At higher temperatures a Julabo SW-21C bath was used. After selected times the samples were removed, weighed and kept in covered Petri dishes prior to moisture content measurement. For each temperature approximately 15 sampling times (runs) and, usually, three replicates were considered. The moisture content was measured by drying the samples to constant weight (approx. 24 h) in a WTB Binder (Tuttlingen, Germany) vacuum oven (pressure < 100 mm Hg) at 70 °C. The soluble-solids loss was calculated by a simple material balance, based on the weight and moisture content of the samples.

Viscosity and pH measurements

A Cannon–Fenske capillary viscometer no. 75 (Schott Geräte) was used to measure the viscosity of the milk solutions. The viscometer was placed in a water bath with glass walls with a temperature controlling device (Hetofrig® for 5 °C and Thermomix® MM, B. Braun, West Germany, for 30 and 55 °C). Measurements were made after 30 min of temperature equilibration and the flow time of the samples was determined manually five times. The density of the milk solutions was measured using a pycnometer. From Poiseuille's equation (Lewis, 1987) one can calculate the viscosity of milk solutions according to:

$$\mu_{milk} = \frac{\mu_{water}}{\rho_{water}\, t_{water}} * \rho_{milk}\, t_{milk} \qquad (2)$$

where μ_{milk}, μ_{water} (Nsm^{-2}) is the dynamic viscosity, respectively, for milk and water, at the same temperature; ρ_{milk}, ρ_{water} (kgm^{-3}) is the density, respectively, of milk and water, at the same temperature and t_{milk}, t_{water} (s) is the time taken, respectively, by the milk and water to flow through the capillary tube at the same temperature. Values of the dynamic viscosity and density for water, at the temperatures tested, were reported by Streeter & Wylie (1982).

The pH values were determined in a Crison pH meter (micropH 2001) after equilibrating the samples for 2 h at the desired temperature (5, 30 or 55 °C).

Table 2 Correspondence between dilution factors and total solids of the milk solutions tested

Dilution factor	Total solids concentration (% w/v)	
	Skimmed milk	Whole milk
0.25	2.38	3.16
0.5	4.76	6.34
0.75	7.13	9.48
1	9.51	12.6
1.25	11.9	15.8
1.5	14.3	19.0

Microscopy

Cereal samples were immersed in milk solutions, as described above. After selected times the samples were rapidly removed to Petri dishes, cut carefully with a scalpel into two halves, and the cross-sectional surface of the samples, without further preparation, was observed under 20 and 50× magnification lenses with an Olympus video microscope OVM 1000NM. These experiments were conducted at 5 and 30 °C for milk solutions with dilution factor of 1.

Regression and statistical analysis

Parameter estimation and model building, to study and include the effects of temperature and total solids concentration on moisture uptake, was by non-linear regression using Stata 5.0 (Computing Research Centre, USA). The equilibrium moisture content was also considered as a model parameter because experimental determination was not feasible in many conditions, due to the fragility of the material. Earlier experiments had shown that this parameter, as well as the shape parameter of the Weibull model (α), were independent of temperature, and therefore this was imposed on the regression procedures.

Results and Discussion

Adequacy of the Weibull model

The Weibull probabilistic model agreed closely with the experimental data of moisture uptake by cereal immersed in milk, for all the conditions tested, by appropriate choice of its variable parameters. Nevertheless, in general residual heteroscedasticity was found, with the sample's standard deviation increasing with moisture uptake because of the greater instability of the cereal structure in this situation. As a remedial measure, the model was applied in its logarithmic form (Seber & Wild, 1989) and fitted to the transformed experimental data. Resulting residuals proved to yield constancy of variance and tended to follow a normal distribution. The coefficients of determination were always above 0.999. Figure 1 shows typical examples of the fit of the model to the data.

The Weibull model parameters

The α parameter was independent of the dilution factor of the milk solutions (Fig. 2a). The equilibrium moisture content was found to decrease linearly with total solids concentration (Fig. 2b). The β parameter decreased with temperature, following an Arrhenius-type relationship:

$$\beta = \beta_{ref} * \exp\left[\frac{Ea}{R} * \left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] \qquad (3)$$

where β is the rate constant at temperature T, β_{ref} is the rate parameter at a reference temperature T_{ref}, Ea is the activation energy and R is the universal gas constant. The use of a finite reference temperature, T_{ref}, is most important, as it decreases the correlation between the pre-exponential factor, β_{ref}, and the activation energy, Ea, thus improving parameter estimation (Haralampu *et al.*, 1985). Reference temperatures for whole and skimmed milk were chosen as the values that would lead to a smaller sum of square of the residuals. The β_{ref} parameter (at a reference temperature of 38 °C for whole milk and 106 °C for skimmed milk) was found to increase linearly with total solids concentration (Fig. 2c), whereas Ea showed a linear decrease (Fig. 2d).

In mathematical modelling of experimental data it is important to assess whether the model is of the correct functional form and to accurately estimate the model parameters (Haralampu *et al.*, 1985). While individual fitting is essential to assess the adequacy of the model and to inspect the dependence of the model parameters on experimental conditions, overall analysis of the complete set of data provides higher precision estimates, avoiding the estimation of intermediate parameters (Cohen & Saguy, 1985; Haralampu *et al.*, 1985). Thus, to increase precision, a global model imposing the above referred relations between the Weibull model parameters and temperature and total solids concentration was fitted to the complete set of experimental data:

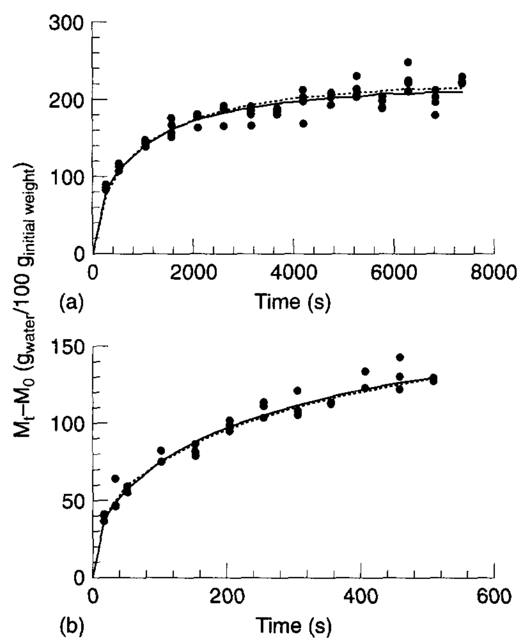
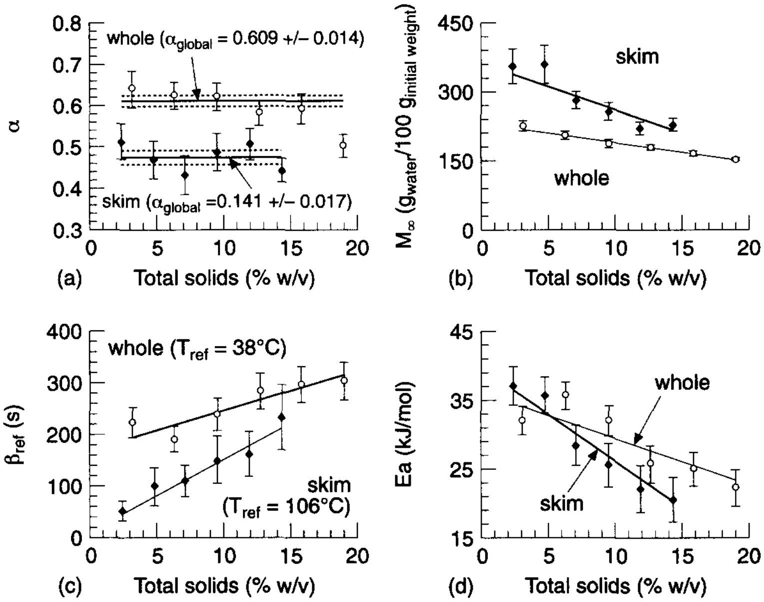


Figure 1 Typical fits of both the global model (—) and the Weibull (- - -) model to the experimental data: (a) whole milk with 3.16% total solids at 55 °C; (b) skimmed milk with 14.3% total solids at 55 °C.

Figure 2 Prediction of the dependency of model parameters on total solids concentration for both skimmed (◆) and whole (O) milk. Straight lines correspond to global model, individual values (and their 95% confidence intervals) were obtained by regression at each total solids concentration value: (a) shape parameter; (b) equilibrium concentration, M_∞; (c) time parameter at a reference temperature, β_{ref} and (d) activation energy, Ea.



$$M_\infty = M_{\infty 0} + M_{\infty m} * C \quad (4)$$

$$\beta_{ref} = \beta_{ref0} + \beta_{refm} * C \quad (5)$$

$$Ea = Ea_0 + Ea_m * C \quad (6)$$

Residual heteroscedasticity was again found and therefore the model was applied in its logarithm form yielding better results (Fig. 3). Residuals tended to follow a normal distribution (Fig. 4). Process description is similar to that obtained with the individual fits (see Fig. 1). The global model parameters are shown in Table 3 and the parameters correlation matrix is summarized in Table 4. Figure 2 shows the dependence of α, M_∞, β_{ref} and Ea on total solids concentration, where it can be seen that results are similar to those obtained with the individual fits. The dependency of the β parameter on temperature and total solids concentration is shown in Fig. 5.

The moisture uptake process

The results show that moisture uptake is influenced by milk fat content, as M_∞ and β values are much lower for whole milk when compared to skimmed milk.

The magnitude of the equilibrium parameter may be correlated with the ability of the cereal matrix to hydrate (Machado *et al.*, 1997). Low concentration milk solutions have a greater amount of 'free water', as well as lower viscosity and fat content, which may explain the higher ability of the material to hydrate in these solutions. This effect is more pronounced with skimmed milk ($M_{\infty m} = -10.2\ g_{H2O}/100g_{initial\ weight}$) than with whole milk ($M_{\infty m} = -4.28\ g_{H2O}/100g_{initial\ weight}$), probably because in whole milk the fat content is so important, even at low concentrations, that increasing its value does not exert a strong influence on the M_∞ values. The differences between skimmed and whole milk for the same total solids concentration (Fig. 2b) are also an indicator of the role of fat on the hydration mechanism.

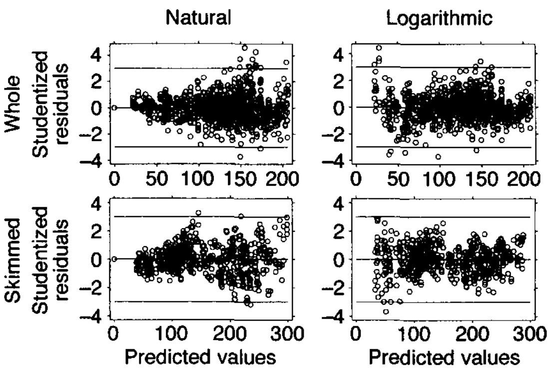


Figure 3 Studentized residuals from global model of both natural and logarithmic forms fitting to experimental data from whole and skimmed milk.

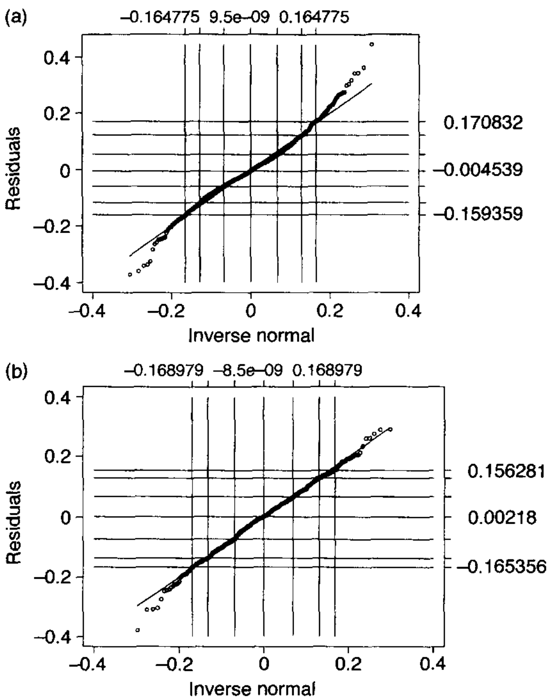


Figure 4 Q–Q plots of the residuals from global model fitting in the logarithmic form: (a) whole milk; (b) skimmed milk.

The decrease of β with temperature (Fig. 5) may be explained both by the lowering of milk viscosity and by the structural changes occurring in the porous structure of the cereal. Sensitivity to temperature decreased with total solids concentration (E_a decreases from 36 to 20 kJmol^{-1} for skimmed milk and from 34 to 23 kJ mol^{-1} for whole milk), and in general whole milk solutions lead to a higher sensitivity. The effect of total solids concentration in the β parameter is quite different for skimmed and whole milk. In whole milk this effect is much smaller than that of temperature, and in general the β value increases with increasing total solids concentration, probably because of the greater solution viscosity. In skimmed milk, the same effect is noticed at 55 °C, but at lower temperatures a maximum is noticeable at intermediate total solids concentration; this means that for the higher concentrations tested, increased concentration actually decreases the β value, probably because the smaller hydration favours the maintenance of the cereal porous structure and thus facilitates moisture movements through the pores.

The shape factor (α) was greater for whole milk (Table 3), thus indicating that moisture uptake mechanisms in skimmed and whole milk are somewhat different, with whole milk showing, in relative terms, a slower process for short times of immersion.

One might think that the moisture uptake process would be dependent mainly on the milk solution viscosity. Figure 6 shows the viscosity of the milk solutions as a function of temperature and total solids concentration. No significant differences were found between skimmed and whole milk and thus Fig. 6 includes the data for all the milk solutions tested. Viscosity increased with increasing milk total solids concentration and decreasing temperature. Temperature dependency followed an Arrhenius-type relationship, both the pre-exponential factor and the activation energy depending exponentially on total solids concentration. Activation energy increased with increasing total solids concentration, from 19 to 26 kJ mol^{-1}, in the range of concentrations tested. Similar results were found by Chang & Hartel (1997). The viscosity of milk can be in part related to the voluminosity of casein micelles, which in turn depends on temperature (Snoeren *et al.*,

Table 3 Parameter estimates for the global model

Milk		α	$M_{\infty 0}$ (g_{water}/ 100$g_{initial\ weight}$)	$M_{\infty m}$ (g_{water}/ 100$g_{initial\ weight}$)	β_{ref0} (s)	β_{refm} (s)	Ea_0 (Jmol^{-1})	Ea_m (Jmol^{-1})
Whole (T_{ref} = 38 °C;	Parameter estimate	0.6088	231.69	−4.28	169.27	7.61	36 049	−666
R^2_{adj} = 0.9996)	Standard error	0.0073	3.76	0.23	11.47	0.89	975	87
Skimmed (T_{ref} = 106 °C;	Parameter estimate	0.4714	361.58	−10.22	11.32	13.94	39 814	−1 365
R^2_{adj} = 0.9996)	Standard error	0.0085	11.278	0.82	4.21	1.57	1 314	146

Table 4 Correlation matrices for the global model

	Whole milk						Skimmed milk					
	α	$M_{\times 0}$	$M_{\times m}$	β_{ref0}	β_{refm}	E_{a0}	α	$M_{\times 0}$	$M_{\times m}$	β_{ref0}	β_{refm}	E_{a0}
$M_{\times 0}$	−0.481	1	—	—	—	—	−0.558	1	—	—	—	—
$M_{\times m}$	0.275	−0.912	1	—	—	—	0.312	−0.903	1	—	—	—
β_{ref0}	−0.559	0.882	−0.830	1	—	—	−0.294	0.249	−0.155	1	—	—
β_{refm}	0.025	−0.482	0.705	−0.689	1	—	−0.792	0.569	−0.338	−0.127	1	—
Ea_0	0.100	0.216	−0.233	0.096	−0.084	1	0.108	0.507	−0.660	−0.453	0.061	1
Ea_m	−0.059	−0.161	0.189	−0.070	0.056	−0.880	0.095	−0.542	0.719	0.461	−0.363	−0.860

1984). Decreasing the temperature increases the voluminosity of the micelles as a consequence of the splitting off of β-casein as well as of the swelling of the micelles. However, it is interesting to note that viscosity was independent of the milk fat content *per se*. This shows that viscosity does not explain the major differences found between moisture uptake in skimmed and whole milk.

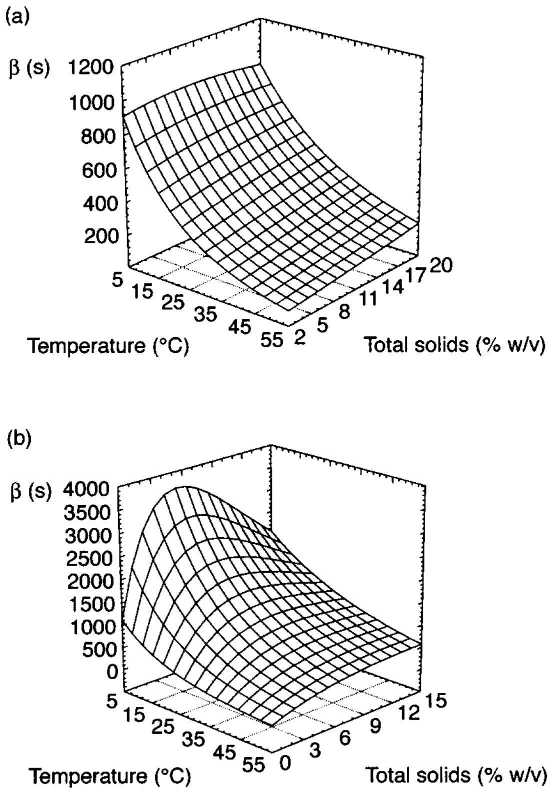


Figure 5 Prediction of the dependency of the β parameter on temperature and total solids concentration: (a) whole milk; (b) skimmed milk.

On the other hand, pH might also be expected to have some role on moisture uptake as low pH, particularly at low temperature, promotes the solubilization of micellar protein, thus increasing viscosity (Dalgleish & Law, 1989; Banon & Hardy, 1992). We have observed that pH values

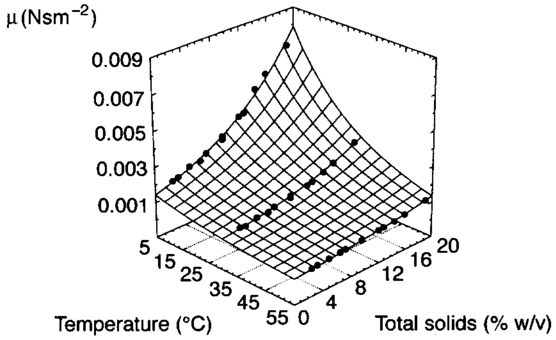


Figure 6 Effect of total solids concentration and temperature on the milk solutions viscosity. $\mu = [7.46e-4 \times \exp(0.0698 * C)] \times \exp[(17.7 + 0.464 \times C)/R \times (1/T - 1/303)$, $R^2_{adj} = 0.998$.

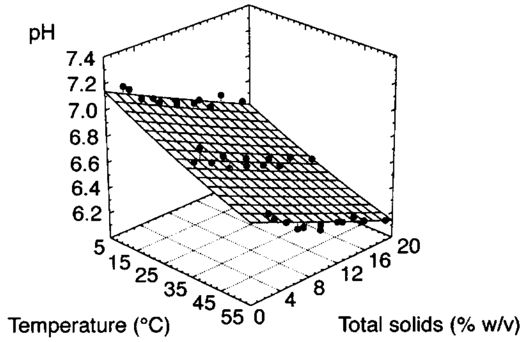


Figure 7 Effect of total solids concentration and temperature on the milk solutions pH. $pH = [6.86 \times \exp(-0.00392 \times C)] \times \exp[1.11/R \times (1/T - 1/303)]$, $R^2_{adj} = 1.00$.

increased with decreased temperature and milk solids concentration (Fig. 7). The effect of temperature results from changes in the buffering capacity of milk salts and the expulsion of CO_2 (Rosenthal, 1991). This temperature dependence followed an Arrhenius-type relationship, with constant activation energy, whereas the pre-exponential factor increased exponentially with total solids concentration. Activation energy was very low (1.1 kJ mol^{-1}), which is in good agreement with results earlier reported by Rosenthal (1991) for skimmed milk. Overall, pH changes were quite small and again fat content did not show any influence on pH, which does not therefore explain the major differences between moisture uptake in skimmed and whole milk either.

The moisture uptake rate

Figure 8 shows the predicted evolution of moisture content during immersion of the cereal in milk solutions, for selected conditions. The predicted values were very similar to the experimental data (see Fig. 1) that are not shown for simplicity sake. It is clear that, in spite of the different sorption mechanisms, for times of practical interest (short times) moisture uptake proceeds at a very similar rate both in skimmed and whole milk, particularly at 5 °C. This results from the opposite effects of fat content on M_∞ and β. As the process continues, moisture content tends to level off in whole milk, whereas in skimmed milk further moisture uptake is still evident. Figure 8c shows the results obtained for the dilution factor 1, and it can be seen that up to 30 min at 5 °C and 5–6 min at 55 °C no major differences were found between skimmed and whole milk.

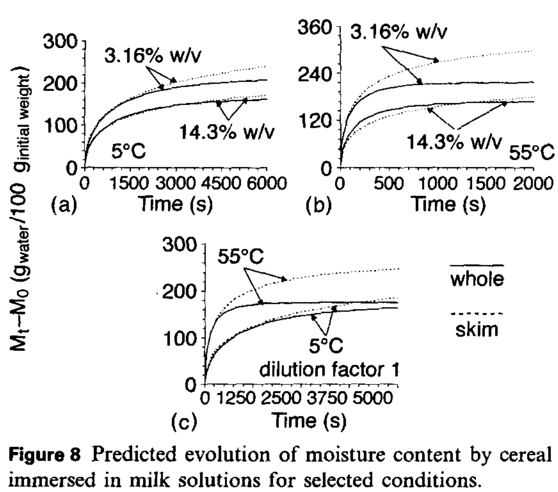


Figure 8 Predicted evolution of moisture content by cereal immersed in milk solutions for selected conditions. (a) at 5 °C, (b) at 55 °C; (c) using the standard dilution recommended by the manufacturer.

Total soluble solids loss/uptake

In the case of immersion of breakfast cereal in milk, it should be stressed that the soluble-solids measurement represents a net value, as the cereal sugar covering is lost into the milk solutions, but milk solids are simultaneously absorbed by the cereal.

Soluble solids loss/uptake occurs at a faster rate than moisture uptake, indicating that most of the soluble solids remain at the cereal surface, creating a barrier that prevents the passage of further solids. Equilibrium values, $M_{s\infty}$, could be measured experimentally and are shown graphically in Fig. 9. The amount of solids lost

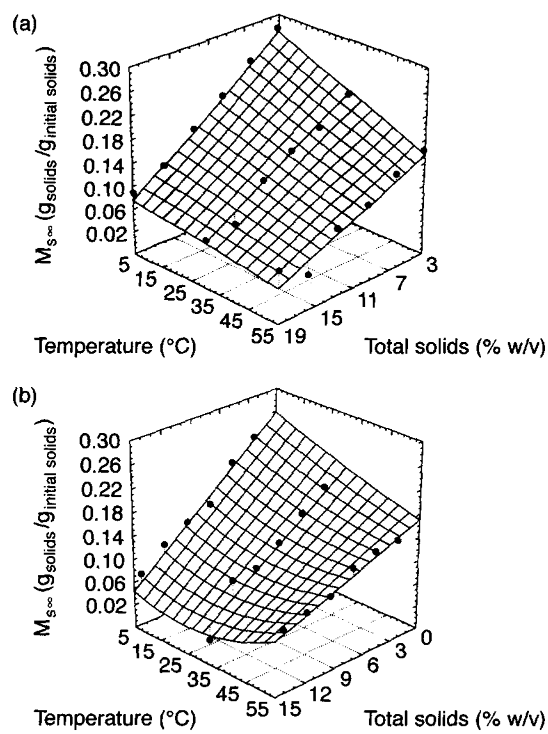


Figure 9 Effect of total solids concentration and temperature on the equilibrium soluble-solids loss/uptake for: (a) whole milk ($M_{s\infty} = 0.32 - 2.62e - 3 \times T - 0.0127 \times C + 1.02e - 4 \times T \times C$, $R^2_{adj} = 0.954$); (b) skimmed milk ($M_{s\infty} = 0.27 - 0.0144 \times C - 2.28e - 3' \times T + 8.56e - 6 \times T^2 + 2.67e - 6 \times C \times T^2$, $R^2_{adj} = 0.919$).

exceeded that of solids uptake. Earlier experiments in water, where only the sugar coating was lost, showed that at equilibrium 0.46 $g_{solids}/g_{initial\ dry\ weight}$ were lost, whereas the results in milk solutions do not exceed a net loss of 0.3 $g_{solids}/g_{initial\ dry\ weight}$. Equilibrium values were found to be significantly different ($P < 0.05$) in the milk solids concentration and temperature range tested. For whole milk $M_{s\infty}$ decreased with temperature, probably because of the higher solubility, whereas in skimmed milk a minimum was found at intermediate temperatures. $M_{s\infty}$ was greater for whole milk, probably because of the adherence of the fat globules to the cereal surface, but the values of skimmed and whole milk tended to approach as the temperature increased. Lower $M_{s\infty}$ were found as the total solids concentration increased, perhaps because in this case the fat barrier at the cereal surface that builds up at the earlier stages would restrict further entry of soluble solids. The time required to reach equilibrium was found to depend both on temperature and total solids concentration, with equilibrium taking between approx. 30 s and 150 min to be achieved (see Fig. 10). As temperature increases and total solids concentration decreases equilibrium is achieved earlier, probably because of the faster loss of the sugar coating. Equilibration times are shorter for whole milk except at 55 °C, where no significant differences were found.

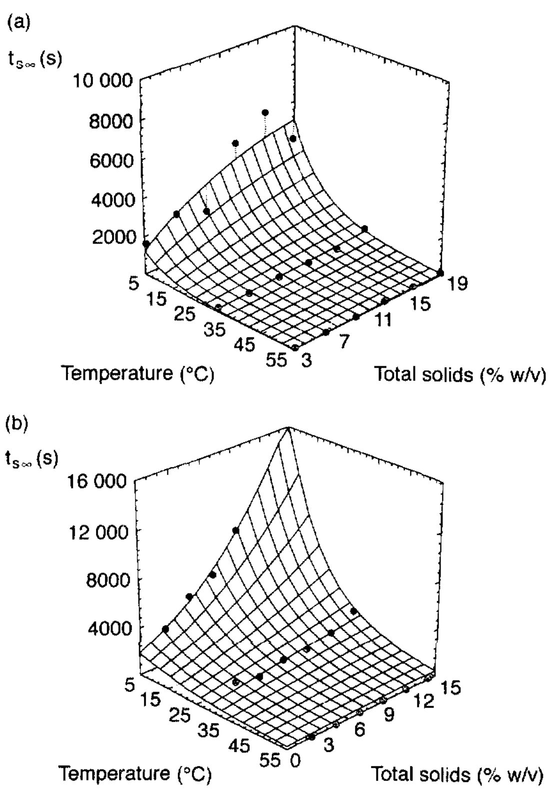


Figure 10 Effect of total solids concentration and temperature on time required for reaching equilibrium in terms of soluble-solids loss/uptake for: (a) whole milk ($_{s\infty}$ = (− 13.292 + 29.963 × C) × exp[(80.928 s1.1016 × C)/R × (1/T − 1/303)], R^2_{adj} = 0.874); (b) skimmed milk ($_{s\infty}$ = (619.408 + 117.371 × C) * exp[(30.459 + 1.611 × C)/R × (1/T − 1/303)], R^2_{adj} = 0.979).

Microstructural changes induced by moisture uptake

The sorption process by breakfast cereal immersed in milk solutions may be related to the product microstructure. Thus, microscopy was

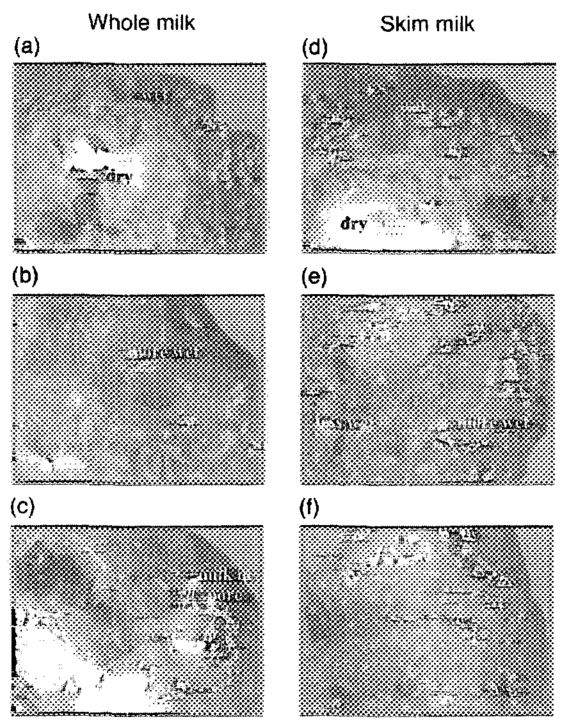


Figure 11 Images of the cross-sectional view (50×) of breakfast cereal immersed in milk solutions with a factor of dilution of 1.0 for 9 min (a, d), 50 min (b, e) and long times of immersion (c, f) at 30 °C.

used to assess microstructural changes during moisture sorption. Prior to immersion, the cereal shows a highly porous cellular structure (porosity averages 0.76). As moisture uptake proceeds, two changes were noted: swelling of the solid matrix and a consequent loss of cellular structure. Figure 11 shows the structural changes at short, medium and long immersion times. When the cereal is immersed in milk, hydration of the solid matrix starts occurring at the surface and proceeds to the centre (Fig. 11a, 1d). As moisture content increases, layers with decreasing degrees of hydration are visible (Fig. 11b, 1e). In skimmed milk, the solid matrix greatly expands as a result of hydration, the pores shrink and eventually the whole structure loses its cellular-like appearance (Fig. 11f); water movements occur basically through the solid matrix. However, with whole milk, the hydration is not so extensive because of the accumulation of fat at the solid matrix surface. The structure better retains its porous nature and water moves both through the solid matrix and from pore to pore (Fig. 11c). From these observations it may be inferred that with whole milk the cereal texture and crispness would be maintained better than with skimmed milk.

Conclusions

The Weibull probabilistic model described the moisture uptake process by corn breakfast cereal adequately. It was found that for short immersion times moisture uptake takes place at approximately the same rate in skimmed and whole milk, although the sorption mechanisms differ. In skimmed milk hydration of the solid matrix occurs to a significant extent, thus increasing the driving force to mass transfer but decreasing the water movement rate through the cereal, as the cellular structure is lost and mass transfer occurs mainly through an enlarged solid matrix. In whole milk, the fat globules that deposit at the surface create a barrier to moisture transfer to the cereal solid matrix, and the cereal retains better its cellular structure, with some mass transfer taking place through the cereal pores. Structural relaxation phenomena of the cereal solid matrix thus appear to control the moisture uptake process.

Nomenclature

C Total solids concentration (%w/v)
Ea Activation energy (J mol^{-1})
Ea_0 Parameter in eqn 6 (J mol^{-1})
Ea_m Parameter in eqn 6 (J mol^{-1})
$M_{s\infty}$ Equilibrium total soluble solids content (g $_{solids}$/100g $_{initial\ dry\ weight}$)
M_t Moisture content at time t (g $_{water}$/100g $_{initial\ weight}$)
M_0 Initial moisture content (g $_{water}$/100g $_{initial\ weight}$)
M_∞ Equilibrium moisture content (g $_{water}$/100g $_{initial\ weight}$)
$M_{\infty m}$ Parameter in eqn 4 (g $_{water}$/100g $_{initial\ weight}$)
$M_{\infty 0}$ Parameter in eqn 4 (g $_{water}$/100g $_{initial\ weight}$)
R Universal gas constant ($Jmol^{-1}K^{-1}$)
R^2_{adj} Adjusted coefficient of determination
t Time (s)
$t_{s\infty}$ Time required to achieve the equilibrium total solids content (s)
T Temperature (°C, K)
T_{ref} Reference temperature (°C, K)
α Shape factor of the Weibull equation
β Time parameter of the Weibull equation (s)
β_{ref} Time parameter of the Weibull equation at a reference temperature (s)
β_{refm} Parameter in eqn 5 (s)
β_{ref0} Parameter in eqn 5 (s)
μ Dynamic viscosity (Nsm^{-2})
ρ Density (kg m^{-3})

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