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SCIENCE DIRECT
Food Chemistry 100 (2007) 1594–1601
Food Chemistry
www.elsevier.com/locate/foodchem

Different approaches for increasing the shelf life of partially baked bread: Low temperatures and hydrocolloid addition

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Received 28 February 2005; received in revised form 1 December 2005; accepted 1 December 2005

Abstract

Partially baked bread is a product with short shelf life that requires sub-zero temperatures for extending it. The storage of par-baked bread at low temperatures and the addition of bread improvers with antistaling effects, such as hydroxypropylmethylcellulose (HPMC), are very attractive alternatives for extending the shelf life of these products. In this study, staling during storage of partially baked bread (in the presence and absence of HPMC) at low temperatures (2 °C) is studied in terms of hardness increase and amylopectin retrogradation. Simultaneously, the staling of the derived full baked breads when stored at 25 °C is assessed. During the storage of par-baked bread at low temperatures, progressive crumb hardening and rapid crystallization of the amylopectin chains were produced. However, heat applied during full baking reversed those processes, and the extent of that improvement was dependent on the time of par-baked bread storage. Concerning the staling of the derived full baked bread, the time of par-baked bread storage did not significantly ($P < 0.05$) affect the staling process of the resulting full baked breads. The addition of HPMC decreased the crumb hardness in both par-baked and full baked breads, and also promoted a reduction of the amylopectin retrogradation. Overall results indicate that HPMC addition significantly retards the staling of par-baked bread during its storage at low temperatures and, moreover, the same effect is observed in the full baked bread.

Keywords: Partially baked bread; Staling; Low temperatures storage; HPMC; Amylopectin retrogradation; Hardness

1. Introduction

Consumer habits have undergone great changes, motivated by the new social lifestyles. Those changes have promoted the increase in the consumption of wheat bread from partially baked bread due to its availability at any time of the day with the quality characteristics of the fresh bread (Leuschner, O'Callaghan, & Arendt, 1997). That is only possible because this bread is made in two stages. The first one is identical to the conventional breadmaking process, with the exception that baking is interrupted when the crumb is completely formed, and just before the crust colour development. Then, this partially baked bread is packaged and, for retarding microbial growth, it can be stored at sub-zero temperatures or under modified atmosphere. In the second stage, the partially baked bread or par-baked bread is baked again, acquiring the crust colour and crumb texture properties of the just baked bread (Leuschner et al., 1997).

The quality of the bread from par-baked bread after its storage at subzero or low temperatures or under modified atmospheres has already been evaluated (Bárcenas, Benedito, & Rosell, 2004; Bárcenas & Rosell, 2006; Fik & Surowka, 2002; Leuschner et al., 1997; Leuschner, O'Callaghan, & Arendt, 1999). However, no information is available about the changes of the par-baked bread during storage, despite its influence on the characteristics of

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doi:10.1016/j.foodchem.2005.12.043

the final full baked bread. A better knowledge of those changes would help in defining the most convenient procedure for obtaining good quality full baked bread.

Hydroxypropylmethylcellulose (HPMC) is a useful bread improver that increases bread volume, improves crumb texture and retards bread staling when used in both conventional breadmaking (Armero & Collar, 1996; Guarda, Rosell, Benedito, & Galotto, 2004; Rosell, Rojas, & Benedito de Barber, 2001), and par-baked bread (Bárcenas et al., 2004; Bárcenas, Haros, & Rosell, 2003; Bárcenas & Rosell, 2006). The ability of HPMC to act as a bread improver has been attributed to its hydrophilic structure, that allows its interaction with water (Sarkar & Walker, 1995; Schiraldi, Piazza, & Riva, 1996). In addition, HPMC is able to increase the interface activity between water and the non-aqueous phases of the bread dough, favouring the formation of emulsions and strong and uniform films (Bell, 1990). Moreover, HPMC has the ability to change from solution to gel during heating, forming a thermostable network that shields the bread dough from volume and moisture content losses during baking (Bell, 1990; Dziezak, 1991). HPMC also increases the viscosity of aqueous systems, interfering with the diffusion phenomena (Caldwell, Goff, & Stanley, 1992).

The aim of this work was to study the effect of HPMC on the shelf life of par-baked bread during its storage at low temperatures and also on the staling of the resulting full baked bread. With this purpose, the crumb hardness increase and the amylopectin retrogradation were evaluated on the par-baked and full baked bread.

2. Materials and methods

2.1. Breadmaking process

A basic recipe was used in this study, which consisted of 6.5 kg commercial flour (14% moisture content, 12.5% proteins): the other ingredients, on flour basis, were 2% compressed yeast, 2% salt and the water amount necessary to reach the optimum consistency (500 Brabender Units). In breads containing hydrocolloid, 0.5% (w/w, flour basis) of HPMC (Methocel K4M from Dow Chemical, France) was added to the dough. All the ingredients were mixed for 21 min with a spiral kneader, after resting for 10 min, the dough was mechanically divided into 150 g portions, hand-moulded, and mechanically sheeted and rolled to obtain wheat dough rolls. Proofing was performed at 28 °C and 85% relative humidity until the dough reached three times its initial volume; then bread dough rolls were partially baked for 7 min at 165 °C in an electric oven. Par-baked loaves were cooled until; the core crumb centre reached 40 °C, before packaging in polypropylene bags, and stored at 2 °C. Loaves were taken after 0, 2, 4, 7, 10 and 15 days of storage and baked in the electric oven at 195 °C for 10 min and cooled for 60 min at 25 °C, giving the so-called full baked bread.

2.2. Hardness determination

Hardness was determined on the crumbs of par-baked bread and full baked bread. To assess bread staling, crumb hardness was determined in the full baked bread stored for 24 h at 25 °C. Bread slices (four replicates) of 2 cm height were compressed at a velocity of 100 mm/min to 50% strain, using a 25 mm plunger in a texture press (texture press, TA-XT2i Stable Microsystems, Surrey, UK).

2.3. DSC analysis

The interrupted breadmaking process was simulated in the oven of the differential scanning calorimeter (Perkin–Elmer DSC-7, USA) (Bárcenas & Rosell, 2005). Briefly, bread dough was prepared as has been described for the breadmaking process; 20 mg of bread dough were precisely weighed in stainless steel pans (Perkin–Elmer 0319-0218), and hermetically sealed by using a press (Perkin–Elmer 0990-8467). An empty pan was used as a reference. Pans were heated in the DSC from 25 °C to 90 °C – in order to simulate the partial baking – followed by cooling to 25 °C and, after different storage times (0, 1, 2, 4, 7 days) at 2 °C, pans were reheated from 25 °C to 110 °C, in order to simulate the full baking process. Full baked bread staling was followed after 24, 48 and 96 h at 25 °C, while par-baked bread staling was followed after 0, 1, 2, 4 and 7 days at 2 °C that corresponds to the storage at low temperature. Amylopectin retrogradation during the storage of both par-baked and full baked bread was determined by heating from 25 °C to 110 °C. All the heating and cooling processes were performed into the DSC oven at 10 °C/min. The endotherms were analyzed by the system programme (Pyris Toolbars Application, version 3.01), obtaining the onset (T_o), peak (T_p) and conclusion (T_c) temperatures (°C), besides the gelatinization (ΔH_g) or the retrogradation (ΔH_r) enthalpies, expressed as mJ/mg of dry matter. The retrogradation index was defined as the ratio between retrogradation and gelatinization enthalpy ($\Delta H_{retrogradation}/\Delta H_{gelatinization}$) (León, Durán, & Benedito de Barber, 1997). The melting temperature range for the retrograded material (ΔT_r) was the difference between the onset and the conclusion temperatures ($T_c - T_o$). Three replicates for each sample were run.

The amylopectin retrogradation index was analyzed by using the Avrami equation:

$$(A_L - A_t)/(A_L - A_0) = \exp(-kt^n)$$

A_0, A_t and A_L being the retrogradation index at time zero, t and infinite (or limited value), respectively; k was the constant rate, and n was the Avrami exponent.

2.4. Statistical analysis

Multiple sample comparison was used for the statistical analysis of the results (Statgraphics Plus 5.1, Statistical Graphics Corporation, UK). Fisher's least significant

differences (LSD) test was used to describe means with 95% confidence.

3. Results and discussion

3.1. Effect of HPMC on the hardness of both partially baked bread stored at low temperatures and its full baked counterpart

Changes in crumb hardness of the par-baked bread stored at low temperatures (2 °C) and that of the resulting full baked breads are shown in Fig. 1. The hardness of par-baked bread significantly ($P < 0.05$) increased during its storage at low temperatures. In this bread, the crumb was completely formed after the partial baking and, as occurred in full baked bread, its hardness increased during storage. Crumb hardening is a complex process caused by simultaneous phenomena (Gray & Bemiller, 2003). Among them, amylopectin retrogradation is the most important (Zobel & Kulp, 1996); however, amylose recrystallization (Hug-Iten, Handschin, Conde-Petit, & Escher, 1999), moisture content lost (He & Hoseney, 1990), interactions between starch and gluten (Martin, Zeleznak, & Hoseney, 1991), and moisture redistribution (Czuchajowska & Pomeranz, 1989), also contribute to bread hardness increase.

Concerning full baked bread, crumb hardness of fresh breads (just baked and cooled) was not significantly ($P < 0.05$) affected by the time of storage of their respective par-baked breads. This behaviour was not surprising because the heat applied during the full baking process promotes the melting of the amylopectin crystals formed during the storage of par-baked bread (Morris, 1990); thus the products recover the softness of just baked bread.

It is important to note that for each time of storage at low temperatures, the hardness of the resulting full baked bread was different from those that of their par-baked counterparts. Up to 2 days at 2 °C, the hardness of the full baked bread was higher than that showed by the respective par-baked bread; nevertheless, the trend was reversed when par-baked bread underwent longer storage. Opposite phenomena are taking place during the full baking process. First, the unfolding of the amylopectin chains and the rupture of the starch–gluten interactions yield a soft crumb and second, the moisture content lost produces an increase in the crumb hardness. During the first days of storage at low temperatures, hardness increase (related to amylopectin retrogradation) in the par-baked bread was minimum, so only the loss of moisture content took place during the full baking, yielding loaves with harder crumbs than their respective par-baked loaves. Longer storage time (>2 days) produced an increase in the crumb hardness of the par-baked bread; thus the balance resulting from the above-described phenomena led to full baked loaves with softer crumbs than those in the par-baked counterparts.

During the staling of full baked bread after 24 h of storage at 25 °C, the crumb hardness was non-dependent of the storage time undergone by the par-baked bread. The hardness increase during aging has been attributed mainly to amylopectin recrystallization, although other phenomena, such as moisture diffusion between crumb and crust, and the starch–gluten interactions, can also contribute to hardness increase.

When HPMC was included in the recipe (Fig. 2), the hardness of par-baked bread did not show significant ($P < 0.05$) differences during the storage at low temperatures. In addition, the hardness of par-baked bread containing HPMC was significantly ($P < 0.05$) lower than that without the hydrocolloid. The same trend was previously observed in bread from conventional breadmaking (Bárcenas & Rosell, 2005; Guarda et al., 2004; Rosell et al., 2001), and full baked bread from frozen par-baked bread (Bárcenas et al., 2004; Bárcenas & Rosell, 2006). The HPMC has the ability to interact with water (Sarkar & Walker, 1995; Schiraldi et al., 1996); therefore, it is pos-

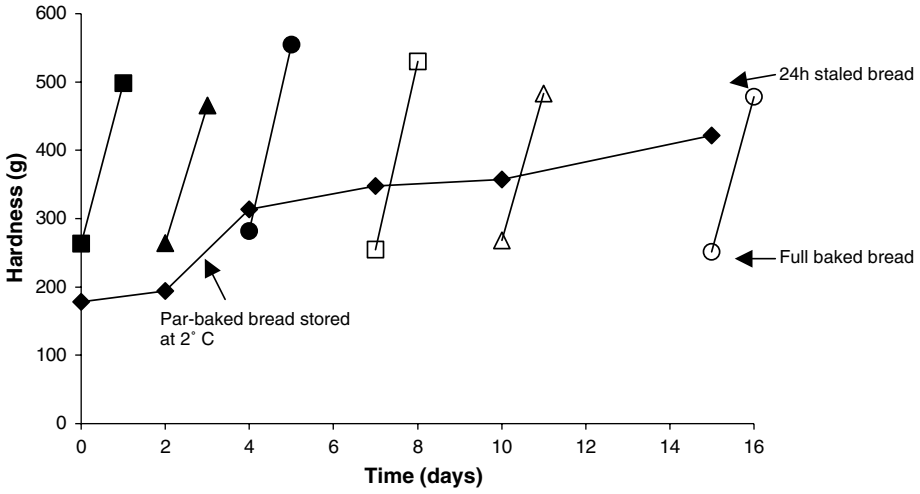

Fig. 1. Hardness trend of the crumb of par-baked breads stored at low temperature (2 °C) (◆), and their full baked counterparts (fresh and 24 h-staled). Par-baked bread (◆), full baked bread (fresh and 24 h-staled) from par-baked bread stored at 2 °C during 0 (■), 2 (▲), 4 (●), 7 (□), 10 (△) and 14 (○) days.

Fig. 2. Hardness trend of the crumb of par-baked breads containing HPMC stored at low temperature (2 °C) (◆), and their full baked counterparts (fresh and 24 h-staled). Par-baked bread (◆), full baked bread (fresh and 24 h-staled) from par-baked bread stored at 2 °C during 0 (■), 2 (▲), 4 (●), 7 (□), 10 (△) and 14 (○) days.

sible that this interaction hinders amylopectin recrystallization and also other phenomena involved in bread hardening. Additionally, studies of scanning electron cryomicroscopy (cryo-SEM) have suggested the existence of interactions between this hydrocolloid and the starch compounds (Bárcenas & Rosell, 2005, 2006). Those interactions could explain the interference of the HPMC in the process of bread hardening. Armero and Collar (1998) also proposed that HPMC decreases hardening by its interactions with gluten.

The crumb hardness of full baked breads containing HPMC was independent of the storage time of the corresponding respective par-baked breads, and was significantly ($P < 0.05$) lower than that observed in full baked bread made in absence of HPMC. Again, the HPMC probably interferes with the moisture content loss and the amylopectin unfolding, the final result being a constant hardness similar to that observed in the par-baked bread.

After 24 h of storage at 25 °C, the crumb hardness of the bread containing HPMC increased due to staling; however the increase was less than that observed in absence of HPMC. These results confirm that the HPMC effectively reduces the crumb hardness of the bread obtained from par-baked bread, as has been observed in bread from conventional breadmaking and that obtained from frozen par-baked bread (Bárcenas et al., 2004; Bárcenas & Rosell, 2005, 2006; Guarda et al., 2004; Rosell et al., 2001).

3.2. Effect of HPMC on the thermal parameters of the retrogradation endotherms of both par-baked bread during low temperature storage and full baked bread during aging at 25 °C

The thermal parameters of par-baked bread retrogradation endotherms during its storage at low temperatures are shown in Table 1. The retrogradation endotherm of par-baked bread in the absence and presence of HPMC did not show any significant ($P < 0.05$) difference in the T_o values with the time of storage at 2 °C, while T_p and T_c showed a significant ($P < 0.05$) decrease when the time of storage increased. In consequence, the retrogradation temperature range (ΔT_r) showed a significant ($P < 0.05$) reduction when compared between the first and seventh day of storage at low temperatures. The heat applied to par-baked bread during full baking melts the amylopectin crystals formed during storage at 2 °C; thus no peaks were detected in the endotherms of the just full baked bread. When full baked bread was stored at 25 °C, a staling endotherm was produced. The thermal parameters of these endotherms obtained after 24 h storage of full baked bread at 25 °C are shown in Table 2. In the presence and absence of HPMC, ΔT_r significantly ($P < 0.05$) increased with long storage time (7 days). At short storage time, bread containing HPMC led to endotherm peaks with lower T_p and T_c without changing T_o and, consequently, ΔT_r were lower than those obtained in the absence of HPMC.

The higher values of ΔT_r and the lower values of T_p observed in par-baked bread (in the presence and absence of HPMC) might be due to the formation of less ordered amylopectin crystals during the storage of par-baked bread in comparison with those formed during aging of full baked bread. This behaviour might be logical, considering that the storage at lower temperatures speeds up the crystallization, although giving less ordered structures (Czuchajowska & Pomeranz, 1989).

3.3. Effect of the HPMC addition on the retrogradation index of par-baked breads stored at low temperatures and their full baked counterparts

The amylopectin retrogradation produced in par-baked bread during its storage at 2 °C, and in full baked bread during its staling at 25 °C, expressed as retrogradation index ($\Delta H_r/\Delta H_g$), is schematically depicted in Fig. 3.

Table 1
Effect of low temperature storage at 2 °C on the thermal parameters of par-baked bread retrogradation endotherms

Time (days)	T_o (°C)	T_p (°C)	T_c (°C)	ΔT_r (°C)
Control				
1	37.31 ± 3.83a	54.98 ± 4.12c	72.83 ± 3.16c	35.52 ± 3.78c
2	37.90 ± 1.85a	54.31 ± 1.05b,c	71.93 ± 0.85c	34.03 ± 1.86a,b,c
4	38.17 ± 1.82a	54.13 ± 1.05b,c	71.64 ± 4.35b,c	34.58 ± 5.04a,b,c
7	37.41 ± 1.33a	52.70 ± 0.94a,b	68.39 ± 2.01a	30.98 ± 2.89a
HPMC				
1	35.83 ± 1.72a	54.11 ± 0.41b,c	71.11 ± 0.53b,c	35.29 ± 1.79b,c
2	36.23 ± 1.96a	53.88 ± 0.69a,b,c	70.54 ± 1.11a,b,c	33.69 ± 2.10a,b,c
4	37.50 ± 0.35a	53.21 ± 1.32a,b,c	69.44 ± 1.99a,b	31.24 ± 2.27a
7	36.91 ± 0.56a	51.89 ± 0.73a	68.75 ± 0.49a	31.91 ± 0.92 a

T_o, initial temperature; T_p, peak temperature; T_c, conclusion temperature; $\Delta T_r = (T_c - T_o)$, retrogradation temperature range.
Mean ± standard deviation ($n = 3$).
Means within columns followed by the same letter are not significantly different ($P < 0.05$).

Table 2
Thermal parameters of the retrogradation endotherms of the bread – from par-baked bread stored 1, 2, 4, 7 days at low temperatures – aged 24 h at 25 °C

Time (days)	T_o (°C)	T_p (°C)	T_c (°C)	ΔT_r (°C)
Control				
1	49.77 ± 0.69b	61.87 ± 0.94c	75.07 ± 0.08d,e	25.30 ± 0.77c
2	49.86 ± 0.80b	60.87 ± 0.23b,c	74.55 ± 0.10c,d	24.70 ± 0.90c
4	48.50 ± 0.70a,b	61.02 ± 0.02b,c	74.17 ± 0.24c	25.18 ± 0.25c
7	47.40 ± 0.94a	60.91 ± 0.88b,c	76.17 ± 0.40f	28.78 ± 0.54e
HPMC				
1	49.03 ± 0.74b	58.69 ± 0.69a	67.44 ± 0.33a	18.41 ± 0.40a
2	48.96 ± 0.06b	58.19 ± 0.26a	69.10 ± 0.14b	20.14 ± 0.20b
4	49.61 ± 0.05b	59.37 ± 1.42a,b	69.15 ± 0.07b	19.55 ± 0.02a,b
7	48.52 ± 0.01a,b	60.70 ± 0.95b,c	75.49 ± 0.62e,f	26.97 ± 0.62d

T_o, initial temperature; T_p, peak temperature; T_c, conclusion temperature; $\Delta T_r = (T_c - T_o)$, retrogradation temperature range.
Mean ± standard deviation ($n = 3$).
Means within columns followed by the same letter are not significantly different ($P < 0.05$).

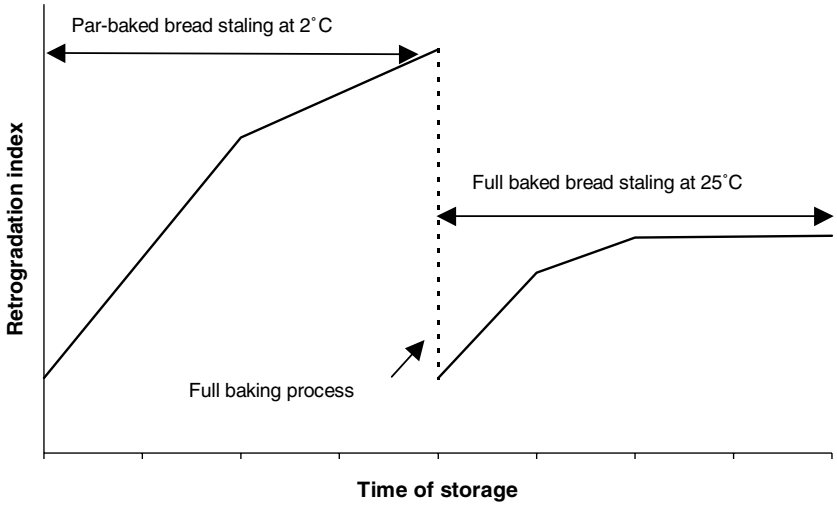

Fig. 3. Scheme of the behaviour of amylopectin retrogradation expressed as retrogradation index ($\Delta H_r/\Delta H_g$), during the interrupted breadmaking process.

Initially, amylopectin retrogradation occurs and, in consequence, the retrogradation index of par-baked bread increases during its storage at low temperature. During the full baking process, the amylopectin chains are again unfolded, leading to a reduction of this parameter. Finally, the retrogradation index rises again during the staling of full baked bread at 25 °C. The resulting trend allows analysis of the changes observed by the retrogradation index in the loaves obtained by the interrupted breadmaking process (Figs. 4 and 5).

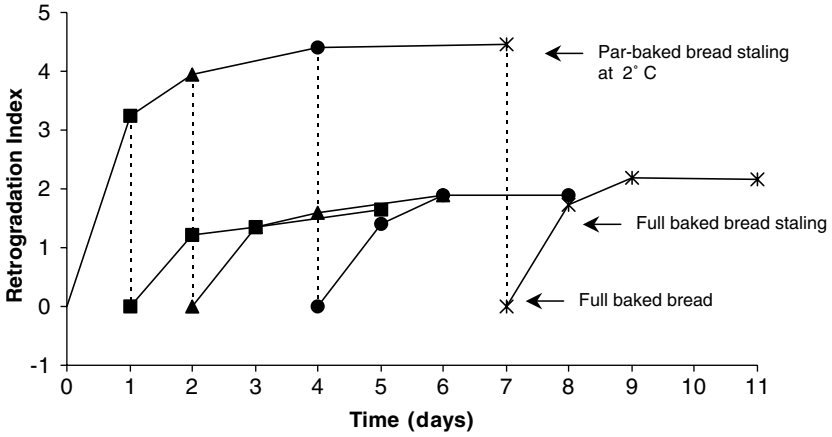

Fig. 4. Effect of the storage time on the amylopectin retrogradation index ($\Delta H_r/\Delta H_g$) of bread: (i) partially baked and (ii) full baked bread obtained from par-baked bread after: 1 (■), 2 (▲), 4 (●), and 7 (✳) days of storage at low temperatures.

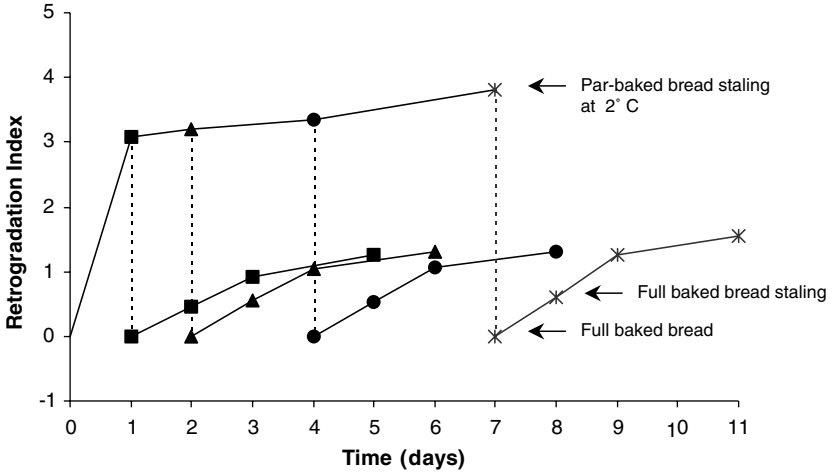

Fig. 5. Effect of the storage time on the amylopectin retrogradation index ($\Delta H_r/\Delta H_g$) of bread containing HPMC: (i) partially baked and (ii) full baked bread obtained from par-baked bread after: 1 (■), 2 (▲), 4 (●), and 7 (✳) days of storage at low temperatures.

The retrogradation index of par-baked bread showed a rapid increase during the first day of storage at 2 °C. This result suggests that, during the first time of storage at low temperatures, the amylopectin molecules undergo retrogradation, bringing about crystal structures strong enough to require a great amount of energy for their melting. The recrystallization process went on during storage but showed an asymptotic trend. The increase of the retrogradation index during this stage can be attributed to the crystal growth and to the reorganization of the crystal structures already formed.

The retrogradation index of the par-baked bread (3.25–4.45) was significantly ($P < 0.05$) higher than that of the sample containing HPMC (3.09–3.81). The amylopectin recrystallization requires the presence of the effective moisture content needed to plasticize macromolecules and to allow the mobility of the polymer chains (Levine & Slade, 1990). Therefore, if the HPMC is able to hold water due to its hydrophilic nature and, in consequence, decrease the availability of water molecules, it will also reduce the amylopectin recrystallization.

The retrogradation index of just full baked bread was zero, because no endotherms were detected. After 24 h of storage, at 25 °C, produced a significant ($P < 0.05$) increase in the retrogradation index. In full baked bread in the absence of HPMC (Fig. 4), the retrogradation index was significantly ($P < 0.05$) augmented when the storage time of par-baked bread at low temperatures increased. The heat applied during full baking melted the amylopectin crystals. Thus, the diverse behaviour observed in staled full baked samples might be related to the different amount of effective water, because the amylopectin crystallization is controlled by the amount of this water during staling (Zeleznak & Hoseney, 1986). Taking into account that the DSC pans were hermetically sealed and, consequently, no water lost could occur, the differences among samples were probably due to the water redistribution between the crystalline and amorphous zones or between the gluten

and starch. It has been reported that when the amylopectin changes from amorphous to crystalline state, water molecules are incorporated into the crystals, remaining immobilized (Leung, Magnuson, & Bruinsma, 1983). In addition, water released from gluten during bread staling is simultaneously absorbed in the starch retrogradation (Chen, Long, Ruan, & Labuza, 1997). The amylopectin unfolding, during full baking, yields free water molecules, which will be available for the new crystallization process. In the par-baked bread stored for long periods of time, the great amylopectin crystallization could bring about a higher amount of free water in full baked bread, which in turn would promote higher crystallization during its aging at 25 °C.

In samples containing HPMC (Fig. 5), the retrogradation index increased during the first 48 h at 25 °C, showing an asymptotic trend at longer times. Moreover, the retrogradation indices of full baked breads were not significantly ($P < 0.05$) affected by the times of storage of their par-baked counterparts.

The retrogradation indices in all the samples containing HPMC were lower than those of their counterparts without HPMC. This hydrocolloid reduces the recrystallization enthalpy of the amylopectin during staling (Bárcenas, Haros, Benedito, & Rosell, 2003). The possible interactions between the HPMC and the bread compounds (Armero & Collar, 1998; Bárcenas & Rosell, 2005, 2006), and also the ability of this hydrocolloid to interact with the effective water present in the system (Sarkar & Walker, 1995; Schiraldi et al., 1996), could explain the interference of the HPMC in the amylopectin recrystallization.

3.4. Kinetics of amylopectin retrogradation in bread from partially baked bread stored at low temperature

It has previously been reported that the Avrami equation is a useful tool for studying the kinetics of amylopectin retrogradation during staling (Baik, Kim, Cheon, Ha, & Kim, 1997; Gujral, Haros, & Rosell, 2003; Kim & D'Appolonia, 1977; Palacios, Schwarz, & D'Appolonia, 2004; Rojas, Rosell, & Benedito de Barber, 2001; Zhang & Jackson, 1992). However, due to the absence of thermodynamic equilibrium in the amylopectin retrogradation, some authors have considered that Avrami parameters do not describe this phenomenon (Marsh & Blanshard, 1988; Miles, Morris, Orford, & Ring, 1985; Slade & Levine, 1989). However, if the Avrami parameters are adequately used they provide a good basis for comparisons of the kinetics resulting from different treatments (Slade & Levine, 1989). In this study, the Avrami equation was used for analysing the retrogradation index of the amylopectin ($\Delta H_r/\Delta H_g$) in full baked bread. The value of n was fixed to unity ($n = 1$), since the relative values of the Avrami kinetic parameters are independent of the n values (Palacios et al., 2004).

In the presence and absence of HPMC, the time of storage of par-baked bread at low temperature did not produce a significant ($P < 0.05$) effect on the constant rate (k) values for full baked bread (Table 3); therefore, the recrystallization rate of the amylopectin in full baked bread was not affected by the time of storage of partially baked bread. Regarding the effect of HPMC, the k values of the samples in the presence and absence of HPMC did not significantly ($P < 0.05$) differ during the first two days of storage. However, in samples with 4 and 7 days at 25 °C, the rate constant was higher in the absence of HPMC. Likely, the interaction of HPMC with a noticeable amount of effective water reduces the recrystallization rate of the amylopectin.

Table 3
Parameters of Avrami equation for the curves of amylopectin retrogradation index ($\Delta H_r/\Delta H_g$) of full baked bread from par-baked bread stored at low temperatures

Time of low temperature storage (days)	k (h^{-1})	$(\Delta H_r/\Delta H_g)_L$	R^2
Control			
1	0.039 ± 0.026a,b,c	1.72 ± 0.09c,d	0.858
2	0.040 ± 0.020a,b,c	1.98 ± 0.36d,e	0.960
4	0.054 ± 0.007b,c	1.87 ± 0.04c,d	0.997
7	0.062 ± 0.003c	2.31 ± 0.04e	0.941
HPMC			
1	0.029 ± 0.013a,b	0.95 ± 0.21a	0.989
2	0.034 ± 0.001a,b,c	1.28 ± 0.05a,b	0.966
4	0.021 ± 0.000a	1.56 ± 0.17b,c	0.972
7	0.024 ± 0.001a	1.86 ± 0.04c,d	0.992

$(\Delta H_r/\Delta H_g)_L$ and k are the retrogradation index at infinite time and the rate constant, respectively.

The retrogradation index at infinite time ($(\Delta H_r/\Delta H_g)_L$), in the absence of HPMC, was barely constant up to 4 days, increasing significantly ($P < 0.05$) after 7 days of storage. In the presence of HPMC, the retrogradation index at infinite time $(\Delta H_r/\Delta H_g)_L$ showed a progressive increase with the time of storage at low temperature, but the values were significantly ($P < 0.05$) lower than those obtained in the absence of HPMC. Again, the results suggest that HPMC is able to interfere with amylopectin crystallization, likely due to its ability to retain water and modify its availability in the system.

4. Conclusions

Partial baked bread underwent a progressive staling during its storage at low temperatures. However, the crumb hardness increase and the amylopectin crystallization produced during staling were reversed due to the heat applied during the full baking process. The storage time of par-baked bread at low temperatures did not affect the crumb hardness of the full baked counterpart, nor its further behaviour during staling at 25 °C. HPMC had the ability to interfere with the staling process of par-baked and full baked bread. The use of this hydrocolloid avoided the crumb hardening of par-baked bread and reduced the crumb hardness of full baked bread. Additionally, HPMC decreased the amylopectin retrogradation and removed the

effect of the time of par-baked bread storage on the amylopectin retrogradation of full baked bread.

Acknowledgements

This work was financially supported by Ministerio de Educación y Ciencia Project (AGL2002-4093-C03-02) and Consejo Superior de Investigaciones Científicas (CSIC), Spain. M.E. Bárcenas acknowledges her grant from Universidad de las Américas, Puebla, México.

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