**IMPACT OF FIBERS ON PHYSICAL CHARACTERISTICS OF FRESH AND
STALED BAKE OFF BREAD**

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ABSTRACT

The technological functionality of different fibers (high methylated ester pectin, resistant starch, insoluble-soluble fiber blend) was tested in partially baked breads stored either under sub-zero or low temperatures, in order to assess their possible role as breadmaking ingredients in bake off technologies (BOT). Fiber-containing formulations affected bread specific volume and crumb hardness, and those characteristics were also dependent on both the breadmaking process (conventional or BOT) and the storage conditions of the par-baked bread (low or sub-zero temperatures). The inclusion of resistant starch (RS) and fiber blend in the bread formulation induced a reduction in the specific volume of the bread and an increase of hardness. Crumb image analysis indicated that breadmaking process affected significantly the number of alveoli. The storage of par-baked breads at low temperatures accelerates crumb hardening during staling, and that effect was greatly dependent on the duration of the storage, being that effect magnified in the case of breads containing fiber blend. Therefore, formulations should be carefully checked with the specific breadmaking process to be followed. Special attention should be paid to the storage conditions of the partially baked bread, since they significantly affect the technological quality of fresh breads and their behaviour during staling.

Key words: partially baked, breadmaking, quality, staling.

INTRODUCTION

Bread quality has long been the target of cereal technologist, looking for ingredients and improvers that provide better volume and improved sensory characteristics. Nowadays, consumer expectations include the term healthy, being necessary to meet the binomial healthy-pleasant when innovative formulations are foreseen. Baked goods also follow that pattern, thus ingredients that provide both physiological beneficial effect and improved volume and texture are being considered for developing new formulations.

Considerable scientific research has confirmed the beneficial role of the dietary fibre in the reduction of chronic ailments such as cardiovascular disease, certain forms of cancer and constipation ([Lairon et al., 2005](#); [Rodríguez et al., 2006](#)). Those statements have raised consumer awareness about the healthy role of dietary fibre intake, gaining popularity fibre enriched cereal based products ([Collar, 2008](#); [Polaki et al., 2010](#)). In conventional breadmaking, fiber replacement of flour disrupt the starch–gluten matrix and restrict and force gas cells to expand in a particular dimension ([Collar et al, 2006](#)) affecting dough viscoelastic behaviour and constraining dough machinability and gassing power ([Collar et al, 2007](#)). The fiber source and the type and degree of processing are the main factors influencing functional properties (solubility, viscosity, gelation, water-binding and oil-binding capacities, mineral and organic molecule binding) ([Rosell et al, 2009](#)). Those characteristics have great impact on the functional quality of the intermediate manufacturing and end products when obtained by conventional breadmaking processes ([Rosell et al, 2006](#); [Collar et al, 2007](#)).

In the last decades bake off or interrupted technologies (BOT) are becoming a common practice for the big bakeries, because they allow solving the constraints on food preparation and shopping imposed by the accelerated consumer lifestyles (Rosell and Gómez, 2007; Rosell, 2009). Those technologies are applied to obtain convenience bakery products available at any time of the day. The partially baked bread (part-baked, par baked bread or pre-baked bread) is performed following the conventional process, but with a two stage baking. It consists in a first baking till the dough structure is fixed giving a product with aerated crumb but without a crispy crust that is formed along the second baking (Fik and Surowska, 2002; Bárcenas and Rosell, 2006a, 2007). Despite the increasing awareness about increasing the fibers intake in breadmaking products, there is scarce literature about their impact on the bread technological quality, despite the different baking time, low baking temperatures and moreover low or sub-zero storage temperatures. It is already established that all polymeric compounds that interact with water can affect the quality of the resulting product (Wang et al, 2002). Hydrocolloids fall within that category, exerting great effect on breadmaking performance and bread quality (Rojas et al., 1999, Mandala et al., 2007). Recently, Mandala et al., (2009) also observed the effect of inulin on the crumb elasticity and crust firmness of par-baked breads stored for one week at sub-zero temperature. Moreover, the addition of different hydrocolloids and fibers to par-baked breads affects the bread microstructure, especially pore roundness and pore size distribution determined by analysis of the scanned crumb images (Polaki et al., 2010).

The objective of this research was to determine the effect of various biopolymeric ingredients (high methylated ester pectin, resistant starch, insoluble-soluble fiber blend)

that fall within the fiber category, on the technological quality (specific volume, texture, crumb structure and crust flaking) of bread obtained from interrupted breadmaking process and to assess their impact on the par-baked storage and bread staling thereof.

MATERIALS AND METHODS

Commercial breadmaking wheat flour was used in this study. The characteristics of the flour were: 14.51% (d.b.) moisture content (ICC 110/1), 9.54% (d.b.) protein content (ICC 105/2), 1.09% (d.b.) fat content (ICC 136), 0.51 % (d.b.) ash content (ICC 104/1), 450s Falling Number (ICC 107/1) and 94.4 % gluten index (ICC 155). The alveographic parameters (ICC 121) were 57 mm, 141 mm and 237 10⁻⁴ J for tenacity (P), extensibility (L) and deformation energy (W), respectively. The bread improver or processing aid (83.2% wheat flour, 15% Multec datem HP20, 1% fungal α -amylase and xylanase, 0.8% ascorbic acid) was provided by Puracor (Groot-Bijgaarden, Belgium). Pectin (GENU® pectin 150 USA-SAG type BA-KING, PKelco), soluble (Raftiline® HP, Orafiti) and insoluble (Oat fiber 300, SunOpta) fibers were provided by Puratos. Resistant starch (tapioca maltodextrin, ActiStar*11700 C) was provided by Cargill SA. The selection of those fibers were based on previous studies (Bollaín and Collar, 2004, Rosell et al, 2009) and with the aim of giving a better overview on the fibres effect on different breadmaking processes, biopolymers of a range of different chemical structure (fructooligosacharides, maltodextrins, poligalacturonic acid, and cellulose/hemicellulose), and nutritional profile (prebiotic, metabolic and physiological effect) were selected. Specifically, resistant starch has a particular type of digestion and functionality (Annison and Topping, 1994), high methoxylated pectin has reported to be a good structuring agent for making baked goods (Bollaín and Collar, 2004), an a combination of soluble (inulin) and insoluble (oat fiber) fibers that has completely

different technological functional properties (Rosell et al, 2009). The rest of the ingredients were acquired in the food market.

Breadmaking process

Two different breadmaking processes were followed: conventional and partially baked bread. Breadmaking procedures were recommended by Puracor (Groot-Bijgaarden, Belgium). Basic wheat dough formula on 100 g flour basis consisted of 3% (w/w) compressed yeast, 1.8% (w/w) salt and 1% (w/w) bread improver. When fibers (10 % resistant starch, 1% pectin, 10% fiber blend) were present, wheat flour was replaced for the corresponding amount of each ingredient. In all cases, the amount of water was modified to keep dough added fibers the same dough consistency as control dough. For conventional processes dough consistency was kept at 420 Brabender Units (BU) as measured by a Farinograph, and for partially baked bread process dough consistency was 580 BU. Specifically the water absorption used for each samples was as follows: in conventional process, control 58%, RS 60%, pectin 58%, and mixed fibers 59%; for partially baked bread 5% less water absorption than their counterparts in conventional process was added. Bread doughs were prepared by mixing ingredients in a spiral mixer (AV18/2, Vimar Industries 1900, S.L., Spain) for nine minutes. After 10 min resting, dough was divided into 70 g pieces and hand moulded. Fermentation was carried out in a proofing cabinet (Infrisa, Spain) at 35°C and 95% relative humidity for one hour. In conventional process, complete baking was carried out in a deck oven (modular deck over with three trays, Eurofours, France) at 230°C for 20 min with steam injection at the beginning of the baking. Partial baking was carried out at 170°C for 16 minutes, and then loaves were cooled down at 25°C for 30 min, being the temperature

of the bread core around 30°C. Partially baked bread was stored at two different temperatures (4°C or -18°C) till its full baking. Partially baked bread stored at 4°C was packed in polypropylene pouches after cooling. Conversely, partially baked loaves stored at -18°C were placed directly in a blaster freezer (Platejunior, Samifi Technik, Germany) at -30°C till the bread core reached -18°C and then packed in polypropylene pouches. For storage studies, partially baked frozen loaves were stored at -18°C for three months in a horizontal freezer (COH 570 FM, Casfri SL, Spain); whereas partially baked refrigerated loaves were stored at 4°C for 10 days. Full baking was carried out at 230°C for 12 minutes. Frozen samples were previously thawed at 25°C for 10 minutes. Partially baked loaves stored at low temperature were referred as PB and partially baked loaves stored at sub-zero temperature were referred as PBF.

Bread quality parameters

Technological parameters were evaluated along the storage period taking samples after 1, 2, and 3 months in PBF or after 3, 7 and 10 days in PB. Parameters of bread quality included: volume, specific volume (rapeseed displacement, [AACC Standard 10-05](#)), moisture content ([AACC Standard 44-15A](#)), crumb hardness, crust flaking, and crumb image analysis. Hardness was measured in a Texture Analyzer TA-XT2i (Stable Micro Systems, Surrey, UK) using two bread slices of 1-cm-thickness, which underwent two double compression cycle up to 50% penetration of its original height at a crosshead speed of 1 mm/s and a 30 s gap between compressions, with a cylindrical stainless steel probe (diameter 25 mm) ([Collar and Bollain, 2005](#)).

Crust flaking test was carried out in specific crushing system developed by [Le Bail et al. \(2005\)](#). Bread was crushed on its flanks and on its base by 30 % of its diameter and

height in crushing system. Crust pieces were collected and weighed and then a digital picture of crust pieces was taken. Using an UTHSCSA Image Tool 3.0 Software, average crust flakes size was measured.

Crumb cell analysis was performed by capturing images of longitudinal and cross sections of bread sample, 10 mm thick, in a flat bed scanner equipped with the software HP PrecisoScan Pro version 3.1 (HP scanjet 4400C, Hewlett-Packard, USA). The default settings for brightness (midtones 2.2) and contrast (highlights 240, midtones 2.2, shadows 5) of the scanner software were used for acquiring the images. Eight images of 10 cm x 10 cm with 350 dpi of resolution were acquired in levels of grey (8 bits, readout 0-255) and captured in jpeg format for each measurement. Images were analyzed by Image J software (National Institutes of Health, Bethesda, Md, USA) using the Otsu's algorithm for assessing the threshold according to [Gonzales-Barron and Butler \(2006\)](#). Values of scanned images were obtained in pixels and converted into mm (23 pixels along a straight line were equivalent to 1mm) by using known length values. Data derived from the crumb structure analysis included: number of cells or alveoli, average cells area and cell circularity, and were used for comparing purposes among different samples. Circularity was calculated using the following equation:

$$\text{Circularity} = 4 \times \pi \times \text{area} / (\text{perimeter})^2$$

A value of 1.0 indicates a perfect circle.

Bread behaviour during storage

Bread staling was assessed using Avrami parameters. Values for the Avrami model factors were estimated by fitting experimental points into the non-linear regression equation ([Armero and Collar, 1998](#)):

$$(T_{\infty} - T_t) / (T_{\infty} - T_0) = \exp(-kt^n)$$

Where T_0 is the crumb hardness at zero time, T_{∞} is the crumb hardness at ∞ time, T_t is the crumb hardness at t time, k is a constant rate of the process (usually used $1/k$ time constant to compare bread hardening rate), and n is the Avrami exponent, which indicates the type of crystals growth (additional information about the physical meaning of the Avrami parameters can be found in Avrami, 1939).

Statistical analysis

Experimental data were statistically analyzed by using Statgraphics V.7.1 program (Bitstream, Cambridge, MN), to determine significant differences among them. When ANOVA indicated significant F values, multiple sample comparison was also performed and Fisher's least significant difference (LSD) procedure was used to discriminate among the means.

RESULTS AND DISCUSSION

Effect of formulation and storage conditions of par-baked bread on specific volume of fully baked bread

Breads were produced using formulations containing different fibers and following the interrupted breadmaking process or BOT technologies. Technological quality of the fully baked breads was assessed after their storage at low or sub-zero temperatures, and the values compared to the bread obtained by conventional breadmaking process (control). Fiber containing formulations affected bread specific volume (Figure 1) and crumb hardness (Figure 2), and those characteristics were also dependent on both the breadmaking process (conventional or BOT) and the storage conditions of the par-baked

bread (PB or PBF). The inclusion of resistant starch (RS) and fiber blend in the bread formulation induced a reduction in the specific volume of the bread obtained by conventional breadmaking (Figure 1). Generally, insoluble fibers prevent the free expansion of dough during fermentation, and also they can induce an early fixing of the structure due to their higher water content (Rogers and Hoseney, 1982; Wang et al., 2002). The same trend was observed when breadmaking followed BOT process. The presence of pectin resulted in a significant increase of the specific volume, but that effect was completely cancelled out in the BOT process. Pectin is a good breadmaking improver for the conventional breadmaking process (Bollaín and Collar, 2004). The presence of ionized carboxyl groups in the pectin structure allows the formation of hydrogen bonds besides stronger interactions like ion–dipole (Bárcenas et al., 2009). However, it seems that its polymeric structure is not strong enough to keep crumb structure when contractions after partial baking and cooling occur and final baking does not allow recovering volume. Par-baked bread is submitted to tensile stresses in response to the compression of gas phase during cooling, being very sensitive to stresses associated to final baking (Lucas et al., 2005).

Storage conditions (low temperature or sub-zero temperature) of partially baked bread affected significantly the specific volume of the fully baked bread, although in some cases formulation was able to counteract those effects. Storage of par-baked control bread for up to 10 days at low temperatures (PB) (Figure 1A) did not significantly affect the specific volume of the fully baked bread. In opposition, frozen storage (PBF) resulted in a progressive reduction of the bread specific volume, more stressed during the first month of storage (Figure 1B).

In fiber containing breads, storage of the par-baked bread at low temperature did not affect the specific volume, regardless bread with fiber blend that showed a dramatic decrease along the storage. The presence of fiber blend could disrupt the crumb structure due to the physical disruption of the gluten network, favouring the crumb collapse during storage at low temperatures, consequently yielding lower specific volume (Mandala et al., 2009).

Conversely, the breads obtained from PBF enriched formulations hardly modified their specific volume along three months of frozen storage. It must be remarked that loaves containing pectin even showed better performance after long storage (three months) than the control samples. Probably, the water binding capacity of the polymers (Bárcenas et al., 2009) exerted a protective effect against ice damage, and as a consequence loaves kept their initial specific volume.

Effect of formulation and storage conditions of par-baked bread on crumb hardness of fully baked bread

Formulation had great impact on the crumb hardness of bread obtained by conventional breadmaking process (Figure 2), namely resistant starch and fiber blend that resulted in a significant increase of the crumb hardness. The fiber blends had a marked effect on crumb hardness yielding a coarse crumb structure (results not shown); similar effect, although in lesser extent was observed in the presence of resistant starch. The same tendency was observed with BOT technologies, again fiber blend gave the highest hardness followed by resistant starch. The presence of pectin did not modify the crumb hardness, and that effect was independent of the breadmaking process.

Storage of par-baked bread led to a steady increase of the crumb hardness, but the slope of the enhancement was strongly dependent on the formulation and storage temperature. In general, storage at low temperatures gave fully baked breads with harder crumbs than their counterpart stored at sub-zero temperatures. This effect was hardly detected in the control bread, but it was especially noticeable in breads containing fiber blend, which indicated that the soluble-insoluble fiber blend lacked structuring effect when submitted to low temperatures. Frozen storage of par-baked bread containing fiber blend showed slow increase of the hardness. Control and breads containing pectin were less affected by the storage conditions. Those results agree with previous observation that at frozen temperatures, the phenomena involved in the hardening were not present or they occurred in a very slow rate ([Bárcenas and Rosell, 2006a](#)).

Technological quality parameters of breads from different formulations

Other technological quality parameters were determined in the fully baked breads obtained from partially baked breads either stored under sub-zero temperature for three months or at low temperatures for 10 days (Table 1). Significant differences were observed also in moisture content and cross-section shape (width/height ratio), being the first significantly increased in the presence of the structuring agents tested (Table 1). Concerning the breadmaking process and the storage conditions, breads from PB had significantly lower moisture content, with exception of the breads containing fiber blend, which was due to the lower amount of water used in the formulation of PB breadmaking process. Similar results were obtained by [Mandala et al. \(2007\)](#) that described only an increase of the moisture content when hydrocolloids were supplemented. Conversely, breads from PBF had significantly higher moisture content

than the bread obtained by conventional breadmaking, again breads containing fiber blend was an exception. The higher moisture content observed in the breads from PBF was attributed to the less water evaporation during the full baking process, because part of the initial heat was required for increasing the sample temperature that were not completely thawed. Barcéas and Rosell (2006b) also observed that bread obtained from frozen part-baked breads had higher water content than their counterpart obtained from refrigerated part-baked breads due to differences in the duration of the final baking (because additional heating were required for complet thawing) or to condensations during thawing. Regarding the fibers blend effect, presumably the different water hydration properties and viscometric profile of the polymers composing the fiber blend might explain its different behaviour (Collar et al., 2006, Rosell et al, 2009). The addition of some hydrocolloids like guar gum or locus bean also led to lower crumb moisture content (Mandala et al., 2008).

Fresh bread obtained from partially baked bread is prone to undergo crust flaking, which consists in the detachment of some part of the crust. It has been associated to excessive drying of the surface during post-baking, namely along chilling, freezing and thawing operations (Lucas et al. 2005, Hamdami et al. 2007). This phenomenon has been associated to two different processes: the ice concentration under the crust due to the presence of the freezing front, and the interfacial differences between crust and crumb resulted from the tensile forces and stresses induced by the thermomechanical shock (Lucas et al. 2005). The effect of the different formulations and the storage conditions were evaluated on the crust flaking (Table 1), obtaining in all cases very low flaking (less than 2%). In the breads obtained from the different formulations (Table 1),

significant differences in crust flaking were observed. Nevertheless, no relationship could be established between the extent of flaking and the formulation or the breadmaking process. In opposition, the size of the flakes was dependent on the bread formulation, obtaining smaller flakes when bread contained resistant starch. Significant differences were also observed in the crust section, but no trend with neither with the formulation nor the breadmaking process could be established.

Crumb structure analysis of breads obtained from conventional breadmaking process indicated that the studied formulations containing polymeric compounds did not affect the number of alveoli. Nonetheless, breadmaking process affected significantly ($P < 0.05$) this parameter, obtaining higher number of alveoli with the conventional breadmaking process, excepting the bread containing pectin. The air entrapped into the dough during the mixing process determines the number of gas cells in the bread crumb ([Baker and Mize, 1942](#)), and further breadmaking operations can only affect the size of those cells. Therefore, results observed in the different breadmaking processes might be attributed to different amount of air incorporated into the dough as a consequence of their different consistency. [Polaki et al. \(2010\)](#) also described that crumb microstructure was significantly influenced by the breadmaking process (partially baking or frozen dough).

Despite the differences observed on the number of alveoli, no general trend could be envisaged on the average area of the gas cells in the crumb structure, due to either formulation or breadmaking process, although in all the cases very small cells were observed. No significant differences were obtained in the cell circularity. It has been reported that inulin, hydroxypropylmethycellulose or locus bean gum did not induce

changes in the pore size of breads obtained by conventional breadmaking, although when those were obtained from frozen dough or partially baking an increase in the pore size of breads were obtained (Polaki et al., 2010).

Influence of formulation and storage conditions on bread staling

The breads staling during storage at 25°C was also assessed to determine the potential of these formulations and also the impact of par-baked storage conditions for extending the freshness of the loaves. Figure 3 shows the crumb hardness increase during staling of the breads obtained from partially baked breads stored at low or sub-zero temperatures. At first glance it was observed that breads from PB underwent faster staling than their counterparts from PBF, and that effect was magnified in the presence of the fiber blend, whereas was minimized in the samples containing pectin. Therefore, the storage of par-baked breads at low temperatures accelerates crumb hardening during staling, and that effect was greatly dependent on the duration of the storage. Moreover, those storage conditions had negative impact on the breads containing fiber blend.

Breads from PBF showed slow crumb hardness increase and that enhancement was independent on the time of storage. Control samples and bread containing pectin obtained from PBF had the same hardening trend than their counterparts obtained by conventional breadmaking process, thus the BOT process did not affect the crumb hardening. In addition, pectin was the polymer that kept softer crumbs during longer period, and also reduced crumb hardness differences among breads stored for different periods at low or sub-zero temperatures (Figure 3). Hydrocolloids affect breadmaking performance and keepability of stored breads (Collar and Armero, 1996; Armero and Collar, 1998; Bárcenas et al, 2003). The origin of this effect has been partially explained

in terms of complex formation between starch polymers (amylose and/ or amylopectin) and hydrocolloid during pasting (Collar, 2003), and also disruption of the gluten structure (Rosell and Foegeding, 2007).

The kinetic of crumb hardening was modelled using the Avrami equation as reported previously for describing crystallization kinetics during storage (Cornford et al, 1994; Collar and Armero, 1996). This equation has been used for explaining bread staling based on starch retrogradation, despite the contribution of the other bread components (Collar and Armero, 1996). Kinetic parameters obtained from the fitted curves are shown in Table 2. Breads containing pectin showed the lowest constant k , indicating slower rate for development of hardening during storage, related to the rate of crystals growing (Torre et al., 1995). Conversely, resistant starch and fiber blend gave the highest values of k . Concerning the Avrami exponent n , although some variation was observed within each formulated bread, overall results indicated that pectin slowed down this parameter, whereas the opposite results were obtained in breads containing resistant starch or fiber blends, which has been related to the type of crystal nucleation and their growing geometry (Torre et al., 1995). However, no differences could be ascribed to either the breadmaking process or the duration of the par-baked storage. 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, has been proposed to additional players that contribute to hardness increase (Zobel and Kulp, 1996). The fibers added has the ability to interact with water therefore, limiting the water available for starch gelatinization/recrystallization and likely modifying the structure of the crystals

produced, as has been previously observed for some hydrocolloids and fibers (Bárcenas et al, 2007, Santos et al, 2008). In fact, flour replacement at different levels by dietary fibers from different sources significantly modifies the qualitative and quantitative thermal profile on starch gelatinisation and amylopectin retrogradation and kinetics during storage in different extend depending on the fiber source (Santos et al, 2008). Specifically, dietary fiber incorporation into water-flour systems delayed endothermic transition temperatures for both gelatinisation and retrogradation phenomena except for the peak temperature of retrogradation, and provided variable associated endothermic enthalpies.

From the above results it was concluded that tested fibers (functional ingredients) affected in different extent the technological quality parameters of the fresh bread and the impact of those ingredients could vary depending on the type of breadmaking process. In fact, the technological functionality of pectin was negatively affected by BOT process or interrupted baking. Storage conditions of the partially baked breads had also great incidence on specific formulations like those containing fiber blend, which were not strong enough to keep crumb structure. The supplementation with pectin or resistant starch resulted in breads from PBF, keeping their specific volume and crumb texture during sub-zero temperature storage. Low temperatures are a recommended alternative for extending the shelf-life of partially baked bread due to their lower energy input, but, although it has reduced impact on the specific volume, crumb hardness and staling of fully baked breads were progressively accelerated along storage.

Therefore, formulations should be carefully checked with the specific breadmaking process to be followed, and in the case of BOT processes, even the storage conditions of the partially baked bread play a fundamental role on the technological quality of fresh breads and their behaviour during staling.

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FIGURE CAPTIONS

Figure 1. Effect of fiber enriched formulation and storage conditions of par-baked bread on the specific volume of fully baked breads. A. partially baked bread stored up to 10 days at low temperatures, B. partially baked bread stored up to three months at sub-zero temperatures. Conv: conventional breadmaking; RS: resistant starch.

Figure 2. Effect of fiber enriched formulation and storage conditions of par-baked bread on the crumb hardness of fully baked breads. A. partially baked bread stored up to 10 days at low temperatures, B. partially baked bread stored up to three months at sub-zero temperatures. Conv: conventional breadmaking; RS: resistant starch.

Figure 3. Evolution of crumb hardness during staling of fiber-enriched breads obtained from conventional breadmaking (C), par-baked breads stored at low temperatures (solid symbols) or sub-zero temperatures (open symbols). **a:** control (without fibers), **b:** resistant starch, **c:** pectin, **d:** fiber blend. Legend is referred to the days of storage at low temperatures or the months of storage at sub-zero temperatures.

530 **Table 1.** Effect of different fiber enriched formulations and storage conditions of par-baked bread on several technological quality
531 parameters of fully baked breads. PB: bread from partially baked bread stored 10 days at low temperatures; PBF: bread from partially
532 baked bread stored three months at sub-zero temperatures. Conv: conventional breadmaking; RS: resistant starch.

Formulation	Process	Moisture content (%)		width/height ratio	Crust flaking		Crust section, mm	Crumb cell analysis		
					CF _M	CF _S , mm ²		Number of alveoli	Average area, mm ²	Circularity
Control	Conv	28.4	B	1.43 f	0.97 c	0.68 d	2.6 c	1243 c	1.42 d	0.74 a
	PB	26.7	A	1.60 j	0.55 b	0.25 ab	3.2 d	901 a	1.68 e	0.74 a
	PBF	31.4	Cd	1.36 d	1.18 d	0.46 c	3.8 e	1007 a	1.49 d	0.73 a
RS	Conv	32.5	E	1.24 b	0.13 a	0.18 a	2.8 c	1158 b	1.04 ab	0.74 a
	PB	31.5	Cd	1.19 a	1.66 f	0.31 b	2.0 a	919 a	1.09 b	0.74 a
	PBF	35.1	G	1.50 g	0.12 a	0.20 a	3.0 d	959 a	0.93 a	0.74 a
Pectin	Conv	31.3	Cd	1.41 e	1.30 d	0.96 ef	3.2 d	1221 c	1.93 f	0.74 a
	PB	30.9	C	1.57 i	0.91 c	0.91 e	2.1 a	1151 b	1.24 c	0.73 a
	PBF	33.7	F	1.32 c	0.65 b	0.88 e	2.1 a	1274 c	1.12 b	0.73 a
Fibers	Conv	32.6	E	1.41 e	0.59 b	0.37 bc	2.8 c	1233 c	0.96 a	0.75 a
	PB	34.6	Fg	1.36 d	1.45 e	0.93 e	2.3 b	956 a	1.03 ab	0.74 a
	PBF	32.1	De	1.56 h	0.84 c	0.98 f	2.5 b	1128 b	0.93 a	0.72 a

533 Means followed by the same letter within a column were not significantly different (P<0.05) (n=4).
534 Process: Con: conventional; PBF: partial baking and frozen storage; PB: partial baking and low temperature storage
535 Formulations: control; RS: resistant starch; pectin; Fibers: fiber blend.
536 CF_M: g crust/100g bread; CF_S: average crust flakes size.

Table 2. Staling kinetic parameters (hardness, g force) during storage of breads obtained from different breadmaking processes fitted to the Avrami equation. PB: bread from partially baked bread stored up to 10 days at low temperatures; PBF: bread from partially baked bread stored up to three months at sub-zero temperatures. Conv: conventional breadmaking; RS: resistant starch.

Formulation	Process	Bread staling kinetics $\frac{T_{\infty} - T_t}{T_{\infty} - T_o} = e^{-kt^n}$					
		Storage time*	T ₀	T _∞	n	k	R ²
control	Conv		56	3559	0.470	0.021	0.844
	PB	0	151	2408	1.104	0.003	0.999
		3	183	1031	2.179	0.001	0.999
		7	118	4594	1.394	0.001	0.977
		10	69	3876	0.972	0.008	0.961
	PBF	0	92	1953	0.793	0.010	0.963
		1	150	602	1.110	0.022	0.998
		2	144	2941	1.270	0.001	0.999
		3	98	582	1.187	0.017	0.999
	RS	0	56	3559	0.470	0.021	0.844
		3	189	4177	0.908	0.011	0.958
		7	214	1865	0.937	0.059	0.998
		10	478	2795	1.163	0.010	0.934
pectin	Conv	0	66	1869	0.830	0.014	0.991
		3	120	1160	1.397	0.005	0.975
		7	235	4451	1.015	0.006	0.975
		10	478	2795	1.163	0.010	0.934
	PB	0	123	675	1.746	0.008	0.994
		1	155	1517	0.938	0.011	0.972
		2	112	1715	1.190	0.004	0.986
		3	107	1546	1.043	0.008	0.967
	PBF	0	120	1160	1.397	0.005	0.975
		3	235	4451	1.015	0.006	0.975
		7	478	2795	1.163	0.010	0.934
		10	144	3389	0.822	0.016	0.996

fiber blend	Conv		345	1995	1.137	0.004	0.914
	PB	0	514	2190	0.818	0.068	0.995
		3	857	2474	1.061	0.141	0.971
		7	118	3483	1.394	0.001	0.998
		10	1046	4108	0.923	0.105	0.986
	PBF	0	131	1622	0.661	0.163	0.997
		1	441	1662	1.201	0.019	0.995
		2	413	2686	0.724	0.032	0.959
		3	490	2193	2.514	0.001	0.997

*Storage time: PB in days, PBF in months

543

544

Figure 1.

A

B

551 **Figure 2.**

552 **A**

553

554 **B**

555

556 **Figure 3.**