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ORIGINAL PAPER

Effect of fermentation conditions on bread staling kinetics

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Abstract The effects of yeast dose, temperature and fermentation time on bread volume, bread density, bread texture (firmness, cohesiveness, resilience, springiness and gumminess) and their change during staling were analysed. Thus, changes in the texture profile (TP) parameters as bread aged were modelled and their initial values and their variation rate were obtained. In white and whole breads, the longer the fermentation time and the higher the yeast dose, the lower the firmness and the firming rate. The fermentation temperature only affected the initial firmness in whole breads. Significant linear correlations were found between bread density and volume ($r^2 = 0.94$ in white bread; $r^2 = 0.96$ in whole bread), between density and the initial firmness ($r^2 = 0.88$ in white bread; $r^2 = 0.61$ in whole bread), and between the first two parameters and the firming rate. Between density and firming rate r^2 obtained was 0.72 in white bread and 0.32 in whole bread and between volume and firming rate r^2 obtained was 0.58 in white bread and 0.29 in whole bread.

Keywords Bread staling · Fermentation · Staling kinetics · Texture · Shelf-life

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Introduction

Bread staling is a complicated process that involves loss of aroma, changes in mouth feel, loss of crumb softness and development of crumbliness. These changes transform freshly baked bread into an unsaleable product. It is thought that 3% of the production of bread is returned for problems of staling in the shape of unsaleable bread [1]. The importance of this phenomenon has kept researchers busy for nearly 150 years and several comprehensive reviews have been published on this topic [1–3]. Starch retrogradation has been considered for many years the main factor responsible for the loss of crumb softness [4–6]. However several aspects of the bread staling process remain unclear and recent studies have stated that gluten [7], non-gluten proteins [8], lipids [9, 10], pentosans [11] and migration of moisture from the crumb to the crust [12, 13] play a significant role in bread staling.

The majority of the studies focused on retarding the staling process deal with the use of enzymes and additives. α-Amylases have been widely used as antistaling agents either alone [4, 14–16] or in combination with other enzymes [17–19]. Additionally, other enzymes such as proteases [17] or xylanases [20] have shown their capacity to reduce the firming of bread over prolonged storage. Among the additives, emulsifiers are the most regularly used antistaling agents [21, 22] but in the last few years studies about the antistaling effect of hydrocolloids [23–25] and maltodextrins [26–28] have become increasingly common. It is also known that the addition of fibres reduces bread staling [29].

The investigations about the influence of the processing parameters on bread staling have been less numerous. They are based on the study of the mixing and resting time [16], the sourdoughs [30–32], the conditions of baking [33], and the storage in modified atmosphere [34, 35]. However, studies about the influence of the fermentation variables on bread staling have been published only by Freilich [36]. In this study, the influence of the amount of yeast and the fermentation time on bread staling was analysed. One of his findings was that differences in staling rates due to the studied fermentation variables were not significant. However, Kulp [37] claimed that a long fermentation time improves freshness retention. Hence, it seemed essential to undertake a detailed study on the influence of the fermentation variables on bread staling.

In this paper, the influence of fermentation time, yeast dose and fermentation temperature on the initial texture of breads has been analysed. For this purpose, changes in different textural parameters (firmness, cohesiveness, resilence, springiness and gumminess) over time will be modelled. The parameters obtained from the modelled equation (*a* and *b*) have been also analysed. This study has been done with white and whole breads.

Materials and methods

Materials

Commercial blends of Spanish wheat flours (white/whole) with 14.48/14.24% moisture, 0.58/1.34% ash content, 11.82/12.45% protein, 8.5/11.8 dry gluten, 325/370 falling number and with Chopin Alveograph parameters (white) of 165×10^{-4} J energy of deformation and 0.4 curve configuration ratio were used. Improver, Line omatic (T-500 Puratos, Spain) containing DATEM, ascorbic acid, and fungal α-amylase was added. Commercial dry yeast (Saf-instant, Lesaffre, France) was used.

Methods

Bread-making procedure

A straight dough process was performed using the following ingredients (% on the flour basis): water (56%), instant yeast (1%), salt (2%), and improver (0.5%). After mixing all the ingredients during 15 min, bread dough was divided (300 g), rounded, rested (15 min), sheeted and molded into the pans. Proofing was carried out at 75% of relative humidity (RH). Fermentation variables tested at three levels (−1, 0, 1) included yeast dose (0.5, 1, 1.5%), time (1, 2.5, 4 h) and temperature (25, 30, 35°C). Loaves were baked for 33 min at 200°C in an electrical oven. After 1 h cooling, bread loaves were packed in polyethylene bags and stored for 1, 3, 5, 9 and 13 days at 20 ± 1°C.

Evaluation of bread quality

After cooling for 1 h, baked breads were weighed and loaf volume was measured using a loaf volume meter (Chopin, France), by rapeseed displacement. Three measurements were made on each loaf and averaged for duplicate loaves. Densities were calculated from the weight and volume of particular loaves.

Crumb texture was determined by a Texture Analyzer TA-XT2i (Stable Microsystems, Surrey, UK) provided with the software “Texture Expert”, and equipped with an aluminium 25 mm diameter cylindrical probe. Slices of 2 cm thickness were compressed to 50% of their original height in a “Texture Profile Analysis” double compression test (TPA), at 1 mm/s speed test, with a 30 s delay between first and second compression. Primary parameters (firmness, cohesiveness, springiness and resilience) and gumminess (secondary mechanical characteristic) were calculated from the TPA graphic.

Changes in each textural parameter were adjusted to different curvilinear models for each combination of studied factors. Mean values of the coefficients of determination for each model are shown in Table 1. When the most suitable models for each texture parameters were chosen, *a* and *b* values which defined each proof were established. These values were analysed using an ANOVA analysis.

Statistical analysis

An experimental design was conducted by means a 3^3 factorial design in order to evaluate all single effects and second order interactions between factors. The resultant design is shown in Table 2. A multiple comparison analysis was carried out to assess significant differences among the samples. Fisher’s least significant differences (LSD) test was used to describe means with 95% confidence. Statgraphics Plus V5.1 (Statsoft Inc., USA) was used as statistical analysis software.

Results and discussion

Modelling of textural parameters

Table 1 shows the means of the coefficients of determination (r^2) obtained when the trend of the different textural parameters over time was adjusted to different simple curvilinear models in every test. Firmness fitted the best to a multiplicative model in white bread, and to a square root model in whole bread. To study firmness, the square root model was chosen due to the high coefficient of determination in both bread types and because the *a* and *b* parameters were readily interpretable in the equation. In the multiplica-

Table 1 Mean of r^2 values of several curvilinear models used to describe the relationship between different textural parameters and the storage time in white and whole breads

Model	Firmness (*N*)		Cohesiveness		Resilence		Springiness		Gumminess (*N*)	
	White	Whole	White	Whole	White	Whole	White	Whole	White	Whole
Linear $y = a + b*x$	91,71	93,47	80,80	67,44	72,18	56,72	89,85	43,68	41,58	74,19
Multiplicative $y = a*x^b$	93,06	96,25	96,85	93,89	96,29	87,61	85,42	55,14	37,09	57,25
Square root-*x* $y = a + b*x^{1/2}$	92,64	96,46	91,03	80,76	84,86	71,22	91,16	49,80	39,54	67,87
Square root-*y* $y = (a + b*x)^2$	90,41	91,96	83,60	69,48	76,55	58,88	89,92	43,73	41,24	73,88
Exponential $y = \exp(a + b*x)$	88,27	90,04	86,15	71,51	80,65	60,93	89,98	43,77	40,86	73,52
Logarithmic-*x* $y = a + b*\ln(x)$	88,25	93,53	96,93	92,19	94,60	85,35	86,33	55,32	36,77	57,12
Double reciprocal $y = 1/(a + b/x)$	87,81	87,38	78,04	93,19	79,53	93,82	61,99	57,80	33,44	36,19
S-curve $y = \exp(a + b/x)$	79,21	81,15	84,49	95,33	88,63	95,77	63,43	58,46	32,50	35,70
Reciprocal-*y* $y = 1/(a + b*x)$	81,78	85,14	90,29	75,34	87,16	65,14	90,05	43,85	40,04	72,62
Reciprocal-*x* $y = a + b/x$	68,72	74,00	89,88	96,87	94,75	96,83	64,86	59,11	31,53	35,17

Table 2 3^3 Factorial design for sampling

Sample n°	Factors[a]		
	A	*B*	*C*
1	−1	−1	−1
2	−1	−1	0
3	−1	−1	1
4	−1	0	−1
5	−1	0	0
6	−1	0	1
7	−1	1	−1
8	−1	1	0
9	−1	1	1
10	0	−1	−1
11	0	−1	0
12	0	−1	1
13	0	0	−1
14	0	0	0
15	0	0	1
16	0	1	−1
17	0	1	0
18	0	1	1
19	1	−1	−1
20	1	−1	0
21	1	−1	1
22	1	0	−1
23	1	0	0
24	1	0	1
25	1	1	−1
26	1	1	0
27	1	1	1

[a] Levels (−1, 0, 1) of factors *A*–*C*: *A* yeast dose: 0.5% (−1), 1% (0), 1.5% (1); *B* fermentation time: 1 h (−1); 2.5 h (0), 4 h (1); *C* fermentation temperature: 25°C (−1), 30°C (0) and 35°C (1)

tive model, the interpretation of b depended on the *a* values. Change in bread firmness during storage has been the most widely used parameter in the evaluation of bread staling. The most frequently adopted model to define this behaviour has been the Avrami equation [38–40], although Ovadia and Walker [41] pointed out that the bread firming kinetics could respond to a discontinuous model. On the other hand, Rasmussen and Hansen [35] stated that the increase in firmness was linear with time during the first 3 days of storage, and then the firming rate decreased with time. Armero and Collar [38] obtained a mean r^2 value of 97.19 when they fitted five points to the Avrami equation with four variables, and Collar and Bollain [39] obtained a mean r^2 value of 96.31 (97.63 in white bread and 95 in whole bread) when seven measurements over time were fitted to the Avrami equation. In our case, we obtained a mean r^2 value of 92.64 for white bread and 96.46 for whole bread, but we fitted five data points to an equation with only two variables. The application of the Avrami model to bread firming is based on starch retrogradation; however, bread staling is a result of several effects and although starch retrogradation is included in these effects, it is not the only cause. Gluten [7], pentosans [11] or lipids [9] play an important role too. Thus, the square root model, because of its simplicity, easy interpretation of *a* and *b* variables, and high coefficient of correlation, constitutes a good model to analyse the variation of crumb firmness in ageing bread.

The rest of the textural parameters have been also used to study the bread staling process [14, 18–20, 39]; although they are less common than firmness in studies modelling bread staling. Collar and Bollain [39] fitted cohesiveness and resilience to a multiplicative model, with a negative *b* value. In cohesiveness they obtained a mean r^2 value of 87.5 for white bread and of 92.38 for whole bread, whilst in resilience the coefficients of determination were 87.6 for white bread and 86.5 for whole bread. These data coincided with the high coefficients of determination found for the multiplicative model in our study. However, to model the cohesiveness we chose the logarithmic model because of its high r^2 value, very similar to the multiplicative model, and its ease of interpretation. To model resilience, the reciprocal-x model was chosen because of the same reasons. Finally, with springiness only the modelling of the white bread was considered, choosing the square root of x. In whole bread, gumminess was modelled using the linear model. They were chosen because they presented the highest coefficients of determination. No adequate models were found for springiness in whole bread and for gumminess in white bread, since no r^2 higher than 60% were obtained.

In all the chosen models, value a corresponded to the initial texture, and value b was related to the increase rate, or decrease rate, of the studied parameter. In general, an increase in firmness and gumminess, and a decrease in cohesiveness, resilience and springiness were observed as time elapsed, thus agreeing with the results obtained in other studies on both white and whole breads [39, 42–44]. These results could be translated to negative b values in the logarithmic model, used for modelling cohesiveness, and in the square root of x chosen for modelling springiness.

Influence of fermentation conditions on texture

In Tables 3 and 4, the individual effects of fermentation conditions on the studied variables for white and whole bread are shown. White bread volume increased when yeast dose, fermentation time and temperature increased, although no significant differences were found between fermentation at 30 and 35°C. This is consequence of the highest gas production due to yeast action in the fermentation process and to the ability of dough to retain these gases. However, the effect of fermentation conditions on whole bread volume was less marked. Significant differences were only found between the minimum and the maximum yeast dose and between the lowest fermentation time and the top two. Salmenkallio-Marttila et al. [45] already found that the

Table 3 Significant single effects of design factors on bread quality and staling kinetics parameters of white breads

Parameters	Overall mean	Level	Yeast	Time	Temperature
Volume	1,026.59	−1	1,074.44a	950.00a	1,194.81a
		0	1,310.00b	1,348.98b	1,304.17b
		1	1,418.33c	1,503.79c	1,303.79b
Density	0.22	−1	0.26c	0.29c	0.23b
		0	0.21b	0.20b	0.21a
		1	0.19a	0.17a	0.21a
a_{firmness}	3.30	−1	5.66b	6.57b	
		0	2.98a	2.15a	
		1	1.26a	1.16a	
b_{firmness}	2.50	−1	3.18b	3.68b	
		0	2.23a	2.07a	
		1	2.08a	1.75a	
$a_{\text{cohesiviness}}$	0.69	−1	0.67a		
		0	0.69ab		
		1	0.71b		
$b_{\text{cohesiviness}}$	−0.131	−1		−0.113b	
		0		−0.137a	
		1		−0.145a	
$a_{\text{resilence}}$	0.105	−1	0.097a	0.116b	0.106ab
		0	0.106ab	0.104ab	0.114b
		1	0.112b	0.095a	0.095a
$b_{\text{resilence}}$	0.181	−1	0.172a	0.148a	
		0	0.181ab	0.190b	
		1	0.191b	0.205b	
$a_{\text{springiness}}$	2.02	−1	1.86a	1.74a	
		0	2.06b	2.12b	
		1	2.13b	2.20b	
$b_{\text{springiness}}$	−0.39	−1		−0.29b	
		0		−0.41a	
		1		−0.47a	

Values for each parameter in the same column followed by the same letters are not significantly different ($p < 0.05$)

Table 4 Significant single effects of design factors on bread quality and staling kinetics parameters of whole breads

Parameters	Overall mean	Level	Yeast	Time	Temperature
Volume	718.33	−1	683.61a	666.67a	
		0	714.72ab	737.78b	
		1	756.67b	750.56b	
Density	0.38	−1	0.40b	0.41b	
		0	0.38ab	0.37a	
		1	0.35a	0.35a	
a_{firmness}	12.19	−1	14.31b	16.16b	13.90b
		0	10.96a	11.17a	12.53b
		1	11.31a	9.25a	10.15a
b_{firmness}	6.18	−1	7.80b	6.84b	
		0	5.54a	5.74a	
		1	5.19a	5.96ab	
$a_{\text{cohesiviness}}$	0.57	−1	0.55a		
		0	0.58b		
		1	0.58b		
$b_{\text{cohesiviness}}$	−0.079	−1	−0.071b	−0.074b	
		0	−0.084a	−0.077b	
		1	−0.080a	−0.085a	
$a_{\text{resilence}}$	0.105	−1		0.112c	
		0		0.105b	
		1		0.099a	
$b_{\text{resilence}}$	0.097	−1	0.086a	0.085a	0.099ab
		0	0.100b	0.096b	0.091a
		1	0.105b	0.110c	0.100b
$a_{\text{gumminess}}$	10.15	−1	11.76b	12.84b	11.27b
		0	9.37a	9.23a	10.12ab
		1	9.33a	8.40a	9.07a
$b_{\text{gumminess}}$	0.24	−1	0.36b		
		0	0.19a		
		1	0.18a		

Values for each parameter in the same column followed by the same letters are not significantly different ($p < 0.05$)

addition of bran reduced bread volume. This could be either due to the lower retention capacity of whole flour doughs owing to the dilution of the gluten matrix, and causing thus the gas to escape despite of a higher production, or because the bran particles force gas cells to expand in a particular dimension [46]. This effect was more important in the final phases of fermentation. This lower capacity to retain gas was therefore manifested in the excessive fermentations, due to the yeast dose or to a prolonged time. Considering the studied fermentation conditions, fermentation time influenced the most bread volume and temperature the least. The differences between the minimum and middle values were also very important; that is, those between the under-fermented and optimum fermented doughs and those between the latter and the over-fermented doughs. Bread density followed an opposite pattern to volume, as expected. Weight loss during the fermentation process increased with fermentation time, temperature and yeast dose (data not shown), primarily due to moist reduction. This fact reinforced the results obtained in bread volume.

The fermentation time and the yeast dose reduced initial firmness (a_{firmness}) in white and whole breads. Whole bread showed higher firmness than white bread, coinciding with the study of Laurikainen et al. [47]. Significant differences were only found between the minimum and the rest of values, so the effect of an incomplete fermentation was more important than the excess of fermentation. Temperature only showed significant effect in whole bread firmness obtained in fermentation at 35°C, being lower than the others. As in the case of volume, the effect of fermentation time was the most important, and it was higher in white than in whole bread. The effect of fermentation on the initial firmness could be largely explained by the increment in volume that fermentation generated in bread.

The effect of fermentation conditions on the firming rate (b_{firmness}) was very similar to the effect on the initial firmness, although less marked. In this case, the effect of temperature was not significant in any case, as the results obtained by Salovaara and Valjakka [48] in sour wheat bread showed. Therefore, the prolonged fermentations, and to a lesser extent the high yeast doses, helped to reduce the firming rate, especially in white bread. These results were not in agreement with those found by Freilich [36], possibly because this author only studied the compressibility changes occurring in bread during the first 3 days, and used a formulation with a high sugar and shortening content, which reduced the firming rate. Axford et al. [49] demonstrated that the firming rate in bread was related to the specific volume. In our study, a high linear correlation between white bread density and firming rate was found ($r = 0.85$). This correlation was much lower in whole bread ($r = 0.57$), because the volume increment was not constant. In both cases the coefficients of correlation were much lower than those found between density and initial firmness. This fact indicated that the effect of fermentation on the firming kinetics could not be explained only by its effect on volume. Wheat flour contains several enzymes, such as amylases, proteases or lipases [50], and in doughs other enzymes derived from micro-organisms or added with the additives can be found [51]. It was demonstrated the efficacy of the α-amylases, alone or in combination with other enzymes, on the reduction of the firming rate in bread [16, 17, 52–54]. In fact, it was demonstrated that the presence of cereal α-amylases reduced recrystalization of the amylopectin in bread crumb [55]. Longer fermentation times would allow a wider action of the dough enzymes, and consequently a reduction in the firming rate. At the

Table 5 Significant second-order interactive effects of design factors on bread quality and staling kinetics parameters of white breads

		Density	a_{firmness}	b_{firmness}	$a_{\text{cohesiviness}}$	$b_{\text{cohesiviness}}$	$a_{\text{resilence}}$	$a_{\text{springiness}}$	$b_{\text{springiness}}$
Yeast	Time								
−1	−1	0.34**	11.33**	5.37***	0.63**	−0.098**		1.44*	−0.22*
−1	0	0.24	3.83	2.64	0.69	−0.135		1.91	−0.40
−1	1	0.20	1.81	1.54	0.70	−0.155		2.24	−0.54
0	−1	0.28	5.65	3.02	0.70	−0.118		1.79	−0.32
0	0	0.19	1.99	1.73	0.70	−0.133		2.19	−0.42
0	1	0.16	1.29	1.51	0.68	−0.139		2.21	−0.46
1	−1	0.24	2.74	2.65	0.72	−0.120		1.98	−0.33
1	0	0.16	0.65	1.84	0.72	−0.140		2.26	−0.41
1	1	0.16	0.38	2.19	0.69	−0.140		2.16	−0.42
Yeast	Temperature								
−1	−1	0.27*		4.01**	0.67***	−0.130*	0.098***		
−1	0	0.26		2.76	0.67	−0.119	0.104		
−1	1	0.24		2.78	0.67	−0.139	0.089		
0	−1	0.24		2.48	0.67	−0.131	0.092		
0	0	0.19		2.05	0.73	−0.132	0.126		
0	1	0.20		1.72	0.67	−0.127	0.100		
1	−1	0.19		1.98	0.75	−0.134	0.128		
1	0	0.18		2.64	0.72	−0.138	0.111		
1	1	0.18		2.08	0.67	−0.135	0.096		
Time	Temperature								
−1	−1				0.67**		0.111*		
−1	0				0.68		0.123		
−1	1				0.69		0.115		
0	−1				0.70		0.107		
0	0				0.72		0.114		
0	1				0.68		0.091		
1	−1				0.71		0.101		
1	0				0.71		0.104		
1	1				0.64		0.079		

*$p < 0.05$

**$p < 0.01$

***$p < 0.001$

same time, higher yeast doses would also increase the quantity of dough enzymes and would minimize the phenomena associated with staling.

In both kinds of bread, their initial cohesiveness tended to rise as yeast dose increased. In addition, the tendency to diminish over time rose when fermentation time and yeast dose increased, although the yeast dose only presented significant effect on whole bread. In general, the differences were more important between the lowest yeast dose and fermentation times and the other studied levels. The initial resilience increased with yeast dose in white bread, but diminished with fermentation time in both kinds of bread. Conversely, its tendency to increase over time rose with yeast dose and fermentation time in white and whole breads. In white bread, an increment in initial springiness with the yeast dose and the fermentation time between the lowest and the rest of levels could be detected. Within its downward tendency, significant differences were only appreciated between the lowest fermentation times and the others, with the greater decrease occurring in the most prolonged fermentations. In whole bread, it was noticeable a decrease in the initial gumminess between the lowest yeast dose and fermentation times and the others. Moreover, its tendency to rise with the longest fermentation times decreased.

The fermentation temperature only affected significantly the initial resilience in white bread, and subsequent changes in resilience and the initial gumminess in whole bread. Only in the initial gumminess a clear tendency to diminish with temperature was observed.

Table 6 Significant second-order interactive effects of design factors on bread quality and staling kinetics parameters of whole breads

		Volume	Density	a_{firmness}	b_{firmness}	$a_{\text{cohesiviness}}$	$a_{\text{resilence}}$	$a_{\text{gumminess}}$
Yeast	Time							
−1	−1		0.46*	20.25*	9.24*			15.88**
−1	0		0.38	13.28	6.81			10.43
−1	1		0.37	9.39	7.36			8.98
0	−1		0.41	14.29	6.16			11.71
0	0		0.37	8.94	5.83			8.37
0	1		0.35	9.66	4.64			8.03
1	−1		0.37	13.94	5.12			10.92
1	0		0.35	11.29	4.58			8.88
1	1		0.34	8.70	5.87			8.18
Yeast	Temperature							
−1	−1	673.33***	0.41***	15.71*		0.56**	0.104*	12.97*
−1	0	628.33	0.43	15.92		0.55	0.104	12.29
−1	1	749.17	0.36	11.29		0.54	0.103	10.03
0	−1	718.33	0.38	12.11		0.57	0.100	9.86
0	0	755.00	0.36	12.37		0.58	0.106	9.74
0	1	670.83	0.40	8.41		0.60	0.108	8.51
1	−1	678.33	0.40	13.88		0.60	0.114	10.97
1	0	826.67	0.32	9.31		0.57	0.109	8.32
1	1	765.00	0.34	10.75		0.57	0.100	8.69

*$p < 0.05$

**$p < 0.01$

***$p < 0.001$

Table 7 Coefficients of correlation of the linear relationship between volume, density and textural parameters of white breads

	Density	a_{Firmness}	b_{Firmness}	$a_{\text{Cohesiveness}}$	$b_{\text{Cohesiveness}}$	$a_{\text{Resilence}}$	$b_{\text{Resilence}}$	$a_{\text{Springiness}}$	$b_{\text{Springiness}}$
Volume	−0.97***	−0.86***	−0.76***	0.36	−0.73***	0.84***	−0.64***	−0.16	0.82***
Density		0.94***	0.85***	−0.43*	0.80***	−0.90***	0.72***	0.17	−0.88***
a_{Firmness}			0.84***	−0.57**	0.84***	−0.92***	0.75***	0.10	−0.90***
b_{Firmness}				−0.45*	0.74***	−0.85***	0.75***	0.14	−0.79***
$a_{\text{Cohesiveness}}$					−0.46*	0.58**	−0.20	0.63***	0.47*
$b_{\text{Cohesiveness}}$						−0.86***	0.88***	0.38	−0.96***
$a_{\text{Resilence}}$							−0.84***	−0.13	0.93***
$b_{\text{Resilence}}$								0.57**	−0.88***
$a_{\text{Springiness}}$									−0.33

*$p < 0.05$

**$p < 0.01$

***$p < 0.001$

The significant interactions were shown in Tables 5 (white bread) and 6 (whole bread). In general, it was observed that as the fermentation conditions increased, the effects on the studied variables became less marked. This would corroborate the individual effects already mentioned. The highest interactions occured between yeast dose and fermentation time, and between yeast dose and fermentation temperature.

Correlation between textural parameters and their subsequent changes

In Tables 7 (white bread) and 8 (whole bread) the coefficients of correlation of the linear relationships between the studied variables were shown. In general, the best correlations were obtained for white bread, since as fermentation conditions increased, bread volume also rose. Both volume and density achieved a high correlation with white bread firmness and resilience, in the initial and in the subsequent values, as well as with the changes in cohesiveness and springiness. In all cases, it was observed that density showed better correlations with texture parameters than volume. In white bread, the best model to correlate density and firmness was the square root of x (Fig. 1) with an $r = 0.96$ for initial firmness and somewhat lower ($r = 0.86$) for changes in firmness. Therefore as the density increased, the increment in firmness decreased. Alternatively, in whole

Table 8 Coefficients of correlation of the linear relationship between volume, density and textural parameters of whole breads

	Density	a_{Firmness}	b_{Firmness}	$a_{\mathrm{Cohesiveness}}$	$b_{\mathrm{Cohesiveness}}$	$a_{\mathrm{Gumminess}}$	$b_{\mathrm{Gumminess}}$	$a_{\mathrm{Springiness}}$	$b_{\mathrm{Springiness}}$
Volume	−0.98***	−0.70***	−0.54**	−0.03	−0.37	−0.77***	−0.36	−0.37	0.40*
Density		0.78***	0.57**	−0.00	0.46*	0.85***	0.39*	0.43*	−0.50**
a_{Firmness}			0.39*	−0.10	0.66***	0.97***	0.15	0.56**	−0.73***
b_{Firmness}				−0.59**	0.59**	0.57**	0.93***	−0.00	−0.51**
$a_{\mathrm{Cohesiveness}}$					−0.62***	−0.12	−0.65***	0.38*	0.45*
$b_{\mathrm{Cohesiveness}}$						0.66***	0.57**	0.46*	−0.90***
$a_{\mathrm{Gumminess}}$							0.32	0.55**	−0.74***
$b_{\mathrm{Gumminess}}$								−0.06	−0.39*
$a_{\mathrm{Springiness}}$									−0.57**

*$p < 0.05$
**$p < 0.01$
***$p < 0.001$

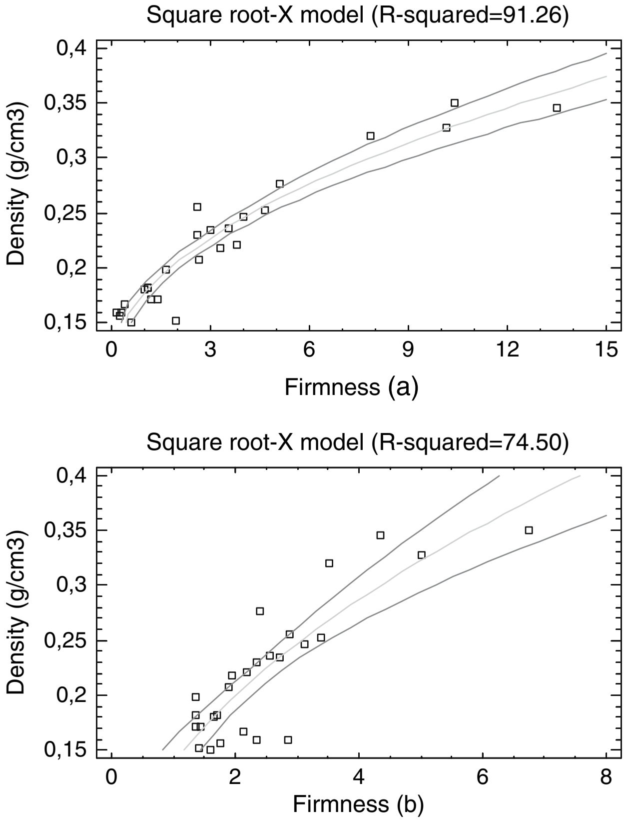

Fig. 1 Best correlation models between bread density of white breads and firming kinetics parameters

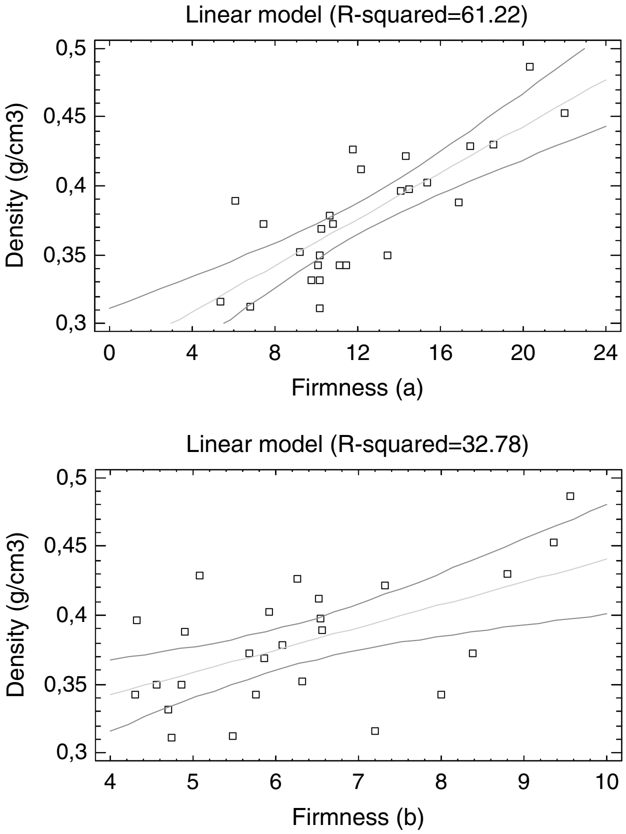

Fig. 2 Best correlation models between bread density of whole breads and firming kinetics parameters

bread the best model was the linear one (Fig. 2) and the coefficients of correlation were slightly lower (0.78 for value *a*, and 0.57 for value *b*). In turn, the firmness values were well correlated with the rest of the textural parameters, except for initial springiness. In whole bread, the high correlations between the initial firmness and gumminess, as well as between their subsequent changes (b_{firmness} and $b_{\mathrm{gumminess}}$) stood out.

Conclusion

Changes in the firmness parameters, for both white and whole bread, could be adjusted to simple curvilinear equations, obtaining high coefficients of correlation, over 90% in most of cases, which greatly facilitated their study. In addition, it was demonstrated that the conditions of the fermentation process delayed the staling of bread, with the effect of fermentation time being the most important, and temperature the least important. The observed differences were greater between the under-fermented and normal doughs than between the latter and the over-fermented doughs. Therefore, whenever a prolonged shelf-life of bread is sought, the fermentation phase should be optimized.

Moreover, this work has allowed sitting the bases for the study of the evolution of the texture parameters along the storage time adjusting this evolution to simple equations. The simplification of methodology and the results interpretation have been obtained, and a new methodology has been proposed which could be used in future studies.

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