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ORIGINAL PAPER

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The effect of storage time on textural and crumb grain characteristics of sourdough wheat bread

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Abstract Texture and crumb grain characteristics are two major quality attributes of bread products. Instrumental methods for measuring textural properties are widely used as tools for the objective measurement of texture properties. Digital image analysis is a relatively new, non-destructive technique that can be used for the evaluation of crumb grain structure. During this study the effects of sourdough on texture and crumb grain characteristics of wheat bread were determined; the effects of storage on these characteristics were measured and possible relationships between texture and structural characteristics were investigated. Sourdough wheat breads with 20 or 40% sourdough were produced according to a standard procedure. Bread with no added sourdough was used as a standard. Crumb texture profile analysis and crust penetration were performed 4, 26, 50 and 74 h after baking. The crumb grain characteristics of the breads were evaluated using an in-house digital image analysis system. Wheat bread with 20% sourdough showed reduced crumb firmness and slower firming over time. Digital image analysis revealed increased crumb shrinkage in both sourdough breads. Possible relationships between crumb shrinkage and crumb firmness, chewiness and resilience were established.

Keywords Wheat sourdough · Digital image analysis · Texture profile analysis · Crumb grain characteristics

Introduction

Texture and appearance are two major sensory characteristics of cereal products. Texture is essentially a summation of the responses of the tactile senses to the product. The textural properties of a food have been described as “that group of physical characteristics that are sensed by the feeling of touch, are related to the deformation, disintegration and flow of the food under the application of a force and are measured objectively by functions of force, time and distance” [1]. This definition restricts the meaning to those properties that can be felt in the mouth or the hand and excludes physical characteristics such as temperature, optical and electrical properties, which have nothing to do with texture [1]. Szczesniak stated that “by definition, texture is a sensory property” [2]. Thus, it is only the human being that can perceive, describe and quantify texture. Furthermore, it is generally recognised that texture, just like flavour is a multi-parameter attribute [2]. However, Szczesniak [2] also points out that sensory evaluations are time consuming, expensive and often of poor reproducibility. Instrumental measurements of texture, on the other hand, are both more rapid and more consistent from day to day, and are therefore widely used in practice.

Bloksma [3] indicates that dough is a composite material, the structure of which can be described at three levels of resolution: millimetre, microscopic and molecular. At the millimetre level, dough can be divided into a continuous liquid dough phase and a disperse gas phase. At the microscopic level, the liquid dough phase is divided into a continuous protein phase with dispersed components in it, such as starch granules, yeast cells and gas cells. At the molecular level, the protein phase is divided into a continuous water phase, in which insoluble proteins are dispersed. Extending this to a general statement, it can be said that the three dimensional structure of a food is characterised by the organisation of its macroscopic, microscopic and molecular components [4]. The overall texture of the food depends on the three-dimensional network formed from its individual components. Thus, the three-dimensional structure of a bakery product influences its textural properties. Texture has gained recognition as a key sensory characteristic [5] and it is therefore important that food manufacturers

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gain an understanding of the textural qualities of bakery products in order to meet consumers' requirements in terms of perceived product quality.

Crumb grain has been described as the exposed cell structure of crumb, when a loaf of bread is sliced [6]. It obviously can be described at the millimetre level. As with bread scoring in general, the traditional basis for evaluation of crumb grain has been subjective, qualitative and imprecise by its very nature. These limitations have been recognised for some time [7]. Digital Image Analysis (DIA) is a relatively new, non-destructive technique that allows the objective and potentially very accurate measurement of the structural characteristics of cereal products. Several researchers have studied the structure of cereal products using image analysis. Fields of application have included differentiation between bread brands [8], direct quantification of technologically relevant bread-crumb grain features [9, 10] and analysis of effects of additives and processing conditions on crumb grain characteristics [4].

The application of sourdough in wheat bread has several documented effects including leavening [11], acidification [12], improvement of aroma [13], anti-staling [14, 15], delayed firmness and staling [16] and microbiological stability [17, 18, 19].

The objective of this study was to determine the effect of various amounts of sourdough on texture and crumb grain characteristics of wheat bread, the effect of storage on these characteristics and to investigate possible relationships between these texture and structural characteristics.

Materials and methods

Ingredients

Commercial baker's wheat flour containing 12.2% protein (dry basis), 0.5% ash (dry basis) and 20 ppm ascorbic acid was used (Odlum Group, Dublin, Ireland). Dried yeast obtained from Mauri Foods (Camellia, NSW, 2142, Australia) and table salt were also used in the formula. A commercial mixed-strain starter culture named Böcker Reinzucht-Suaerteig Weizen (BRSW) specifically designed for use in wheat sourdough was used (Böcker, Minden, Germany). The starter is based on a coarse-grain material that contains a high number of living bacteria cells, including four Lactobacillus strains (one *Lb. crispatus* and three *Lb. pontis*) (ca. 10^9 CFU g^{-1}) and a *Saccharomyces cerevisiae* yeast strain (ca. 8×10^6 CFU g^{-1}).

Sourdough preparation

Sourdough was prepared from 10% (flour basis) of mixed-strain starter added to equal quantities of water and wheat flour thereby giving a dough yield (DY) of 200. The coarse-grain mixed-strain starter was homogenously dispersed in the water and flour was added. The resultant dough was mixed thoroughly by hand for 1 min, poured into a large beaker, covered and then placed in an incubator (Memmert GmbH & Co, Schwabach, Germany) at 30 °C for 20 hours. The total titratable acidity and pH values of the sourdough were determined in a suspension of sourdough (10 g), acetone (5 ml) and distilled water (95 ml) according to a standard method [20].

Table 1 Recipe formulations used to prepare different bread types, standard bread, bread containing 20% sourdough (20% SD) and bread containing 40% sourdough (40% SD)[a]

	Standard	20% SD	40% SD
Flour	1000	800	600
Sourdough[b]		400	800
Added water[c]	608	352	136
Salt	20	20	20
Yeast[d]	15	15	15
Total water in recipe	608	552	536

[a] Quantities based on 1 kg flour
[b] Sourdough had a dough yield of 200 i.e. 1 part water and 1 part flour
[c] Water addition for each formula was based on farinograph water absorption
[d] Instant active dried yeast

Farinogram

Flour moisture was determined using AACC method 44-15A [21]. Farinograms were performed using a farinograph (Brabender OHG, Duisburg, Germany) with a 300 g mixing bowl and a mixing speed of 63±2 min^{-1} according to the International Cereal Chemistry standard method No. 115/1 [22]. The standard method was modified by the addition of sourdough, which was premixed with the flour at the beginning of the mixing period prior to the addition of water. Each result is the average of three measurements.

Dough preparation

Dough formulations are detailed in Table 1. A straight dough baking procedure was used. Doughs based on a flour quantity of 3500 g were mixed in a 30 quart capacity planetary mixer (Hunt 30, John Hunt Ltd, Bolton, Lancashire BL3 5BZ, UK) using a dough hook for 1 min at a disc speed of 44 rpm (shaft speed 88 rpm) and 7 min at a disc speed of 135 rpm (shaft speed 270 rpm). Water temperature was varied to yield a final dough temperature in the range 27–30 °C. The dough was rested in bulk for 20 min, scaled into 400 g portions, moulded in a small scale moulder (Machinefabriek Holtkamp BV, Almelo, Holland), placed in tins of size 180 mm×120 mm×60 mm (Sasa UK Ltd., Enfield, Middx EN3 7UL, UK) and placed in the proofer (Koma BV Roremond, Netherlands) that was set to 30 °C and 85% relative humidity for 60 min. Baking was carried out at 230 °C top heat/230 °C bottom heat for 30 min in a deck oven (MIWE, Arnstein, Germany). The oven was pre-steamed (0.3 l water) before loading and upon loading was steamed via the injection of 0.7 l water. The loaves were depanned and allowed to cool for 120 min on cooling racks at room temperature. Individual loaves were heat sealed in PA/PE-C bags and stored at 25 °C.

Bread evaluation

Three loaves were used for each analysis. Analyses were performed at the four time intervals 4, 26, 50 and 74 h. Loaf volume was measured using the rapeseed displacement method and loaf weight was also recorded. Loaf specific volume (ml g^{-1}) was calculated. Crust colour was measured using a CR300 series chroma meter (Minolta, Osaka, Japan). The CIE L*a*b* colour spaces were recorded, representing brightness, red/green and yellow/blue, respectively. Bread was sliced transversely using a slice regulator and bread knife to obtain uniform slices of 25 mm thickness. Instrumental textural evaluation of the crumb was carried out using a Universal Testing Machine (TA-XT2i Texture Analyser, Stable Micro Systems, Godalming, Surrey, UK) equipped with a 25 kg load cell and a 35 mm aluminium cylindrical probe. A crosshead speed of 5.0 mm s-1 with a trigger force of 20 g was used to compress the central area of the bread slice to 40% of its original height. Each sample was compressed twice in a reciprocating motion to give a two-bite texture profile curve. A range of values for textural attributes was extracted from the resulting curve including hardness, springiness, gumminess and chewiness [23] and, additionally, resilience [24]. The measurements were carried out on two slices taken from the centre of the loaf. A crust penetration test was carried out on 10 mm deep and 25 mm wide crust pieces from the top of the loaf using the Stable Micro Systems blade set (Stable Micro Systems, Godalming, Surrey, UK). The pH and total titratable acidity (TTA) of the bread was determined using a standard method [20]. The moisture content of crust and crumb were determined via a two-stage drying process as described in AACC standard method 44-15A [1].

Image acquisition and analysis

The crumb grain of the loaves was assessed using a previously described digital image analysis system [4]. Both sides of two central slices of each of three loaves were used for crumb grain measurements, thereby yielding twelve digital images per batch. Images were taken from the centre of the bread slice and were captured using a Hewlett Packard flatbed scanner (HP ScanJet 4c, Hewlett Packard, USA) supporting DeskScan II software (Hewlett Packard, USA). A single 60 mm×60 mm square field of view (FOV) was evaluated for each image. Brightness was adjusted to 150 units and contrast to 170 units. Images were scanned fullscale in 256 grey levels at 150 dots per inch (dpi) each comprising 355 columns by 355 rows of picture elements (pixels). Data was processed using SigmaScan Pro software (Jandel Corporation, U.S.) and Microsoft Excel V7.0 (Microsoft Corporation, US). Five crumb grain features were determined from the FOV and were subsequently analysed to generate a crumb grain profile for each bread type. The crumb grain features chosen were: total number of cells, total cell area, mean cell area, number of cells per cm^2 and cell-to-total area ratio. To investigate the sensitivity of the system, images were compared to classification photographs in Dallmann's 'Porentabelle' [25]. Visual estimation of the number of cells per cm^2, cell to total area ratio and mean cell area (mm^2) was carried out on random slices during the trial.

Statistical evaluation

Statistical analyses were performed on the data using the SPSS V8.0.0 computerised statistical analysis software package (SPSS Inc., USA). The data were examined using one-way Analysis of Variance (ANOVA). Initially, an F-test was conducted and where this showed significant differences ($P<0.05$), Tukey's HSD (Honestly Significant Difference) was employed as a multiple comparison test. ANOVA was performed between different bread types at each analysis time and within each bread type over the total storage time. Pearson correlation coefficients were calculated between data from texture analysis and image analysis.

Results and discussion

Effect of sourdough addition on acidity, loaf volume and moisture

Acidity

The pH values obtained were 4.11, 6.01, 5.21 and 4.75 for sourdough, standard bread, bread containing 20% sourdough and bread containing 40% sourdough, respectively. The corresponding Total Titratable Acidity (TTA) values were 12.35, 2.6, 5.2 and 8.18 ml. All values were within typical ranges expected for wheat sourdough breads [14]. As expected, increasing the level of sourdough in the bread resulted in decreasing pH values and consequently higher TTA values.

Loaf volume

Tests performed on standard bread and bread containing 20 and 40% sourdough showed that addition of sourdough had an effect on baking characteristics. Loaf specific volume increased significantly in bread containing 20% sourdough (3.40±0.08 ml g^{-1}) compared to the other two bread types. The specific volume of bread containing 40% sourdough was similar to standard bread (3.15±0.12 ml g^{-1} and 3.18±0.03 ml g^{-1}, respectively). Increases in specific volume in bread containing optimal levels of sourdough have been reported [14, 26, 27]. Increased specific volume has also been linked with reduced staling of the product [28, 29].

Moisture

Crust moisture was significantly lower in bread containing 20% sourdough (17.8% moisture) than both the standard bread (19.4% moisture) and the bread containing 40% sourdough (20.5% moisture). Also, crust firmness values indicated that the standard bread and bread containing 20% sourdough had firmer crusts in comparison to the bread containing 40% sourdough, although this was not significantly the case (Table 2). These results were generally reflected in sensory observations, that the firmer crusts were more crisp and friable. During storage, these differences converged and after 74 hours, crust moisture in the three bread types was 26±1% (data not shown). This was observed as an increasingly rubbery and soft crust and was also in accordance with the crust firmness values (Fig. 1). Crumb moisture values for each of the three bread types remained constant during storage. The values were: standard bread: 46.33±0.17%, bread containing 20% sourdough: 44.45±0.21%, and bread containing 40% sourdough: 43.28±0.13%. A slightly darker crust was observed in bread containing 40% sourdough but generally colour was not affected by sourdough addition (data not shown).

Effect of sourdough addition on textural characteristics

The addition of sourdough had a significant impact on the textural characteristics of the bread. Initial texture analysis, performed four hours after baking, revealed a significantly softer crumb and lower chewiness and resilience values in bread containing 20% sourdough compared with standard bread (Table 2). The textural characteristics of the bread prepared with the addition of 40%

Table 2 Differences in texture and crumb grain between bread types within each storage time

	Storage time (hours) and bread type											
	4			26			50			74		
	St.	20% SD	40% SD	St.	20% SD	40% SD	St.	20% SD	40% SD	St.	20% SD	40% SD
Crust Firmness (g)	18191[a]	17832[a]	13373[a]	15609[a,b]	16807[a]	12819[b]	10707[b]	12444[a]	9809[b]	10297[a]	9739[a]	9220[a]
Crumb Firmness (g)	481[a]	438[b]	466[a,b]	966[a]	979[a]	994[a]	1303[b]	1197[c]	1417[a]	1566[b]	1502[b]	1765[a]
Chewiness	286[a]	262[b]	276[a,b]	500[a]	506[a]	506[a]	635[a]	563[b]	633[a]	672[a]	637[a]	693[a]
Resilience	0.504[a]	0.493[a,b]	0.483[b]	0.402[a]	0.403[a]	0.383[b]	0.345[a]	0.334[a,b]	0.309[b]	0.302[a]	0.294[a]	0.260[b]
Number of Cells	1141[b]	1072[b]	1581[a]	1184[b]	1227[b]	1620[a]	1175[c]	1302[b]	1741[a]	1146[c]	1324[b]	1892[a]
Cell to Total Area Ratio	0.321[a]	0.367[a]	0.305[a]	0.330[a,b]	0.341[a]	0.286[b]	0.331[a]	0.313[a]	0.272[b]	0.339[a]	0.342[a]	0.275[b]
Mean Cell Area (mm^2)	1.03[a,b]	1.28[a]	0.70[b]	1.01[a]	1.01[a]	0.65[b]	1.01[a]	0.88[a]	0.57[b]	1.09[a]	0.92[a]	0.52[b]

[a–c] Mean values for each characteristic within each time annotated by the same letter are not significantly different ($P<0.05$). Sample size =6

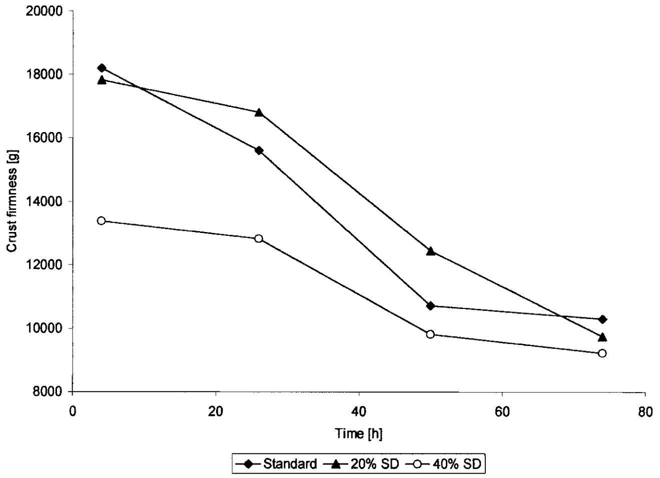

Fig. 1 Changes in crust firmness values during storage for standard bread, bread containing 20% sourdough (20% SD) and bread containing 40% sourdough (40% SD). Mean values presented at each storage time annotated by the same letter are not significantly different ($P<0.05$). Sample size = 6

sourdough were not significantly different to those of the standard bread at this evaluation point with the exception that the crumb was less resilient (Table 2).

Effect of sourdough addition on crumb grain characteristics

From initial crumb grain measurements, it was also noted that there were significant differences in the crumb grain of the three bread types. Digital image analysis revealed that a significantly higher number of cells were detected in the field of view (FOV) of bread containing 40% sourdough than in the other bread types (Table 2). Given that a fixed FOV was used, this result was also reflected in the number of cells detected per cm^2 (data not shown). Bread containing 40% sourdough had a lower mean cell area than both the standard and the 20% SD bread, although this relationship was only significant in relation to the 20% SD (Table 2). Furthermore, the cell-to-total area ratio was lowest for the bread containing 40% sourdough, although this difference was not significant (Table 2). These results were reflected visually in a considerably denser crumb structure being observed in bread containing 40% sourdough. Inferior crumb structure has been observed in bread containing high levels of sourdough [26]. Crumb grain measurements in this study quantify these observations. The observed crumb structure of bread containing 20% sourdough was comparable to standard bread.

Changes in texture and crumb grain characteristics during storage time

Subsequent to initial evaluation of the bread four hours after baking, analyses at 26, 50 and 74 h were used to investigate how the different bread types changed texturally and structurally over an extended period of storage in a stable environment. Table 3 details the changes over storage time within a particular bread type, whilst Table 2 illustrates the differences between the three bread types at each storage time. Only data for those parameters where significant differences were found are shown.

There was a distinct change in the textural and crumb grain characteristics of all breads over the storage period examined. Table 3 illustrates that, for all bread types, crumb firmness, gumminess and chewiness significantly increased over storage time, whilst crust firmness and crumb resilience significantly decreased. Figures 1 and 2 are presented as illustrative supplements to Table 3 in so far as these figures highlight the degree of change in crust and crumb firmness with time. All textural changes found are considered to have a negative impact on the

Table 3 Changes in texture and crumb grain within each bread type between 4 and 74 hours storage

Characteristic	Bread Type and Storage time (hours)											
	Standard Bread				20% Sourdough				40% Sourdough			
	4	26	50	74	4	26	50	74	4	26	50	74
Crust Firmness (g)	18191[a]	15609[a,b]	10707[b,c]	10297[c]	17832[a]	16807[a,b]	12444[b,c]	9739[c]	13373[a]	12819[a,b]	9809[b,c]	9220[c]
Crumb Firmness (g)	481[d]	966[c]	1303[b]	1566[a]	438[d]	979[c]	1197[b]	1502[a]	466[d]	994[c]	1417[b]	1765[a]
Gumminess	301[c]	529[b]	672[a]	718[a]	278[d]	537[c]	595[b]	676[a]	292[c]	538[b]	674[a]	741[a]
Chewiness	286[c]	500[b]	635[a]	672[a]	262[d]	506[c]	563[b]	637[a]	276[c]	506[b]	633[a]	693[a]
Springiness	0.950[a]	0.945[a,b]	0.946[a,b]	0.963[b]	0.944[a]	0.944[a]	0.946[a]	0.943[a]	0.945[a]	0.940[a]	0.939[a]	0.935[a]
Resilience	0.504[a]	0.402[b]	0.345[c]	0.302[d]	0.493[a]	0.403[b]	0.334[c]	0.294[d]	0.483[a]	0.383[b]	0.309[c]	0.260[d]
Number of Cells	1141[a]	1184[a]	1175[a]	1146[a]	1072[c]	1227[a,b]	1302[a]	1324[a]	1581[c]	1620[b,c]	1741[b]	1892[a]
Cells per cm^2	31.7[a]	32.9[a]	32.6[a]	31.9[a]	29.8[c]	34.1[a,b]	36.2[a]	36.8[a]	43.9[c]	45.0[b,c]	48.4[b]	52.5[a]
Mean Cell Area (mm^2)	1.03[a]	1.01[a]	1.01[a]	1.09[a]	1.28[a]	1.01[a,b]	0.88[b]	0.92[a,b]	0.70[a]	0.65[a,b]	0.57[a,b]	0.52[b]

[a–d] Mean values for each characteristic within each bread type annotated by the same letter are not significantly different (P<0.05). Sample size =6

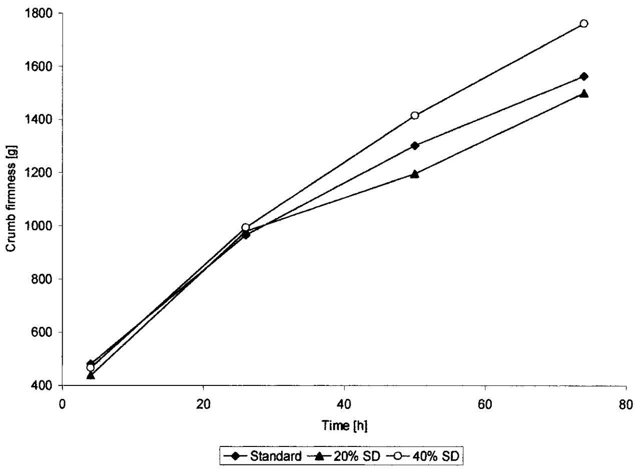

Fig. 2 Changes in crumb firmness values during storage for standard bread, bread containing 20% sourdough (20% SD) and bread containing 40% sourdough (40% SD). Mean values presented at each storage time annotated by the same letter are not significantly different (P<0.05). Sample size = 6

quality of this type of bread, e.g. the crumb becomes harder (increased firmness), requires more energy to disintegrate during chewing (increased gumminess) and requires a longer time for mastication (increased chewiness) [30]. Crust crispness is reduced due to the equilibration of moisture within the loaf as may be seen from the decreased crust firmness values (Table 3). This is in keeping with the report by Czuchajowska and Pomeranz [31] that during a storage period of 100 h, the crust moisture increased from 15 to 28%.

Generally, bread containing 20% sourdough maintained superior texture characteristics over the storage period while increasing the sourdough content to 40% had a negative effect. Bread containing 20% sourdough maintained a softer crumb than the two other bread types throughout storage (Table 2 and Fig. 2), although this was not significant in all cases. A trend towards lower crumb chewiness values (Table 2) was noted in bread containing 20% sourdough similar to the trend observed for crumb firmness. Loss of resilience (the ability of the crumb to recover from compression) was similar in standard bread and bread containing 20% sourdough, but the extent of loss was greatest in bread containing 40% sourdough (Table 2).

With regards to the changes in crumb grain characteristics during storage, there were no significant differences evident for the standard bread with regards to number of cells, cells per cm^2 or mean cell area (Table 3). There was however a significant increase in the number of cells and a subsequent increase in the number of cells per cm^2 for both the 20% and the 40% sourdough bread during storage. A concomitant significant decrease in the mean cell area during the 74 hour storage period was also observed for both these bread types (Table 3). These changes may be attributed to crumb grain shrinkage in view of the fact that a fixed FOV was used.

Investigation of relationships between texture and structural characteristics

There is evidence from the literature that in baked products the small holes or voids in the crumb, usually referred to as crumb cell structure or crumb grain, contribute to texture, eating quality, mechanical strength and perceived product freshness [32]. While it is obvious that the overall texture of a food depends on its three-dimensional structural characteristics, very little is known about the relationship between dispersion characteristics of these holes or cells and product texture. With regard

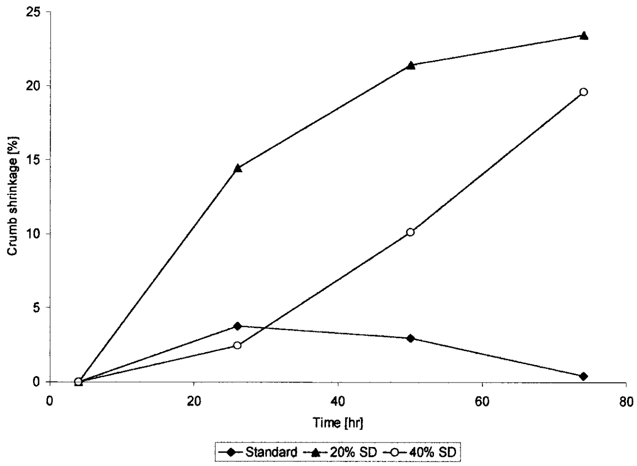

Fig. 3 Crumb shrinkage during storage time for standard bread, bread containing 20% sourdough (20% SD) and bread containing 40% sourdough (40% SD)

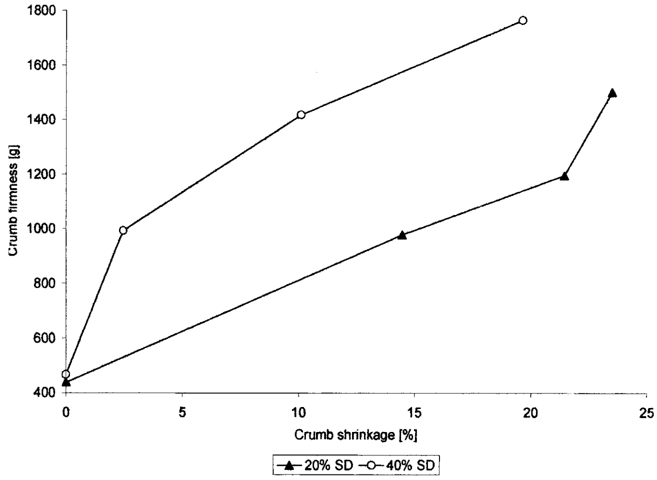

Fig. 4 Crumb firmness plotted against crumb shrinkage during storage for bread containing 20% sourdough (20% SD) and bread containing 40% sourdough (40% SD)

to such a relationship, the literature describes that it is not the holes themselves, rather the space they occupy and the extent to which they influence the surrounding matrix that is important [32]. The surrounding matrix, or cell wall structure, is the significant factor in the mechanical strength and structural architecture of the baked product [32].

Storage over 74 hours resulted in quantifiable changes in bread crumb texture of all three breads. For the two sourdough breads, changes in crumb grain over time were also detected. These changes were attributed to shrinkage as has been discussed above. Shrinkage detected by image analysis, obviously takes place at the millimetre level of resolution. To examine whether shrinkage might contribute to differences in firmness, a variable that characterizes crumb shrinkage quantitatively was defined as follows: the difference between the number of cells in the field of view at a certain time minus the number of cells in the field of view initially (4 h); this difference was then divided by the number of cells in the field of view at 4 h. It is therefore a measure of the relative increase in the number of cells detected in a fixed area due to shrinkage. Figure 3 shows a plot of the crumb shrinkage over the storage time. Since shrinkage only occurred in the sourdough bread and not in the standard bread, shrinkage may be due to the effect acid has on the gluten network and other bread components. Studies performed in our laboratory show that acid leads to an increase in water uptake by gluten and especially to a softening of the gluten (unpublished data). The softening effect on gluten is in accordance with the fact that the gluten protein can be solubilized, at least partly, in acids [33]. Furthermore, proteinase activity of certain lactic acid bacteria can cause hydrolysis of the gluten subunits [16] and thus weaken the gluten in wheat sourdough bread. During bread storage, moisture redistribution takes place [34]. This might lead to a deswelling and tightening of the gluten network and therefore could result in the observed shrinkage. It has also been reported that starch is affected by acid [14] as well as enzymes released by lactic acid bacteria [16]. The increased breakdown of starch molecules, which leads to a different retrogradation pattern, could also contribute to the increased shrinkage in sourdough bread in combination with a reduced firming. Nevertheless, reduced firming was not detectable for the 40% sourdough bread (Fig. 2). Therefore, in seeking to understand the reason why shrinkage was observed only in the sourdough breads, the textural data measured in the present study are not helpful. Differences in the amount and rate of deformation applied during the textural measurements and occurring during shrinkage may be the reason. As a matter of fact, shrinkage is assumed to be a comparatively slow phenomenon.

In view of the fact that shrinkage was not detectable in the standard bread, crumb firmness and resilience were plotted against shrinkage only for the sourdough breads, independently for the 20 and the 40% level (Figs. 4 and 5). For both sourdough breads, relationships seem to be quite obvious whereby increased shrinkage is in keeping with an increased firmness and a decreased resilience for both. These relationships, visible from the graphs, are supported by correlation coefficients. The Pearson correlation coefficient between firmness and shrinkage was 0.978 and 0.946 for the 20 and 40% sourdough bread, respectively, whilst the correlation coefficient between resilience and shrinkage was –0.983 and –0.925. Chewiness increased as shrinkage increased (data not shown), similar to crumb firmness and the correlation coefficients between chewiness and shrinkage were 0.991 and 0.874. For comparison reasons, the same correlation coefficients were also calculated for the standard bread, in which no shrinkage was obvious. These were 0.174, 0.319 and –0.236, be-

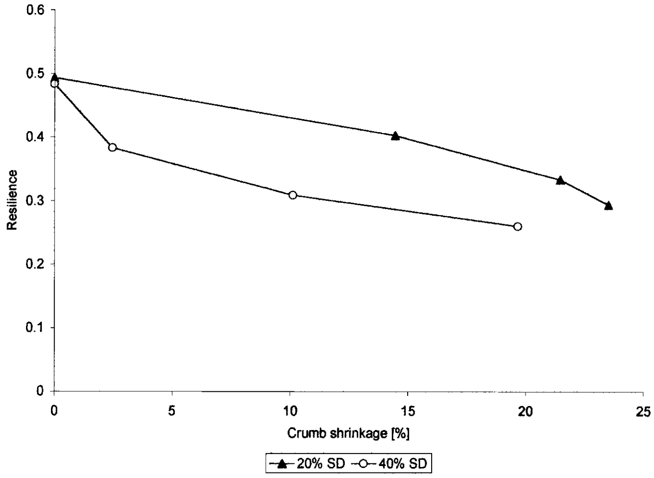

Fig. 5 Resilience plotted against crumb shrinkage during storage for bread containing 20% sourdough (20% SD) and bread containing 40% sourdough (40% SD)

tween shrinkage and firmness, chewiness and resilience, respectively.

A possible explanation for the relationships between the textural parameters and shrinkage for the sourdough breads may be that as the crumb shrinks, the product matrix becomes denser and therefore harder to compress (increase in crumb firmness), chewier and furthermore, less able to recover from deformation (resilience). As is generally the case, a correlation does not necessarily prove that there is a causal relationship between two variables. Nevertheless, the hypothesis that an increasing crumb density contributes to the textural changes during the storage of bread seems to be logical within the limitations of the approach of the current study. Clearly, image analysis as performed in this and similar studies, as has been identified by Crowley et al [4], can only show changes in the crumb grain on the millimetre level. Nevertheless, changes in bread during storage also take place on the molecular level. Retrogradation of the starch for example, is a change that occurs on the molecular level, which is generally associated with bread staling [35].

Conclusion

The addition of sourdough to wheat bread had significant effects on texture and crumb grain characteristics of the baked product. The level of sourdough addition affected the nature and extent of these effects. Digital image analysis is a useful tool to objectively quantify crumb grain characteristics of different bread types and to track changes in crumb structure during storage. From the results obtained, the addition of 20% sourdough was most favourable for the production of bread with the highest volume, most desirable crumb grain and the lowest rate of quality degradation during storage. Increasing the rate of sourdough addition to 40% had a negative effect on the majority of measured product characteristics and the product was inferior to standard bread. Investigation of potential relationships between texture and structure indicated that crumb firming, increasing crumb chewiness and decreasing crumb resilience might be connected with crumb shrinkage during storage.

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