

Effects of Flour Strength, Baking Absorption, and Processing Conditions on the Structure and Mechanical Properties of Bread Crumb

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ABSTRACT

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The objective of this study was to determine the effects of flour type, baking absorption, variation in sheeting, and dough proofing time on the density, crumb grain (visual texture), and mechanical properties (physical texture) of bread crumb. All response variables were measured on the same bread crumb specimens. Bread loaves were prepared by a short-time bread-making process using four spring wheat flours of varying strength. After crumb density measurement, digital image analysis (DIA) was used to determine crumb grain properties including crumb brightness, cell size, cell wall thickness, and crumb uniformity. Tensile tests were performed on bone-shaped specimens cut from the same bread slices used for DIA to obtain values for Young's modulus, fracture stress, fracture strain, and fracture energy. Proof time had the most profound influence on the bread with substantial effects on loaf volume, crumb density, crumb brightness, and grain, as well as crumb mechanical properties. Increasing proof time resulted in higher loaf volume, lower crumb density and brightness, coarser

crumb with fewer and larger cells with thicker cell walls, and weaker crumb tensile properties. Varying flour type also led to significant differences in most of the measured crumb parameters that appeared to correspond to differences in gluten strength among the flour samples. With increasing flour strength, there was a clear trend to increasing loaf volume, finer and more uniform crumb grain, and stronger and more extensible bread crumb. Increasing baking absorption had virtually no effect on crumb structure but significantly weakened crumb strength and increased fracture strain. In contrast, varying the number of sheeting passes had a minor effect on crumb cellular structure but no effect on mechanical properties. The experimental data were consistent with a cause-effect relationship between flour strength and the tensile strength of bread crumb arising as a result of stronger flours exhibiting greater resistance to gas cell coalescence, thereby having fewer crumb defects.

The visual and physical texture of bread crumb are key quality attributes that largely determine overall product quality to the baker and consumer (Pylar 1988). Although the traditional method for evaluating the visual texture (or crumb grain) of bread is subjective and qualitative, digital image analysis (DIA) has been increasingly applied in the past 5 to 10 years for objective and quantitative measurement of crumb grain (Sapirstein 1999). Instrumental measurement of the physical texture of bread has a longer history. Compression testing of bread crumb (Bailey 1932, Elton 1969, Brady and Mayer 1985) has been the method of choice because of its simplicity, but tensile testing of bread has also been used for physical texture measurements (Nussinovitch et al 1990, Chen et al 1994, Scanlon et al 1997). Despite some challenges related to sample gripping and dimension requirements, tensile testing provides texture parameters that can be readily interpreted (Nussinovitch et al 1990) and, additionally, can be used to measure crumb coherence from its energy to fracture (Scanlon et al 1997), as well as provide values for crumb extensibility. Furthermore, tensile measurements are particularly sensitive for detecting and quantifying structural defects in food products (Luyten et al 1992).

The visual and physical texture of leavened baked goods are influenced by many factors including flour strength and protein content (Ponte et al 1962, Pylar 1988, Scanlon et al 1997), oxidants (Sapirstein et al 1994), baking absorption (Larsen and Greenwood 1991, Piazza and Masi 1995), and shortening (Lasztity 1980). Processing conditions such as sheeting (Stenvert et al 1979, Hibberd and Parker 1985, Levine 1998, Whitworth and Alava 1999) and proof time (Freilich 1949, Ponte et al 1962) can also affect crumb grain and texture. In earlier work, either the grain of crumb or its physical properties were evaluated in response to various treatments. The objective of this study was to obtain a better understanding of the effects of flour strength, baking absorption, and bread-making conditions (sheeting and proofing) on the direct relationship between bread crumb structure and crumb texture. This was achieved by nondestructive measurement of bread crumb grain by DIA followed by tensile testing of the same specimens to determine their mechanical properties.

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MATERIALS AND METHODS

Flour

Flour representative of three Canadian wheat classes of widely different strength were used: Canada Western Extra Strong (CWES), Canada Western Red Spring (CWRS), and Canada Prairie Spring (CPS). A fourth flour (blend) was created from a 50% blend of CWES and CPS wheats. Wheat was milled to straight-grade flour on the pilot mill of the Canadian International Grains Institute (CIGI), Winnipeg, Canada.

Technological Quality

Dough extensibility was measured with the extensigraph according to Approved Method 54-10 (AACC 2000). Duplicate extensigrams were obtained using a rest time of 135 min (Holas and Tipples 1978). Dough mixing properties were determined using a 2-g computerized direct drive mixograph (National Mfg., Lincoln, NE). All flour samples were mixed in duplicate at 88 rpm and at 25°C using 2 g of flour (14% mb) and constant water absorption (60%). In addition, the CWES and CWRS flours were mixed at 63 and 65% water absorption, respectively, which corresponded to optimal baking absorptions. Computer analysis of the mixograms was performed as previously described (Köksel et al 1998).

Baking

Pan bread (225 g of flour, 14% mb) was prepared using a straight-dough, short-time procedure (Kilborn and Tipples 1981b) with two modifications (shortening and salt levels were increased to 3 and 1.8% fwb, respectively). To investigate the effect of water absorption on bread characteristics, constant (60%) and optimum levels were used. The latter was determined on the basis of the farinograph absorption and dough-handling properties at the panning stage. The baking absorptions used for the CWRS, CWES, blend, and CPS flours were 65, 63, 60, and 60%, respectively. Dough development was achieved by mixing to a time of 10% past peak dough resistance on a GRL 200 mixer (Kilborn and Tipples 1981b).

After an intermediate proof of 20 min, doughs were sheeted three times by successively reducing the gap between the Teflon-coated steel rolls (National), as described by Kilborn and Tipples (1981a); roll gaps were 11/32, 3/16, and 1/8 in. The effects of a different sheeting treatment were investigated by adding two extra sheeting passes through the smallest roll gap (1/8 in) for a total of five sheeting

passes. The molded dough pieces were placed in aluminized steel bake pans with internal dimensions of bottom, 166 × 72 mm; top, 187 × 90 mm; and height, 55 mm. Four final proofing times (35, 45, 60, and 85 min) were used to create a range of density and structure in the bread crumb. These proof times were selected so that the resulting densities of bread crumb were approximately evenly distributed.

The panned and proofed dough was baked for 27 min at 223°C. Bread loaves were allowed to cool for 30 min before loaf volume measurement by rapeseed displacement. Loaves were double bagged in polyethylene bags of 1.7 mil (43 μm) wall thickness (Topsyn Flexible Packaging Ltd., Winnipeg, MB), and stored overnight at 21°C for moisture equilibration. Bread for a given proof time was prepared by randomizing all other treatments (flour type, water absorption, and sheeting) over a single day of baking. Bread baking was performed in triplicate.

Density Measurement

Bread loaves were mechanically sliced with a commercial slicer (Oliver model 697, Grand Rapids, MI), yielding 11 slices for each loaf. For each loaf, five central slices were cut by a slow sawing motion (to prevent crumb compression and structural damage) around a template (40 × 110 mm) with a pathology trimming blade. Five of these specimens from a given loaf were stacked together and stored in an airtight 946-mL plastic container (Rubbermaid Inc. Wooster, OH) to prevent moisture loss. To further minimize moisture loss when removing or returning specimens and to eliminate headspace in the container, three residual bread slices from each end of the loaf were trimmed to the dimensions of the container and were stacked above and below the crumb specimens. Crumb density measurements were performed as described by Zghal et al (1999).

Image Analysis

Image acquisition and analysis was performed after measuring bread crumb density as previously described (Zghal et al 1999). The crumb grain features that were determined by the DIA were those described by Sapirstein et al (1994). These features included crumb brightness, cell wall thickness (CWT), mean cell area (MCA), void fraction (VF), number of cells per square centimeter, and grain uniformity. The latter was determined as the ratio of small to large cell counts (i.e., the ratio of the number of cells with areas less than, to those greater than, 4 mm²); higher values indicate greater uniformity of crumb grain.

Tensile Testing

The same crumb specimens used for imaging and density measurements were cut into bone-shaped specimens for tensile testing. A sharp circular stainless-steel hole-cutting bit, 42 mm in diameter, and a drill press (Delta International Machinery Corp., Guelph, ON) were used to cut four circular sections, two on each side of the bread specimen (Fig. 1A and B). The crumb remaining between the two circular cuts was then manually trimmed with a high-speed rotary tool (Dremel, Racine, WI) and 2.4-cm diameter cutoff wheel (Dremel no. 409) to give the final bone-shaped specimen (Fig. 1C). Preparation time was ≈2 min. The gage length and width of the specimens were 30 and 10 mm, respectively, with a cross sectional area of 1.25 × 10⁻⁴ m² (10 × 12.5 mm). Specimens were allowed to rest 4 hr in an airtight container to permit moisture equilibration before tensile testing. The ends of the specimens were secured for tensile testing using a TA-226 “tug” fixture comprising four pins in a diamond-shaped pattern (Texture Technology Corp, Scarsdale, NY).

Tensile testing was performed using a TA.XT2i texture analyzer equipped with a 5 kgf load cell. Crumb specimens were subjected to tensile loading using a crosshead speed of 0.2 mm/sec, which corresponds to a strain rate of 6.66 × 10⁻³/sec. The mechanical properties were determined by the TA.XT2i software from the stress-strain curve. These properties included Young’s modulus (kN m⁻², the slope of the stress-strain curve between 0 and 2% strain), fracture stress (kN m⁻², maximum tensile force/initial cross sectional area), fracture strain (deformation to fracture/gage length), and fracture energy (J m⁻³, area under the curve to the point of fracture). The moisture contents of the mechanically tested bread specimens (one per loaf) were determined using an air oven operating at 103°C for 5 hr (Fontanet et al 1997). Room temperature was monitored during the experiment and its effect on the mechanical properties was evaluated.

Statistical Analysis

Data were analyzed by SAS (version 6.12; SAS Institute Inc., Cary, NC). The experimental design is shown in Table I. The data were subdivided into three categories: constant water absorption (baking absorption), optimum baking absorption, and optimum versus constant baking absorption, each representing a complete factorial set of treatments to simplify the statistical analysis. Analysis of variance, using the SAS GLM procedure, was performed in

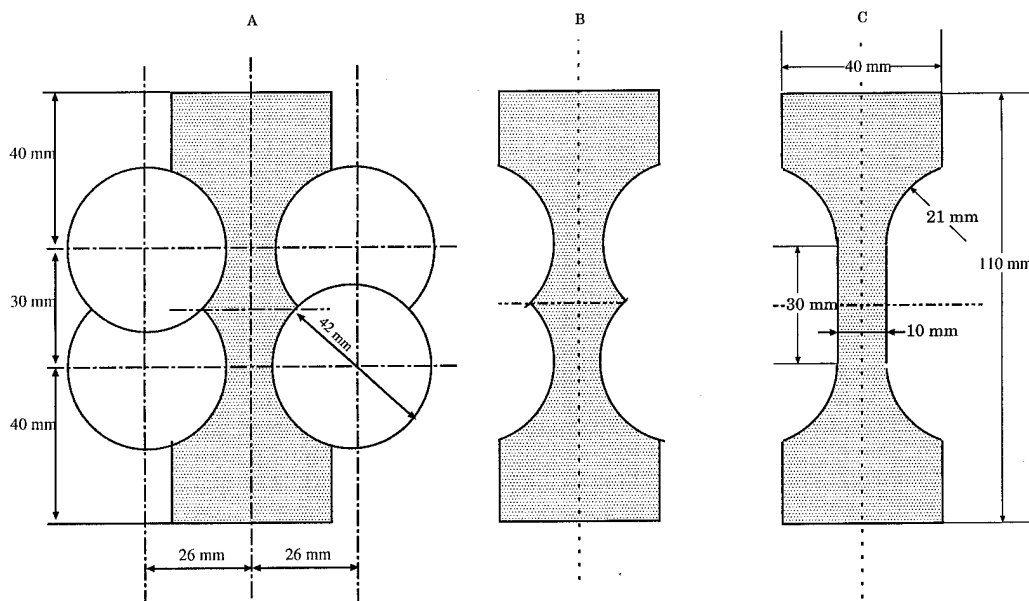


Fig. 1. Schematic representation of bread specimen used in tensile testing: **A** and **B**, tapering the end pieces of the gage length from the bread specimen using the hole-cutting bit; **C**, a bone-shaped tensile specimen obtained after the remaining material between the two cuts was trimmed.

three stages to determine significant differences and interactions for the various treatments on crumb structure and texture. The effects of variation in room temperature during tensile testing and variability in bread crumb moisture content among replicates of the same treatment were also assessed by incorporating these two factors in the GLM models as covariates. The statistical results indicated that variation in room temperature or crumb moisture content did not have a significant effect on any mechanical properties (Zghal 1999).

RESULTS AND DISCUSSION

Technological Quality Characteristics of Flour Samples

The quality characteristics of the flours are presented in Table II. The protein contents of flour samples ranged from 10.0 to 12.9%, which were typical for the types of flour used. Amylograph and

falling number results indicated that flour samples were sound. The extensigraph and mixograph properties indicated that the four flour samples covered a wide range of strength. As expected, the CWES and CPS flours were characteristically very strong and weak, respectively. The CWRS and blend flours were of intermediate strength, with the latter showing stronger dough properties.

For the mixograph, increasing water absorption from 60% to optimum levels increased Mixograph development time and decreased peak dough resistance and bandwidth at peak dough resistance (Table II). These results are consistent with those reported by Larsen and Greenwood (1991). The changes in mixograph parameters as a function of water absorption were generally dependent on flour type, with CWES flour showing less sensitivity to increasing water absorption than the CWRS flour. This could be due, in part, to the fact that less water was added to the CWES flour. In addition, the

TABLE I
Experimental Design and Statistical Analysis

Treatments	Levels ^a			
	CWRS	CWES	CPS	Blend
Flours	CWRS	CWES	CPS	Blend
Baking absorption (%)	60	65 (CWRS)	63 (CWES)	
Sheeting passes	3	5		
Proof time (min)	35	45	60	85
Analysis I: Constant water absorption				
Flours	CWRS	CWES	CPS	Blend
Baking absorption (%)	60	60	60	60
Sheeting passes	3	5		
Proof time (min)	35	45	60	85
Analysis II: Optimum water absorption				
Flours	CWRS	CWES	CPS	Blend
Baking absorption (%)	60	63	60	60
Sheeting passes	3	5		
Proof time (min)	35	45	60	85
Analysis III: Constant vs. optimum water absorption				
Flours	CWRS	CWRS	CWES	CWES
Baking absorption (%)	60	65	60	63
Sheeting passes	3	5		
Proof time (min)	35	45	60	85

^a Canada Western Red Spring (CWRS), Canada Western Extra Strong (CWES), Canada Prairie Spring (CPS), and a fourth flour created from a 50% blend of CWES and CPS.

TABLE III
Effects of Flour Type on Characteristics of Bread Crumb Prepared at Constant Baking Absorption^a

Characteristics	Flour ^b			
	CWES	CWRS	Blend	CPS
Loaf volume (cm ³)	2,240a	2,199b	2,139c	1,967d
Density (g cm ⁻³)	0.128c	0.131b	0.132b	0.135a
Crumb grain				
No. cells/cm ²	87.7	88.6	88.0	84.5
MCA (mm ²)	0.566	0.555	0.560	0.581
CWT (mm)	0.782	0.785	0.779	0.808
Uniformity	40.2a	37.8a	34.1b	33.1b
Crumb brightness	180.9b	184.5a	183.9a	181.5b
Void fraction	0.486a	0.481bc	0.483ab	0.479c
Mechanical properties				
Modulus (kN m ⁻²)	11.53ab	12.60a	11.96a	10.46b
Fracture stress (kN m ⁻²)	2.32a	2.40a	1.97b	1.47c
Fracture strain	0.45a	0.41b	0.36c	0.30d
Fracture energy (J m ⁻³)	673a	625a	462b	283c

^a Data of various proof times and sheeting treatments were combined for each type of flour. Values followed by the same letter in the same row are not significantly different ($P < 0.05$). MCA = mean cell area, CWT = cell wall thickness.

^b Canada Western Red Spring (CWRS), Canada Western Extra Strong (CWES), Canada Prairie Spring (CPS), and a fourth flour created from a 50% blend of CWES and CPS.

TABLE II
Technological Quality Characteristics of Flour Samples

Characteristics ^b	Flour ^a					
	CWRS	CWRS	CWES	CWES	CPS	Blend
Moisture content (%)	11.2 ± 0.0	...	12.2 ± 0.0	...	11.4 ± 0.1	11.8
Protein (%)	12.9 ± 0.1	...	12.8 ± 0.0	...	10.0 ± 0.1	11.4
Ash (%)	0.56 ± 0.01	...	0.57 ± 0.00	...	0.46 ± 0.00	0.52
Amylograph (BU)	965 ± 7	...	428 ± 11	...	755 ± 7	625 ± 7
Falling number (sec)	739 ± 33	...	447 ± 10	...	526 ± 18	467 ± 5
Extensigraph						
BA (%)	64.5	...	63.8	...	60.5	61.1
RMAX (BU)	530 ± 14	...	915 ± 0	...	480 ± 0	690 ± 70
EXT (cm)	19 ± 0.0	...	14.8 ± 0.4	...	17.9 ± 0.5	16.9 ± 0.4
EA (cm ²)	130 ± 1	...	172 ± 0	...	116 ± 2	154 ± 6
RMAX/EXT (BU.cm ⁻¹)	27.9	...	62.0	...	26.9	40.8
Mixograph						
BA (%)	60	65	60	63	60	60
MDT (min)	3.28 ± 0.04	3.77 ± 0.01	5.01 ± 0.06	5.31 ± 0.24	3.40 ± 0.11	4.18 ± 0.06
PDR (%)	38.5 ± 0.8	34.9 ± 1.8	46.4 ± 1.2	44.9 ± 1.8	30.8 ± 0.7	40.3 ± 0.2
BWPR (%)	24.6 ± 0.2	21.8 ± 1.2	32.2 ± 0.4	31.6 ± 0.5	19.1 ± 0.0	25.3 ± 0.4
RBD (%)	1.4 ± 0.4	2.4 ± 0.0	0.7 ± 0.6	0.2 ± 0.7	13.1 ± 4.1	3.4 ± 0.3
BWBD (%)	6.7 ± 0.2	5.1 ± 0.2	7.2 ± 0.4	7.2 ± 0.4	7.7 ± 0.3	9.5 ± 0.2
WIP (W.tq.min)	85 ± 2	88 ± 4	145 ± 0	144 ± 12	64 ± 3	105 ± 1

^a Canada Western Red Spring (CWRS), Canada Western Extra Strong (CWES), Canada Prairie Spring (CPS), and a fourth flour created from a 50% blend of CWES and CPS.

^b Means and standard deviations of two determinations. Values for moisture, protein, and ash of blend flour are means of CWES and CPS flours. BA = baking absorption, RMAX = maximum resistance, EXT = extensibility, EA = area under the curve, MDT = Mixograph development time, PDR = peak dough resistance, BWPR = bandwidth at peak dough resistance, BWBD = bandwidth breakdown, RBD = resistance breakdown, and WIP = work input to PDR.

higher inherent strength of CWES flour may be responsible for the relatively smaller change in its rheological properties when extra water was added to the dough.

Effects of Flour Type on Crumb Structure of Bread Prepared at Constant Absorption

Flour type had a substantial effect on loaf volume, density, and the mechanical properties of bread crumb prepared at 60% water absorption (Table III). Except for the blend flour, flour type had a significant effect on loaf volume, which decreased in the same order as flour strength. The loaf volume of the blend flour was significantly lower than that of the CWRS flour, despite the former's relatively higher dough strength (Table II). This indicates that the carrying capacity of the CWES flour was manifest more in the rheological properties of the dough than in its baking performance. Crumb density was also significantly affected by flour type and showed the same trend as for loaf volume, except that the crumb density of the CWRS bread was not significantly different from that of the blend (Table III).

Unlike loaf volume and crumb density, bread crumb grain determined by DIA did not show as much variation in response to flour type; CWT, number of cells per square centimeter, and MCA were not significantly affected. However, crumb brightness, void fraction, and crumb uniformity were significantly influenced by the flour type ($P < 0.001$). The void fraction, which is strongly correlated with loaf volume and crumb density (Zghal et al 1999), was highest for the CWES bread. CWES bread also had the most uniform crumb grain. This suggests that the degree of gas cell coalescence was low in the CWES dough and that the CWES flour, on its own, had superior breadmaking performance. It is likely that the low rate of gas cell coalescence in CWES was due to its higher rate of strain hardening when the dough was subjected to extension, such as occurs during fermentation and proofing (Dobraszczyk and Roberts 1994). This strain-hardening phenomenon, which is measured as the increase in slope of the dough stress-strain curve with increasing extension, limits the growth of large gas cells, permitting smaller cells to expand and, thus, creating a more uniform and fine crumb grain (van Vliet et al 1992). Stronger doughs exhibit greater rates of strain hardening due to orientation of the glutenin macropolymer, thus stabilizing the dough's cell walls against rupture and leading to a more uniform crumb grain.

In contrast to the high crumb grain scores of the CWES bread, CPS bread, which was produced from relatively weak flour, had the poorest crumb grain scores across all parameters but crumb brightness (Table III). These results suggest that a higher degree of

gas cell coalescence had occurred in CPS dough during processing, because weak dough is generally known to exhibit a low rate of strain hardening and poor gas cell stability (Dobraszczyk and Roberts 1994). Therefore, among the four flours of this study, CPS flour was least suited for breadmaking. The overall crumb grain features of CWRS and the CWES-CPS blend were generally very similar, and more comparable to those of CWES bread. Like the CPS bread, blend bread had significantly poorer crumb grain uniformity than either the CWES and CWRS breads. Interestingly, both the CWRS and blend breads had significantly brighter crumb than the other two breads; there was no clear explanation for this result.

Effects of Flour Type on the Texture of Bread Prepared at Constant Absorption

The effect of flour type on bread crumb mechanical properties was considerable. Depending on the specific parameter that was measured (e.g., fracture strain and energy), varying flour type had even greater effect on the mechanical properties of the crumb than did proof time.

Although Young's modulus was significantly affected by flour type, the modulus did not vary with respect to flour strength. For example, the Young's modulus of CWES bread was not significantly different from that of CPS bread (Table III), despite the large difference in dough mixing requirements (Table II). Although the Young's modulus of these two types of bread were almost equal, the stiffness of the cell walls themselves may well be affected by flour strength. It is known that the Young's modulus (E) of cellular materials (Gibson and Ashby 1997), including starch bread (Keetels et al 1996a), starch foams (Shogren et al 1998), and sponge cake (Attenburrow et al 1989), are a function of the Young's modulus of the cell walls (E_s) and the relative density of the bread crumb ($E \propto E_s[\rho/\rho_s]^{1/m}$). Because CWES bread had significantly lower crumb density compared to CPS bread, even though the moduli were comparable, it is reasonable to infer that the stiffness of CWES crumb cell walls is greater than that of CPS.

The fracture stresses of CWES and CWRS breads were comparable, but for the blend and CPS bread, fracture stresses were markedly smaller; on average, by 17 and 40% of the fracture stress of CWES bread, respectively. Although the mechanism of cell wall failure in bread crumb has not been established (Keetels et al 1996b), finite element analysis of two-dimensional cellular solids (Silva and Gibson 1997) has indicated that strength is substantially impaired by defects in the cellular structure, even though such defects have very little effect on the Young's modulus (Silva et al 1995). Fracture stress generally decreased in the order of decreasing flour strength

TABLE IV
Effects of Number of Sheeting Passes on Characteristics of Bread Crumb Prepared at Constant Baking Absorption^a

Characteristics	No. of Sheeting Passes	
	3	5
Loaf volume (cm ³)	2,169a	2,103b
Density (g cm ⁻³)	0.129b	0.134a
Crumb grain		
No. cells/cm ²	87.0	87.4
MCA (mm ²)	0.570	0.561
CWT (mm)	0.780	0.797
Uniformity	35.2b	37.5a
Crumb brightness	182.7	182.7
Void fraction	0.484a	0.480b
Mechanical properties		
Modulus (kN m ⁻²)	11.62	11.65
Fracture stress (kN m ⁻²)	2.05	2.01
Fracture strain	0.38	0.38
Fracture energy (J m ⁻³)	521	501

^a Data of various flour types and proof times were combined for each sheeting treatment. Values followed by the same letter in the same row are not significantly different ($P < 0.05$). MCA = mean cell area, CWT = cell wall thickness.

TABLE V
Effects of Proof Time on Characteristics of Bread Crumb Prepared at Constant Baking Absorption^a

Characteristics	Proof Time (min)			
	35	45	60	85
Loaf volume (cm ³)	1,678d	1,969c	2,270b	2,628a
Density (g cm ⁻³)	0.163a	0.138b	0.120c	0.105d
Crumb grain				
No. cells/cm ²	93.6a	90.9a	87.3b	77.0c
MCA (mm ²)	0.508d	0.535c	0.565b	0.654a
CWT (mm)	0.761b	0.760b	0.784b	0.848a
Uniformity	42.4a	36.8b	35.3b	30.8c
Crumb brightness	187.7a	185.9a	181.4b	175.7c
Void fraction	0.469d	0.481c	0.487b	0.492a
Mechanical properties				
Modulus (kN m ⁻²)	14.79a	13.97a	9.20b	8.59b
Fracture stress (kN m ⁻²)	2.35a	2.22a	1.87b	1.67b
Fracture strain	0.35b	0.35b	0.43a	0.40a
Fracture energy (J m ⁻³)	555a	527a	520a	440b

^a Data of various flour types and sheeting treatments were combined for each proof time. Values followed by the same letter in the same row are not significantly different ($P < 0.05$). MCA = mean cell area, CWT = cell wall thickness.

(CWES, CWRS, blend, and CPS) and decreasing crumb uniformity, despite the offsetting effect of increasing crumb density (Table III). Therefore, it is evident that the strength of bread crumb is likely dictated by the presence of defects that arise during breadmaking as a result of gas-cell coalescence.

Effects of Dough Sheeting on Visual and Physical Texture at Constant Absorption

Dough sheeting is a crucial step in bread making and it serves many functions. These functions include dough development, alignment of gluten protein, gas repulsion, and lamination (Levine 1998). Excessive sheeting beyond optimal levels had a detrimental effect on loaf volume and crumb grain of relatively weak flour, but no effects were observed for strong flour (Stenvert et al 1979). The results of this study indicated that two additional passes through the smallest gap of the rollers resulted in small but significant changes in loaf volume, crumb density, and some crumb grain features (Table IV). On average, loaf volume decreased by 66 cm³, while crumb density increased by 0.005 g cm⁻³. The two additional sheeting passes lowered the void fraction and increased crumb uniformity. The increase in crumb density and concomitant decrease in void fraction due to the extra sheeting passes confirmed the strong relationship between crumb density and void fraction reported previously (Zghal et al 1999). Although, on average, the mean cell size did not significantly change with the sheeting treatment, the distribution of cell sizes in the crumb was likely altered (Stenvert et al 1979) because crumb uniformity increased with the two extra sheeting passes. The number of sheeting passes did not produce any significant effect on the mechanical properties of the crumb despite the significant increase in crumb density. The latter effect probably originates in the extra degassing of dough during the additional sheeting passes (i.e., denser dough, by sheeting, produces denser bread). Although dough proofing would mitigate the sheeting effect, the sheeting effect persisted for all but the longest proofing time.

Effects of Proof Time on Visual and Physical Texture at Constant Absorption

There were considerable effects of proof time on average density, crumb grain features, and mechanical properties of bread prepared using constant baking absorption (Table V). As expected, loaf volume significantly increased as proof time was extended from 35 to 85 min (Pylar 1988, Zghal et al 1999). This trend was observed for all types of flours and both sheeting treatments. The density of bread crumb significantly decreased with increasing proof time. A significant interaction effect between proof time and the number of sheeting passes on crumb density (Zghal 1999) showed that the difference in crumb density between three and five sheeting passes de-

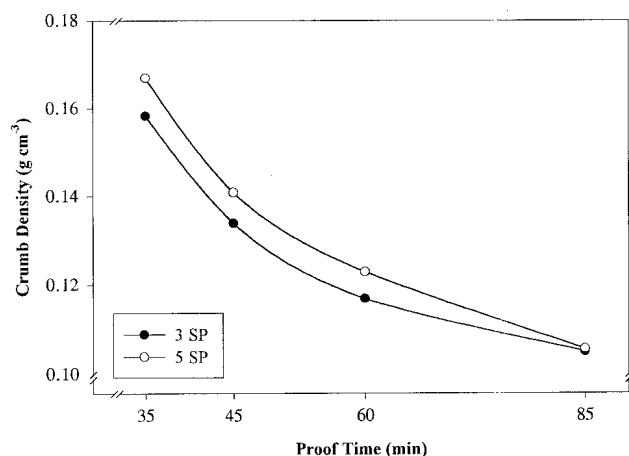


Fig. 2. Relationship between crumb density of bread prepared at constant baking absorption as a function of proof time and number of sheeting passes averaged over the four flour types used.

creased with increasing proof time and resulted in the same density at 85 min (Fig. 2). A similar trend for loaf volume as a function of proof time and sheeting passes was also found, but it was not statistically significant. These results would appear to indicate that the two additional sheeting passes did not cause structural damage to the dough system and so did not have any negative effect on its gas retention properties. This is only observed if sufficient proofing time is allowed that the yeast can generate sufficient gas to counter the degassing effect of the two extra sheeting passes (Table IV) before proofing.

All crumb grain features were significantly influenced by proof time. With increasing proof time, cell size and CWT increased, the crumb became less bright and less uniform, and the void fraction increased. These results are consistent with those reported by Zghal et al (1999).

Proof time also had a major effect on the mechanical properties of bread crumb. On average, as proof time was increased from 35 to 85 min, Young's modulus decreased by 42%. The fracture stress and fracture energy of bread crumb also significantly decreased with increasing proof time, on average, by 29 and 21%, respectively. The changes in the mechanical properties of bread crumb with increasing proof time were believed to be mainly due to the large reduction in bread crumb density (Ponte et al 1962, Wassermann 1979), but changes in bread crumb structure may also explain some of the change in mechanical properties (Kamman 1970, Pylar 1988). The fracture strain or extensibility of bread crumb significantly increased with increasing proof time, although it may have reached a maximum at ≈60 min. The general increase in extensibility of bread crumb with decreasing density is in agreement with results reported for baked starch foams (Shogren et al 1998).

Effects of Optimum Baking Absorption

For bread prepared with optimum baking absorption, the effects of sheeting passes and proof time on all bread characteristics including loaf volume, density, and the visual and physical texture of the bread crumb were similar to those observed for bread baked at constant baking absorption (Zghal 1999). One point worthy of mention, because of its relationship to flour strength, is fracture strain at optimum absorption; similar results to those in Table III were obtained, with values of 0.46 for CWES and 0.38 for CWRS. But, at optimum water absorption, the fracture strain of bread crumb can be compared directly with dough extensibility as measured by the extensigraph (Table II). It is apparent that no relationship exists between extensibility in the dough and extensibility in the bread crumb. Particularly noteworthy were the results for CWES flour,

TABLE VI
Effects of Baking Absorption on Characteristics of Bread Crumb^a

Characteristics	Baking Absorption	
	Constant	Optimum
Loaf volume (cm ³)	2,220b	2,269a
Density (g cm ⁻³)	0.130	0.130
Crumb grain		
No. cells/cm ²	88.1	88.8
MCA (mm ²)	0.560	0.555
CWT (mm)	0.783	0.794
Uniformity	39.0	37.6
Crumb brightness	182.7a	180.7b
Void fraction	0.483	0.483
Mechanical properties		
Modulus (kN m ⁻²)	12.06a	10.46b
Fracture stress (kN m ⁻²)	2.36a	2.11b
Fracture strain	0.43	0.42
Fracture energy (J m ⁻³)	649a	565b

^a Data of various types of wheat flour (Canada Western Extra Strong and Canada Western Red Spring), sheeting treatments, and proof times were combined for each level of water absorption. Values followed by the same letter in the same row are not significantly different ($P < 0.05$). MCA = mean cell area, CWT = cell wall thickness.

which had the lowest dough extensigraph extensibility value but the highest fracture strain. Therefore, it appears that extensibility in dough and bread are governed by different factors. In dough, extensibility is enhanced by the amount of water added and likely a higher gliadin to glutenin ratio, as has been recently reported (Uthayakumaran et al 1999). For bread crumb, maintenance of a coherent structure, as described above, would implicate the glutenins (Bloksma 1990b).

Effects of Constant vs. Optimum Baking Absorption

Increasing the baking absorption by 5 and 3% for CWRS and CWES, respectively, significantly increased loaf volume and brought about a significant weakening effect on the bread crumb (Table VI). On average, there was $\approx 50 \text{ cm}^3$ or 2.2% increase in loaf volume. Final proof heights were unaffected, in many cases, by the higher baking absorption levels (Zghal 1999). Therefore, the increased loaf volume cannot be fully explained by an increased expansion of the dough during final proofing (Bloksma 1990b, Spies 1990). It is likely that the higher baking absorption led to greater amounts of water vapor being driven off during the oven spring phase, hence, contributing to the higher loaf volume (Bloksma 1990a).

On average, bread crumb density was unaffected by increasing baking absorption to optimum, despite the increase in loaf volume. The absence of effect is likely due to the weight increase of bread from higher moisture content being cancelled out by the volume increase. The moisture content of bread specimens was strongly related ($R^2 = 0.99$) to dough baking absorption. The average moisture content was 37.1% for CWRS, CWES, CPS, and blend bread prepared at 60% baking absorption, 38.1% for CWES bread prepared at 63% baking absorption, and 39.0% for CWRS bread prepared at 65% baking absorption.

Interaction effects between proofing time and the number of sheeting passes was observed for the density of bread crumb (Zghal 1999). This interaction, which is similar to that observed for all flour samples baked at 60% baking absorption (Fig. 2) and at optimum baking absorption, confirmed that the two extra sheeting passes resulted in dough degassing only and, apparently, did not cause any structural breakdown of the dough.

Varying baking absorption had only minor effects on the cellular structure of bread crumb (Table VI). The absence of an effect of baking absorption on most crumb grain features determined by DIA is in agreement with the results reported by Larsen and Greenwood (1991), who indicated that bread crumb grain scores were unaffected by baking absorption at levels ranging between 60 and 66%. Unlike the other crumb grain features, average crumb brightness decreased with increasing baking absorption from 60% to optimum levels (Table VI). The change in crumb brightness as a function of baking absorption, although relatively small, was highly significant ($P < 0.01$). The greater degree of starch gelatinization with increasing water absorption might have contributed a creamy color to the bread, making it appear less bright (A. W. MacGregor, *personal communication*). This brightness result suggests that DIA is sensitive to changes in crumb structure even at the supramolecular level.

In contrast to the virtual absence of effect of varying baking absorption on crumb structure, increasing absorption to optimal amounts had a large and significant influence on crumb mechanical properties. On average, Young's modulus, fracture stress, and fracture energy of bread crumb significantly decreased with increasing baking absorption (Table VI). The substantial reduction in Young's modulus of bread crumb with increasing baking absorption is consistent with the results of Piazza and Masi (1995). Those studies indicated that the effect was due to the plasticizing effect of water on the mechanical properties of the crumb cell walls.

SUMMARY AND CONCLUSIONS

To begin to develop an understanding of the relationship between flour strength, crumb grain, and bread mechanical properties, mechanical properties and crumb grain were quantified for the same bread

specimens in relation to the effects of four common breadmaking variables: flour type, baking absorption, sheeting, and proofing. Among these factors, proof time had the most profound influence, with substantial effects on loaf volume, crumb density, crumb brightness, and grain, as well as crumb mechanical properties; increasing proof time resulted in higher loaf volume, lower crumb density and brightness, coarser crumb with fewer and larger cells with thicker cell walls, and weaker crumb tensile properties. Varying flour type also led to significant differences in most of the measured crumb parameters that appeared to correspond to differences in gluten strength among the flour samples. With increasing flour strength, there was a clear trend to increasing loaf volume, finer and more uniform crumb grain, and stronger and more extensible bread crumb. Interestingly, varying flour type had a greater effect on crumb strength, fracture strain, and fracture energy than varying dough proof time. The crumb uniformity and strength results for flours of different strength indicate the importance of defects in crumb structure in influencing bread textural properties. By comparison, varying the number of sheeting passes and baking absorption had smaller effects on crumb grain and texture. Increasing the number of sheeting passes from three to five resulted in a minor effect on crumb cellular structure and no effect on mechanical properties. Increasing baking absorption had no effect on crumb grain but significantly weakened crumb strength and energy to fracture.

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