THE RELATIONSHIP BETWEEN BREAD PHYSICAL TEXTURE AND ITS STRUCTURE DETERMINED BY DIGITAL IMAGE ANALYSIS.

By

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation	Description
A	Area under the extensigraph curve
BU	Brabender Units
BWBD	Bandwidth breakdown
BWPR	Bandwidth peak resistance
CB	Crumb brightness
CPS	Canada Prairie Spring
CWES	Canada Western Extra Strong
CWRS	Canada Western Red Spring
CWT	Cell wall thickness
DDT	Dough development time
DIA	Digital image analysis
E	Young's modulus
E_s	Young's modulus of the cell walls
EXT	Extensibility
FOV	Field of view
FU	Farrand units
FWA	Farinograph water absorption
GL	Gray level
MCA	Mean cell area
MDD	Mechanical dough development
MT	Mixing time
MTI	Mixing tolerance index
PDR	Peak dough resistance
PT	Proof time
RBD	Resistance breakdown
RMAX	Maximum resistance
SLCC	Ratio of small-to-large cell count
SP	Sheeting passes
U_f	Energy to fracture
VF	Void fraction
WA	Water absorption
WI	Work input
ε_f	Fracture strain
ρ or ρ_b	Bulk density
ρ_s	Solid density
σ	Stress
σ_c	Critical stress
σ_f	Fracture stress of the cell walls

The Relationship Between Bread Physical Texture and its Structure Determined by Digital Image Analysis

ABSTRACT

The visual (cellular structure) and physical (mechanical properties) texture of bread crumb are quality attributes that were anticipated to be interrelated. This study was undertaken to evaluate the influence of bread crumb cellular structure on its mechanical properties. Crumb structural properties were characterised by density and six crumb grain features measured using a digital image analysis (DIA) system. These grain features included crumb brightness, mean cell wall thickness (CWT), void fraction (VF), mean cell area (MCA), crumb fineness (number of cells/cm^2), and a measure of crumb uniformity—SLCC (small-to-large cell count ratio). The mechanical properties were determined by tensile testing of bone-shaped specimens cut from the same bread samples used for DIA. Tensile parameters included Young's modulus, fracture stress, fracture strain, and fracture energy.

Crumb density, which can be easily and accurately measured, is strongly related to the mechanical properties and crumb grain features of bread crumb. The accuracy of the DIA system for crumb grain measurement was evaluated, based on its capability to predict bread crumb density from computed crumb grain parameters. Bread was prepared from representative flour samples of two different wheat classes. Dough mixing and proofing conditions were varied to manipulate loaf volume and crumb density. With increasing crumb density, crumb brightness and fineness increased, while VF, MCA, and CWT decreased. Approximately 80% of the variation in bread crumb density could be

accounted for using a linear regression model comprising two variables, CWT and VF, after images had been correctly classified into cells and background.

Variations in bread formulation and processing conditions are known to have a great impact on the quality of bread. The effects of flour type, water absorption (WA), sheeting passes (SP) and proof time (PT) on density, grain features, and mechanical properties of bread crumb were assessed. Bread loaves were prepared by a short time breadmaking process using four spring wheat flours of varying strength. The effect of WA was assessed for two flours (CWRS and CWES). Structural and mechanical properties were significantly affected by flour type, with CWES bread having the lowest density, more uniform grain, and greater mechanical strength. WA only affected the mechanical strength of bread crumb, which generally decreased with increasing WA. Number of SP only had a small influence on crumb structure. With increasing PT, the effect of the two extra SP on crumb density and VF decreased, suggesting that the extra SP did not alter the gas retention properties of the dough. Increasing PT resulted in a bread crumb with coarser grain, lower density and mechanical strength, and higher extensibility. The decrease in mechanical strength was not observed for all PT despite the changes in density and grain features. This indicated that the mechanical properties of the cell walls were enhanced with increasing PT through a strain-hardening phenomenon that occurred during proofing and the early stage of baking. The structural parameters of bread crumb were strongly related to Young's modulus and fracture stress, with crumb density and brightness (separately) showing highly significant correlations. It was found that Young's modulus and fracture stress increased with increasing density, crumb brightness and crumb fineness, and with decreasing VF, MCA and CWT. In addition,

Young's modulus and fracture stress were successfully fitted to the power law model proposed by Gibson and Ashby (1997) for characterizing the properties of industrial cellular solids. Models for predicting the mechanical properties of bread crumb from its structure were attempted using regression analysis. A three-variable model comprising crumb density, crumb brightness and SLCC permitted the prediction of Young's modulus and fracture strength (R^2 values were 0.90 and 0.95, respectively). Fracture strain and energy did not show any dependence on crumb structure, and seemed to be influenced by the properties of cell walls.

FORWARD

The following publications or presentations have resulted from the studies reported in this thesis:

Publications

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3. Zghal, M.C., Scanlon, M.G., and Sapirstein, H.D. 1999. Structure and its influence on the mechanical properties of bread crumb. (in preparation).

Presentations

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3. Scanlon, M.G., Zghal, M.C., and Sapirstein, H.D. 1998. Quantifying the effect of structure on the texture of bread crumb. Cereal Foods World 43: 552. 83rd AACC Annual Meeting: Minneapolis.

1. Literature Review

1.1. Introduction

Understanding the fundamentals of the mechanical and structural properties of bread crumb is crucial, since these two interrelated properties are the major factors in determining bread quality, and hence, consumer acceptability. Both bread formulation (e.g., flour type, water absorption, shortening, and salt) and baking processes (e.g. mixing and fermentation time) are known to have tremendous effects on the quality of the final product, in terms of loaf volume, physical texture and cellular structure of the bread crumb. Changes in the mechanical properties of bread crumb are believed to be caused by modifications in the structure and properties of the cell wall material. However, bread crumb mechanical and structural properties have not been previously correlated. Theoretical models, which were developed by Ashby (1983) and discussed in greater details by Gibson and Ashby (1997), provide evidence that mechanical and structural properties of synthetic cellular materials are strongly related. Not until recently have food scientists realized the importance of the relationship and become interested in applying these theories to study the mechanical properties of porous food material of cereal origin, e.g., cakes (Attenburrow et al 1989), breads (Keetels et al 1996b), and starch foams (Hutchinson et al 1987; Shogren et al 1998).

1.2. Effects of Ingredients on Bread Quality

1.2.1. Flour Strength

Flour strength and dough strength are used interchangeably in the literature as an indication of flour quality or suitability for breadmaking. From a commercial point of view, a strong flour is one that produces dough with good handling properties, does not require an excessively long mixing time, and yields good bread over a wide range of processing conditions (Tipples et al 1982). These workers pointed out that the concept of flour strength includes two interrelated aspects: the chemical and physical properties of flour or dough, and the ability of flour to yield good bread quality. The physical aspects will be discussed below (1.2.2).

The chemical aspect of flour strength is related to the protein component of flour. It has long been established that loaf volume increases linearly with increasing protein content of the flour (Larmour 1931). Finney and Barmore (1948) showed that the relationship between loaf volume and protein content was linear within a single variety. Among different wheat varieties, the variation in the slope of the regression line of loaf volume versus protein content appeared to reflect the differences in protein quality, with better cultivars having a higher slope. In the past decade, identification of the molecular basis of protein quality and its relation to baking performance has been intensively investigated.

Gluten, which is primarily dough protein formed upon mixing flour with water, was demonstrated by Finney (1943) as being responsible for wheat quality. Gluten or storage protein contains two components, glutenin and gliadin. These two components, which represent 80% of total wheat protein, were first identified by Osborne (1907), who separated wheat proteins into four main fractions based on their solubility in different solvents. Glutenins are very large polymeric proteins, representing 50% of gluten protein. They are made up of disulfide-linked high molecular weight (95,000-140,000) and low molecular weight (30,000-51,000) subunits (Payne and Corfield 1979), with their relative molecular weights reaching up to tens of millions (Donald 1994; Wrigley 1996). The glutenin fraction of wheat protein is responsible for the elasticity (springiness) and extensibility of the dough (Bushuk 1987; Spies 1990; Khatkar and Schofield 1997). On the other hand, gliadins are single chain polypeptides (30,000-80,000) making up the other half of gluten protein and are responsible for the viscous properties of the dough (Spies 1990; Uthayakumaran et al 1999). The interaction between high molecular weight glutenins and gliadins gives the developed dough its unique viscoelastic character (Bushuk 1987).

Glutenins are considered by many researchers as an important protein quality factor which contributes to the baking performance of wheat flour. Based on the variation in glutenin solubility and different fractionation and reconstitution procedures, the molecular weight and distribution of glutenins were shown to influence breadmaking quality (Orth and Bushuk 1972; MacRitchie 1987; Chakraborty and Khan 1988; Gupta et al 1993). In all of these studies and many others, it was clearly shown that high molecular weight glutenin subunits and their proportion in the parent gluten have a considerable positive effect on loaf volume. In contrast, gliadins were shown to have a lesser effect on breadmaking quality (bringing about only a small reduction in loaf volume), but a positive effect on dough development since gliadins significantly decreased the dough mixing requirement (MacRitchie 1987; Uthayakumaran et al 1999). From all these results, it appears that flour quality is dependent on a good balance of glutenin and gliadin proteins. Uthayakumaran et al (1999) indicated that protein content and glutenin-to-gliadin ratio independently affected dough properties and baking performance. They showed that for a constant glutenin-to-gliadin ratio, loaf volume increased with increasing protein content. On the other hand, for a constant protein content, an increase in the glutenin-to-gliadin ratio (0.58-1.55) resulted in an increase in loaf volume.

1.2.2. Water Absorption

Water plays a major role in breadmaking, since it hydrates flour particles and helps flour components to interact producing a homogeneous mass of dough (Bushuk and Hlynka 1964; Hoseney and Finney 1974). Water absorption was defined by Bushuk and Hlynka (1964) as the amount of water necessary to obtain a dough with proper or optimum consistency for the production of bread that has a superior quality. In commercial baking of bread, water absorption is looked at as an important element since it affects shelf life of the finished products and bakery profitability (Czuchajowska et al 1989; Puhr and D'Appolonia 1992). In addition, depending on the amount of added water, problems associated with the handling of doughs (e.g. slack and sticky or tough dough) may be encountered (Atkins and Larsen 1990). The amount of water added to a dough system, which is in general subjective, depends on flour moisture content, flour strength, and handling properties of the dough at the time of panning (Kilborn and Tipples 1981a). It is greatly influenced by the protein content and quality and the extent of damaged starch (Bushuk and Hlynka 1964). Water absorption is also affected by flour particle size, with flour containing finer particle sizes exhibiting greater water absorption (Bushuk and Hlynka 1964; Scanlon et al 1988; Lindahl and Eliasson 1992). Dough ingredients such as salt and shortening are also known to influence water absorption of dough (Bushuk and Hlynka 1964; Pyler 1988; Spies 1990). According to an estimate of water distribution in dough suggested by Bushuk (1966), 45.5% of the total water is associated with starch, 31.2% with protein, and 23.4% with the small amount of pentosans present in the flour.

Skeggs and Kingwood (1981) found that water absorption is dependent on the size of the mixing bowl and geometry of blades because these two factors affect the shear profile applied to the dough system thus altering the amount of water absorbed by the flour. In addition, increasing farinograph mixing speed led to an increase in water absorption (Hlynka 1962). For various levels of water absorption, the work input required to develop doughs remained the same, but mixing time and dough consistency (height of the mixing curve) were dramatically affected (Larsen and Greenwood 1991). As more water was added (in the range 54-68%), mixing time to peak dough development increased and dough consistency decreased.

Water is the second most important factor that influences the rheological properties of the dough (Kamman 1970). Casutt et al (1984) studied the effects of water absorption on extensigraph properties of CWRS dough. They showed that a 2% increase or decrease in water absorption did not affect dough extensibility (extensigraph length), whereas, a 2% increase in absorption led to a significant decrease in dough resistance (extensigraph height) and area under the curve.

Water governs the major changes that take place during baking, e.g., starch gelatinization, protein denaturation, yeast and enzyme inactivation, and flavor and color development. It has been known for many years that water absorption is one of the most vital factors in the production of bread because of its influence on loaf volume and crumb grain (Harrel 1926). Harrel (1926) reported that there was an improvement in crumb grain and loaf volume as water absorption was increased from 50 to 65%. Further increase in water absorption up to 75% resulted in a deterioration in the overall quality of the bread. Czuchajowska et al (1989) who studied the effects of water absorption (optimum, +3%, and –3%) on moisture content and water activity of dough and bread, reported that decreasing water absorption resulted in a considerable reduction in loaf volume. Larsen and Greenwood (1991) found that optimized water absorption (based on mixing curve dough consistency) did not always produce optimal quality bread. They also indicated that increasing water absorption above the optimum level had small and inconsistent effects on loaf volume and bread score, but significant negative effects on the appearance of the crumb (crumb grain). The deterioration of crumb grain with increasing water absorption could be due to a decrease in dough consistency, which may have led to a greater degree of coalescence (Spies 1990). The moisture content of bread crumb at the center of the bread slice was highly correlated (R = 0.99) with the amount of water added to mix the dough (Larsen and Greenwood 1991). They reported that differences in moisture content of the bread crumb at the center and corner of the loaf were as high as 10.6%. The effect of moisture content of bread on the softness and staling rate was examined by Maleki et al (1980). They found that higher moisture content bread produced softer bread as measured by compressibility with a penetrometer. Piazza and Masi (1995) studied the mechanical properties of bread crumb during aging, taking into consideration the water content in the various areas of the bread. For the three types of breads used in the experiment, they showed that the modulus of elasticity linearly decreased with increasing moisture content.

1.2.3 Assessment of Dough Properties

The physical aspect of flour strength (or dough strength) and its relation to baking performance can be assessed by characterizing the rheological properties of the dough using instruments such as the farinograph, mixograph, or/and extensigraph.

The farinograph is designed to measure the resistance of dough to a constant mechanical shear. The farinograph parameters that reflect flour strength are stability time (min, time difference between departure and arrival time), dough development time (DDT, min) and mixing tolerance (measured in arbitrary units: BU). Stability is considered by Pyler (1988) to be the primary index of flour quality. The DDT on the other hand, is considered an indicator of protein quality, with stronger flour requiring longer mixing time. Kunerth and D'Appolonia (1987) reported that farinograph parameters (DDT, tolerance, and stability) of 240 flour samples had highly significant correlations to gluten content. They also showed that these same farinograph parameters were significantly correlated with loaf volume. Branlard et al (1991) studied the relationship between bread quality and farinograph parameters for 40 winter wheat cultivars. They found that loaf volume and crumb score were significantly correlated with farinograph DDT and mixing tolerance. Atkins and Larsen (1990) reported that all farinograph parameters (stability, DDT and mixing tolerance) were significantly correlated with work input required to develop the dough to optimum consistency on 125g mechanical dough development standard bake test. However, only DDT was significantly correlated with loaf volume.

The mixograph has been extensively used to measure dough strength or flour quality. The mixograph is a device that measures and records the torque produced during dough mixing as a function of time. Mixograph parameters include development time, peak dough resistance (PDR), band width at peak, work input to peak, and breakdown (change in dough resistance with time). Several studies have correlated various mixograph parameters of the dough with the resulting bread quality (Finney and Shogren 1972; Branlard et al 1991; Khatkar et al 1996; Uthayakumaran et al 1999). Branlard et al (1991) indicated that mixograph development time and peak dough resistance (PDR) successfully predicted loaf volume. In a more recent study, Khatkar and co-workers (1996) studied the inter-relationships between mixograph parameters and breadmaking quality of unfractionated flours, reconstituted flours, and gluten from 13 wheat cultivars, representing a wide range of flour strength. They reported that peak dough resistance was significantly correlated ($p < 0.001$) with loaf volumes for flour, reconstituted flour, and gluten samples ($r^2 > 0.65$ for flour samples and as high as 0.85 for gluten samples). Other mixograph parameters were correlated to loaf volume to a lesser extent, except development time and work input which were shown to have no relationships with loaf volume. The discrepancy between the results of Branlard et al (1991) and Khatkar et al (1996) regarding the relationship between loaf volume and dough development time could be due to differences in the wheat sample set used. Uthayakumaran et al (1999) investigated the effects of varying protein content and glutenin-to-gliadin ratio of six wheat cultivars on the functional properties of wheat dough (mixograph and extension test) and baking performance. For most of the cultivars, increases in protein content at constant glutenin-to-gliadin ratio strongly correlated with mixing time, mixograph peak resistance and loaf volume, but not with resistance breakdown (change in dough resistance two min after PDR). On the other hand, at a constant protein content, increases in glutenin-to-gliadin ratio generally increased mixing time and loaf volume, reduced resistance breakdown, but had no effect on PDR. The magnitude of the observed changes in mixograph parameters was dependent on the cultivar used.

The extensigraph is an instrument that records the force of stretching a molded and rested dough piece as a function of time to obtain a measure of dough resistance (maximum dough resistance, RMAX) and extensibility (EXT). The extensigraph has been used to determine dough strength and to study the effects of dough ingredients and processing conditions on the rheological properties of dough (Preston and Hoseney 1991). Spies (1990) indicated that the maximum resistance of the dough is related to its elastic properties, whereas, the extensibility is related to the viscous component. He indicated that a good balance between the elastic and viscous properties of the dough is critical to breadmaking. Highly viscous dough tended to flow during processing steps and therefore, it would not maintain a desirable final shape, whereas, highly elastic dough (bucky dough) was difficult to process since it would not retain the desired shape after rounding, sheeting, and moulding. Uthayakumaran et al (1999) studied the effects of protein content and glutenin-to-gliadin ratio on extensigraph parameters (measured by microextension tester) and loaf volume. Their results indicated that at a constant glutenin-to-gliadin ratio, increasing protein content resulted in an increase in extensibility, maximum resistance to extension and loaf volume. At fixed protein content, increasing glutenin-to-gliadin ratio produced an increase in maximum resistance to extension and loaf volume, and a decrease in extensibility. From these results, it appears that glutenin proteins increased dough resistance and elasticity, but had no clear effect on extensibility (the decrease in extensibility could be due to either the lower gliadin and/or higher glutenin content).

The area under the curve has been also used to measure dough strength. Preston and Hoseney (1991) classified wheat flour strength into four categories according to the areas of the extensigrams. These categories of wheat flour were weak, medium, strong and very strong, which corresponded to extensigram areas of <80, 80-120, 129-200 and >200 cm^2, respectively.

1.3. Effects of Processing Conditions on Bread Quality

1.3.1. Dough Mixing

Dough mixing is a critical step that blends bread ingredients into a homogeneous dough mass, occludes air into the dough, develops the gluten proteins into a continuous phase, and yields a dough with optimum consistency (Hoseney and Finney 1974; Spies 1990). Hoseney and Finney (1974) defined optimum consistency of a dough as the height of the mixing curve at the peak, which is also referred to as the point of minimum mobility or optimum mixing time. Baker (1941) indicated that during mixing, dough development is achieved by means of stretching and folding. In his study it was concluded that the stretching operation draws gluten from the matrix of the endosperm particle to the surface of air nuclei (tiny air cells incorporated by mixing) so that gluten concentrates at this point and becomes available for holding the entrapped air. In addition to the positive effects of mixing on the rheology and gas retention properties of doughs, the entrapped air during mixing is of equal importance, since it was shown that this occluded air was the only source of air cells in the dough (Baker and Mize 1941).

During fermentation, as CO_2 is produced by the yeast it diffuses into the air nuclei leading to an increase in pressure and causing these air nuclei (created by mixing) to expand into larger gas cells which form the cellular structure of the fermented dough, and consequently of the baked bread. Shimiya and Nakamura (1997) further confirmed from microscopic observation that groups of small air cells entrained during the mixing stage are the original cause of the cellular structure of bread.

Tipples and Kilborn (1974) pointed out that dough mixed below its peak or optimum consistency had poor rheological (low extensibility) and gas retention properties, which led to unacceptable bread quality (small loaves with coarse crumb structure). Kamman (1970) indicated that under-mixed dough produced uneven crumb grain with large cells, dull color, and thick cell walls. Further mixing beyond optimum consistency caused dough breakdown and resulted in a wet and sticky dough (difficult to handle) with altered protein structure that was less capable of retaining gas (Hoseney and Finney 1974). Over-mixed dough produced bread with reduced loaf volume and poor external appearance, crumb with large round gas cells, and streaks (Kamman 1970). Dough under-mixing has much more negative effects on bread characteristics than over-mixing because the latter tend to recover during fermentation (Hoseney and Finney 1974).

1.3.2. Dough Sheeting

Sheeting is a process that elongates the dough through the application of shear when the dough passes through rollers. This process has been used in the production of many types of foods of cereal origin such as various kinds of noodles, biscuits, cookies, crackers, and pizza crusts (Levine and Drew 1990). In general, the functions of sheeting include dough development (as achieved by mixing), protein alignment, gas repulsion, and lamination of the dough (Levine 1998). Kilborn and Tipples (1974) indicated that dough development by repeated sheeting required the same work input into the dough as that of mixing, with the sheeting rolls being much more energy efficient (only 10-15% of the energy used by a high-speed mixer). The optimum dough development by sheeting corresponded to a point where maximum energy per pass was reached. The development of dough by sheeting led to changes in physical properties (extensibility and resistance) which were similar to those produced by mixing (Kilborn and Tipples 1974). Levine (1998) reported that repeated sheeting beyond optimum dough development causes breakdown of the protein network and results in a loss of gas holding capacity similar to that of dough that has been over-mixed.

Stenvert et al (1979) studied the effects of dough sheeting (0 to 30 passes) on dough microstructure and the quality of no-time and fermented breads made from flours of various strengths and protein contents. For no-time bread of all flour samples, satisfactory breads having a slightly open structure were obtained without dough sheeting. Sheeting of a developed dough caused degassing and reduction in bubble size, and produced bread with a very fine crumb grain and reduced loaf volume. Increasing the number of sheeting passes (11-14 passes, depending on flour strength) resulted in finer bread structure, with stronger flour requiring more passes and showing more tolerance to further sheeting. It was reported that 30 sheeting passes caused severe breakdown of dough structure of a relatively weaker flour (dough development time, DDT = 4.3 min), and resulted in a very open crumb grain. These effects were evident to a lesser extent for the flour with intermediate strength (DDT = 6.2 min), but no effects were observed for the strong flour (DDT = 9.0 min). In breadmaking, the sheeting process was shown to affect the physical properties in the dough system and bread by creating structural and material anisotropy (Levine 1998; Whitworth and Alava 1999). The anisotropy in turn affects the rheological properties of dough, since the sheeted dough is much stronger and more elastic in the direction of sheeting than in the cross direction (Levine 1998).

1.3.3. Dough Proofing

The final proofing or last fermentation, is the stage that follows dough sheeting, molding and panning. During this stage, dough is allowed to regain an extensible character, and time permits the yeast to produce CO_2, resulting in a high level of porosity, which in turn contributes to the volume and grain of the final product. Proofing conditions, including time, temperature and humidity, vary for different baking procedures. All these factors have a major effect on the characteristics of final products in term of visual and physical texture (Pyler 1988). The relative humidity is usually maintained at 85% or higher, while proof time-temperature protocol tends to vary from one procedure to another (Kilborn and Tipples 1981a; Kilborn and Tipples 1981b; Yamada and Preston 1992). Proofing temperatures normally range from 30 to 40°C. Although proofing at lower temperature resulted in better crumb grain and loaf volume (Siffring and Bruinsma 1993), higher temperatures are commonly used in the baking industry as a means of reducing proof time and increasing production volume and profits (Pyler 1988).

There has been an interest in studying the effects of fermentation time on the rheological properties of dough and the underlying breadmaking quality for many years.

Bailey and Levesconte (1924) showed that the extensibility of leavened doughs stretched on a Chopin Extensimeter increased with fermentation time. In a more recent study, Casutt et al (1984) investigated the effects of fermentation time on properties of wheat dough of varying strength using an extensigraph. They indicated that increasing fermentation time led to an overall decrease in the strength of dough, as was clearly shown from decreasing extensibility, resistance to extension, and areas of the extensigrams. It was also pointed out that the decrease in physical strength of the dough upon fermentation is dependent on the inherent strength of flour, and this decrease was much more evident for weaker flour.

Freilich (1949) studied the effects of varying proof time from 0 to 150 min on bread loaf volume and crumb grain. Proof times ranging from 45 to 60 min were found to be acceptable, since the bread produced had satisfactory crumb grain and texture. Kamman (1970) indicated that under-proofed dough gives a compact loaf with an uneven grain. On the other hand, over-proofed dough produces a very large and bulky loaf, with a coarse grain comprised of round gas cells.

1.4. Evaluating Bread Crumb Cellular Structure

Crumb visual texture and crumb grain are used interchangeably to describe the exposed cellular structure of the crumb when a loaf of bread is sliced (Kamman 1970). In general, the term texture has been used in the literature to refer to the mechanical properties of foods. However, in the case of bread crumb evaluation or grading, Bourne (1982) has indicated that the term texture is exclusively used to describe bread crumb cellular structure in terms of uniformity and cell size distribution. To avoid this conflict, the term physical texture will be used in this thesis to refer to the mechanical properties of bread. On the other hand, visual texture will be utilised to describe crumb cellular structure.

In addition to crumb colour and physical texture, crumb cellular structure or grain is an important quality criterion used in commercial baking and research laboratories to judge bread quality (Kamman 1970; Pyler 1988; Zayas 1993). Bread crumb visual texture accounts for approximately 20% of the weighting used in judging bread quality (Pyler 1988). Regardless of the weight assigned to it, crumb grain is believed to have a considerable importance in defining bread quality since the accuracy in scoring other quality attributes in bread (i.e. loaf volume, loaf symmetry) depends on the underlying crumb grain characteristics.

In bread crumb scoring, the examined parameters are crumb fineness (open versus closed cells), uniformity, cell shape, and cell wall thickness (Pyler 1988). The traditional method for crumb grain scoring or inspection is qualitative and subjective in nature since it relies on human vision which is known to be inconsistent among different experts and could vary over a period of time even for the same expert (Coles and Wang 1997). The development of a modern baking industry, which nowadays uses automated and continuous processes, necessitates more sophisticated methods (fast, precise, consistent and reliable) for evaluating the quality of finished bakery products such as bread and other baked goods. In recent years, there has been increasing interest in adapting digital image analysis (DIA) for objective and quantitative evaluation of bread crumb grain. A large number of investigators have studied the cellular structure of bread crumb using different methods (Bertrand et al 1992; Zayas 1993; Zayas et al 1993; Sapirstein et al

1994; Rogers et al 1995). These methods, which differ in the way crumb grain features are extracted, can be generally classified into image texture analysis and image segmentation.

1.4.1. Image Texture Analysis

Image texture analysis is a region descriptive approach that provides a measure of properties such as smoothness, coarseness and regularity (Gonzalez and Wintz 1983). This approach has been used in many studies (discussed below) to extract bread crumb characteristics, which are then used mainly for scoring purposes. The drawback of this approach lies in its inability to provide quantitative measurements of bread cellular structure.

The first application of video image analysis to describe the textural appearance of bread crumb was performed by Bertrand and colleagues in 1992. They characterized bread crumb from seven white bread formulations differing in surfactant composition using mathematical methods based on a two-dimensional Haar transform. This method permitted the extraction of 66 texture characteristics per image, each corresponding to a coefficient determined according to the size of the Haar mask used. Stepwise discriminant analysis was performed to identify images of bread crumb according to the experimental treatments. Six texture characteristics permitted 82% of bread images to be correctly classified according to surfactant type used in the bread formulation.

Zayas (1993) evaluated the crumb grain of two commercial bread brands by digital image texture analysis of a whole slice using a statistical approach. Eighteen bread crumb features were extracted based on first–order statistical measures (e.g., mean and variance) and second-order statistical measures (e.g., angular second moment).

Multivariate discriminant analysis, which was applied to the image texture features to distinguish the two brands of bread, resulted in more than 97% of the images of bread slices being correctly identified. A ranking scale was developed on the basis of percent fineness or coarseness of sub-images within a bread slice. The author indicated that this scale is flexible and can be adapted to meet the requirements of laboratory and commercial users for bread scoring. Although this method was shown to be effective in evaluating the visual texture of bread crumb, the long computational time required for feature extraction may limit its practical application (Wang and Coles 1994).

In another study, Zayas et al (1993) investigated the sensitivity of image texture analysis of crumb grain along with shape and size characteristics of the bread slice to differentiate technological bread factors (shortening, water absorption and mixing time). Image features were extracted from co-occurrence matrices of 64 x 64 pixel sub-images. This approach of features extraction considers not only the distribution of gray level intensity, but also the positions of pixels with equal or nearly equal intensity values. Zayas and coworkers indicated that co-occurrence matrix and gray level features effectively characterized crumb grain and allowed sub-images ranking according to porosity patterns. They also reported that differences in water absorption and mixing time were better identified by image texture features, whereas, the presence of shortening in bread formulation was distinguished by slice shape features.

Wang and Coles (1994) developed a spatial method for image texture analysis, which was derived from their two previous techniques (edge detection and Fast Fourier Transform), to enhance the speed and precision in predicting bread score. In their study, the bread images were first processed by edge detection, and then subdivided into sub-images from which crumb features were derived from statistics of gray level values. This method ignored sub-images containing large bubbles (in order to minimize their catastrophic effect on bread scoring); this reasoning was based on the claim that these large bubbles are overlooked by bread judges during scoring. The average edge density, which was calculated from the density (or gray level) of bubble edges in each sub-image after eliminating 20% of the smallest values, was used as a texture fineness index. For two batches of bread samples, the experimental results showed that the fineness indices were highly correlated with subjective scores of expert judges ($R^2 \geq 0.85$). Despite the strength of this relationship, this approach may not be effective in evaluating other types of breads or even the same bread using different scoring standards. The limitation of this technique is due to the fact that the extracted crumb features were greatly affected by the subjective elimination of large bubbles with no defined cell size threshold. In addition, local processing of sub-images may cause an overestimation of crumb fineness, especially in bread with a coarse grain. This is because portions of gas cells lying on the border of a sub-image (sectioned as a result of local processing) are considered to be small in size, when in fact they are only a section of larger cells.

Rogers et al (1995) developed a simple imaging system, based on Fourier transform analysis of images acquired by a document scanner, to evaluate the visual texture of bread crumb. Characterization of crumb grain was achieved by spectral estimation analysis of a localized area. There may be some controversy about the validity of using a document scanner because of the importance to image analysis of using configurable lighting; thus lighting can be adjusted to emphasize structural features of the objects which are being examined (Chan and Batchelor 1993). Although a document scanner does not provide configurable lighting, Rogers et al (1995) showed that their system was capable of accurately estimating loaf volume (R = 0.98), computing crust thickness, and determining crust color relative to that of the crumb.

1.4.2. Image Segmentation

Image segmentation is a process that separates or classifies object(s) of interest within an image from its background, yielding a binary image. Thresholding and edge detection are segmentation methods which are based on discontinuity of gray-level values within a digital image (Gonzalez and Wintz 1983). The only DIA system that uses image segmentation to extract bread crumb features was published by Sapirstein and coworkers (1992; 1994). In their studies, they applied the *K*-means algorithm to find an objectively determined gray level threshold for segmenting each image of bread separately. This algorithm, discussed in detail by Hartigan (1975), automatically partitions the gray-level distribution into two (or more) clusters representing cells and background. In a recent publication, Sapirstein (1999) indicated that this algorithm accounts for any significant variation in the overall reflectance of bread crumb images caused by differences in cellular structure. The validity of this approach was demonstrated in the 1994 publication, by clearly differentiating crumb grain of oxidized and non-oxidized bread. The advantage of utilizing segmentation for features extraction is not only to give an estimation of crumb fineness but also to accurately measure various structural parameters of the bread crumb. The computed crumb grain features, determined by Sapirstein and coworkers (1994), included equivalent cell size, cell size distribution, crumb fineness (number of cells/cm^2), mean cell area, cell wall thickness, average gray level, and void fraction. These parameters represented a good characterization of crumb cellular structure.

Although this segmentation algorithm produced a satisfactory classification of crumb images into gas cells and cell walls, Sapirstein et al (1994) pointed out that this algorithm tended to underestimate the void fraction and overestimate cell wall thickness. The reason for this imprecise segmentation of the images is mainly due to the complex cellular structure of bread crumb. The structure of bread crumb is not uniform since it comprises a wide distribution of cell sizes with regions having large numbers of small cells while others have only a few large cells. Because the intensity of the reflected light (or crumb brightness) depends on the cellular structure of the bread crumb, regions with finer structure reflect more light and result in high-contrast areas, whereas regions with coarser structure reflect less light and result in low-contrast areas (Burhans and Clapp 1942). In the high-contrast areas, the gray level value of the cell walls is higher than that of low-contrast areas, so that selecting a single threshold value would lead to under- and over-estimation of the cell sizes in high- and low-contrast areas, respectively. In order to overcome this limitation and deal with the complex and subtle details of a bread crumb image, a more sophisticated segmentation approach such as a multiple threshold technique is required. An example of multiple thresholding is local segmentation where a neighborhood of pixels is used to detect individual objects within an image (Eggleston 1998), or individual gas cells in the case of bread crumb. This approach determines a gray level threshold for each gas cell, and therefore it accounts for the variation in the cellular structure within the bread slice.

1.5. Mechanical Properties of Bread Crumb

Mechanical properties of bread crumb have been extensively studied and successfully related to quality attributes. The evaluation of the mechanical properties of bread crumb is very important not only for quality assurance, but also for assessing the effects of various dough ingredients, processing conditions and storage time on bread characteristics.

The mechanical behaviour of bread crumb is known to be very complex. This behaviour is described as viscoelastic, and the range of stresses over which bread crumb behaves in an elastic manner is narrow and poorly defined (Lasztity 1980). The latter statement is in agreement with the observation of Gibson and Ashby (1997), who indicated that the elasticity range of synthetic cellular materials corresponds to a narrow range of strain (few percent). The difficulty in characterising the stress strain curve (Lasztity 1980; Ponte and Faubion 1987) was attributed in part to the porous structure of bread crumb in which a complex combination of stresses, shear and flexural, occur when a bread sample is subjected to mechanical testing (Lasztity 1980; Ponte and Faubion 1987). In addition, the non-homogeneous nature of the cellular structure of bread crumb (i.e. variation in cell size and cell wall thickness) contributes to its complex mechanical behaviour. This non-homogeneity is known to potentially cause greater differences in the mechanical properties of bread crumb within a single loaf than between loaves of different treatments (Ponte and Faubion 1987). Ponte et al (1962) and Short and Roberts (1971) showed that bread crumb firmness, determined by compression testing, varied across bread slices with the highest value in the centre. This finding was later confirmed by Hibberd and Parker (1985) who studied factors causing variability in bread firming measurements. They demonstrated that bread crumb is not homogeneous in terms of physical texture. The variability in bread firmness within a bread loaf was explained by the sequence of events that occur during baking (Lasztity 1980). The temperature gradient across the loaf in the oven, which in turn creates a moisture gradient, causes variation in the degree of starch gelatinization, protein denaturation, and enzyme inactivation within a bread loaf. Although this explanation seems reasonable, other factors such as structural differences across a bread loaf resulting from variability in the manner in which the loaves were prepared may also account for the differences in mechanical properties (Hibberd and Parker 1985). Examples of the structural differences include elongation of bubbles in the direction of sheeting, and appearance of large bubbles at the centre of the bread loaf or at the interface between layers of sheeted dough (Whitworth and Alava 1999).

1.5.1. Methods for Measuring Mechanical Properties

The most commonly used method to measure crumb texture is the compression test. This objective method yields bread firmness, which is a measure of resistance of bread crumb to deformation (Ponte and Faubion 1987; Piazza and Masi 1995). The bread firmness measured in compression, which is analogous to the subjective method of assessing crumb firmness by touch or mouthfeel, has been shown to be significantly correlated to sensory measurement (Elton 1969; Bashford and Hartung 1976; Brady and Mayer 1985). The advantage of the compression test is its simplicity, since performing this test requires only a small sample size that can be easily prepared.

On the other hand, tensile tests have rarely been used in testing the texture of bread or other spongy foods, despite the many advantages they have over the compression test.

These advantages will be discussed below. Two reasons were attributed to the limited use of this method. Firstly, the difficulty of griping the sample, since slippage could occur when the specimen is held by a pair of alligator grips (Luyten et al 1992; Chen et al 1994) or stress concentration might occur so that fracture originates at the grip. Secondly, specimen size and shape requirements (ratio of gauge length to width) are very difficult if not impossible to obtain under certain circumstances. Despite these limitations, the tensile test has a number of advantages over the compression test, in that it provides parameters which are simple to interpret (Nussinovitch et al 1990) and better reflect the fundamental mechanical properties of materials in general. In the case of bread, tensile parameters (e.g. strength, energy of fracture) represent a measure of crumb coherence and its resistance to tearing (Scanlon et al 1997). In addition to these parameters, the elastic properties of bread crumb were considered a key factor of bread quality (Nussinovitch et al 1992; Piazza and Masi 1995). Furthermore, when samples are subjected to tensile testing, the fracture starts at the outside of the sample, and thus, the mechanical behaviour can be clearly observed and understood, whereas, in the compression test the fracture starts from the inside (Luyten et al 1992). The high sensitivity of tensile tests for detecting defects in specimens allows the observer to examine the effect of artificially made notches on fracture behaviour, and therefore, determine the notch-sensitivity and the inherent defect size of the materials tested (Luyten et al 1992). All these advantages associated with the tensile test encouraged food scientists to find ways to overcome the limitations of this method and explore its application for determining the texture of spongy foods, namely, bread crumb.

1.5.2. Mechanical Behaviour of Bread Crumb in Tensile Testing

Bread crumb has cellular structure containing interconnected gas cells (Gan et al 1990) which implies that bread can be described as a spongy food. It was indicated by Attenburrow et al (1989), Chen et al (1994), Keetels et al (1996b), and Fontanet et al (1997) that the mechanical behaviour of bread crumb is similar to that of non-food cellular materials which were extensively analyzed by Gibson and Ashby (1988; 1997). The mechanical properties of the cellular materials are generally dependent on the proportion of void space in the material, the geometry of the structure, and the mechanical properties of the cell walls. According to Gibson and Ashby (1997), the tensile response of cellular materials, and thus of bread crumb, can be classified into four deformation modes. Firstly, a linear elastic mode, which involves cell wall bending and stretching. This linear elastic behaviour (as indicated above) corresponds to small strains (a few percent) from which the modulus of elasticity is calculated. This modulus is the same as that determined in the compression test (Gibson and Ashby 1997). The second deformation mode is the non-linear elastic regime, where cell edges rotate toward the tensile axis, resulting in a decrease in the bending moment that acts on them, and consequently, stiffness increases. Thirdly, plastic collapse, which occurs as cell edges become substantially aligned and further deformation causes the cell walls to yield, and therefore, deform plastically. Fourthly, fracture takes place progressively as the initiated single crack propagates and the enhanced stress concentration causes further cell walls to fail.

1.5.3. Evaluation of Bread by the Tensile Test

Platt and Kratz (1933) were the first to apply the tensile test to measure the strength of spongy food materials. Although the testing conditions were crude, they were able to show an inverse relationship between tensile strength and the volume of the sponge cake. The experimental set-up of this study involved the use of spring clamps to grip each end of the sample. The application of an increasing force to the specimen as a function of time was achieved by supplying a constant stream of water into a cup that was attached to the bottom grip.

Six decades later, the second application of a tensile test was performed by Nussinovitch et al (1990) to evaluate the use of tensile testing for assessing the physical texture of bread crumb. In this study, bone shaped specimens (gauge length: width = 15:12 mm) were prepared by punching out bread slices of various commercial types of bread with a sharp stainless steel template, and taping the ends with an adhesive tape. They studied uncompressed bread and bread compressed by placing it under a 5 kg load for 30 min. For white bread, they found that by compressing bread samples prior to testing and increasing the deformation rate from 10 to 50 mm min^{-1} higher values of strength and deformation to fracture were obtained. This increase in the mechanical properties with increasing deformation rate, which was also observed for starch bread, was explained by two mechanisms in terms of energy dissipation (Keetels et al 1996a). Firstly, due to the viscoelastic nature of bread crumb material, its flow causes energy dissipation which increases with increasing deformation rate. Secondly, friction between structural elements causes more energy dissipation at a higher deformation rate.

The reproducibility of tensile testing of bread crumb (*C.V.* between 8 and 20%) was considered acceptable by Nussinovitch and colleagues (1990). It was shown from their study that compression of specimens prior to testing reduced reproducibility at a deformation rate of 50 mm min^{-1}, but no effect was noted at the lower deformation rate (10 mm min^{-1}). The same authors concluded that there was no relationship between density and mechanical properties (strength and deformation to failure) of bread crumb. This conclusion could be misleading, because they did not take into consideration the fact that bread samples were made from different grain sources, which may have different physical and chemical properties of cells walls, as well as density differences. Therefore, the relationship between mechanical properties and density may not necessarily exist in this particular case.

Chen et al (1994) examined the possibility of characterising tensile parameters of bread crumb by a mathematical model that could be applied for texture evaluation. They used bone-shaped bread specimens which were prepared as described by Nussinovitch et al (1990), but with modified dimensions (gauge length by width were 20 x 20 mm). In this study, the pre-failure tensile force-deformation curves of all four types of breads (two brands of white, Canadian brown, and whole wheat breads) were successfully fitted ($R^2 \geq 0.99$) by the following equation:

$$F = C_1 \times D/(C_2 + D) \qquad (1)$$

Where, F is force in Newton (N), D is deformation in mm, and C_1 and C_2 are fitting constants having units of N and mm, respectively. The shape of the downward concavity observed in the force deformation curve was attributed to the progressive decrease in the specimen's cross sectional area, and the lack of strain hardening in bread crumb. In their study, Chen and co-workers clearly showed that the poor reproducibility in textural properties (*C.V.* ranged between 10 and 20%) is mainly due to natural variability and structural non-uniformity of bread crumb. This was demonstrated by subjecting 10 samples of both paper towel and facial tissue to the same test conditions used for bread (*C.V.* ranged from 1 to 6.5%). To alleviate the observed large variation in the mechanical properties of bread crumb, Chen and co-workers suggested the use of smaller and wider bread specimens. However, this may raise some concerns regarding the validity of the tensile test, since using wider specimen would reduce the ratio of gauge length to width, and therefore, specimen dimensions will not comply with the standardised techniques for tensile testing of materials (ASTM, 1993).

Scanlon et al (1997) used the tensile test to quantify the fracture resistance of two types of breads, since failure in tension mode is analogous to the tearing phenomenon associated with bread handling during application of food spreads such as butter. They concluded that the critical apparent energy release rate (the energy needed to propagate a crack) could be used to assess the fracture properties of bread crumb. Their conclusion was based on the fact that the critical apparent energy release rate reflected the relative difference in flour strength from which the breads were made, and therefore, it could be related to aspects of bread quality.

1.6. Relationship Between Structure and Texture of Cellular Materials

Almost every scientist that has studied the texture or cellular structure of bread crumb has indicated that these two properties are strongly related to each other. Kamman (1970) indicated that physical and visual texture of bread crumb are interrelated quality factors that should be considered as a single entity. He speculated that crumb texture is largely determined by the character of the grain e.g., cell wall thickness, cell size and uniformity. Pyler (1988) pointed out that the crumb texture sensed by how the crumb feels to the touch or by mouthfeel is greatly influenced by the grain or cell structure of the crumb. He reported that finer, thin-walled, uniformly-sized cells yield a softer and more elastic texture than a coarse, open and thick-walled cell structure. Based on an analogy to other naturally occurring and synthetic cellular materials discussed by Gibson and Ashby (1988), Chen et al (1994) pointed out that the mechanical properties of bread crumb are determined by both the mechanical properties of the cell wall materials and the geometrical characteristics of the cellular structure. For non-food cellular materials, Gibson and Ashby (1997) indicated that the single most important structural characteristic of a cellular solid is its relative density, ρ/ρ_s (where, ρ is the bulk density and ρ_s is the density of the cell walls or the solids in the structure). This theory has been developed for materials with ideal cellular structure (uniform cell size and cell wall thickness). They also pointed out that cell shape and size distributions, along with cell wall thickness, and whether the cells are open or closed, are factors that influence the mechanical properties of cellular materials.

1.6.1. Bulk Density

Bulk density is defined as mass per unit volume (kg m^{-3}). Ponte et al (1962), who studied the crumb firmness and firming rates of breads made from ten wheat flours, found a strong relationship between compression force and specific volume (inverse of bulk density) of bread crumb as it varied across a bread slice (R = 0.93). Wassermann

(1979) also showed that the specific volume of bread crumb (varied by changing proof time) was responsible for firmness and relative elasticity (ratio of elastic deformation to the sum of elastic and plastic deformation derived from the hysteresis curve with constant deformation) of bread crumb. For bread crumbs differing in composition (100% rye, 50% blend of wheat and rye, and 100% wheat), the crumb firmness linearly decreased while crumb elasticity linearly increased with increasing specific volume. The rate of change in mechanical properties of bread crumb as a function of specific volume was dependent on bread composition, with rye bread having the highest slope, while wheat bread had the lowest slope. Lasztity (1980) speculated that changes in bread crumb textural properties (both elastic and plastic) upon addition of shortening was partly due to the increase in volume, since the volume is inversely proportional to density. Attenburrow et al (1989) examined the relationship between mechanical properties in compression and the structure of sponge cake which had been conditioned to different water activities (0, 0.33, 0.57, and 0.75). It was found from stress-strain data, that both the logarithm of initial modulus and the logarithm of critical stress, were linearly related to the logarithm of bulk density. The suggested relations between bulk density (ρ_b), and Young's modulus (E) and critical stress (σ_c) were in the following forms:

$$E = K_1 \rho_b^2 \tag{2}$$

$$\sigma_c = K_2 \rho_b^2 \tag{3}$$

where, K_2 and K_1 are constants which depended on water activity of the sponge cake. They assumed that the density of cell walls of sponge cake was invariant over the range of bulk density studied. Based on this assumption they indicated that these two relations were in agreement with the proposed model of Gibson and Ashby (1988) discussed below. The validity of the assumption that the solid density of sponge cake is invariant is questionable and requires further investigation, since, it was clearly shown in many studies that cell wall materials dramatically vary with both formulation and processing conditions (Warburton et al 1990; Donald 1994; Bhatnagar and Hanna 1997). Shogren et al (1998) indicated that strength and rigidity of baked starch foams increased with increasing density, whereas, deformation to fracture increased with decreasing density.

1.6.2. Relative Density

Relative density, which is the dominant physical character representing the 3-dimensional structure of cellular materials (Warbuton et al 1990; Gibson and Ashby 1997), has been used in many studies to quantify the dependence of the modulus and crushing stress on structure. The theory predicts scaling laws between the physical properties of cellular materials (Young's modulus and fracture stress) and its relative density.

$$E/E_s \propto (\rho/\rho_s)^m \tag{4}$$

$$\sigma/\sigma_s \propto (\rho/\rho_s)^n \tag{5}$$

where, E : is the Young's modulus of the cellular material

E_s: is the Young's modulus of the cell walls

ρ : is the density of the cellular material

ρ_s: is the density of the cell walls

σ : is the fracture stress of the cellular material

σ_s: is the fracture stress of the cell walls

m, n: power law indices

The power law depends on whether the cellular structure contains open or closed cells. For open cells, $m = 2$ and $n = 3/2$, and for closed cells, $m = 3$ and $n = 2$ (Gibson and Ashby 1997). As mentioned above, this theory is applicable to ideal cellular materials that have uniform cell size and cell wall thickness. Despite the large variation in cellular structure of bread crumb, Keetels et al (1996b) have indicated that this theory can still be used to relate the microstructure and the overall shape of the stress-strain curve. Hutchinson et al (1987) found a strong relationship between mechanical properties (from compression, tension and flexure tests according to British standards of plastics) and the bulk density of extruded maize using Equations 4 and 5. They found that the power law indices m and n were 1.7 and 1.5 in tension and 2.3 and 1.6 in compression test, respectively. For baked starch foams subjected to a tensile test, Shogren and co-workers (1998) showed that $\ln E$ and $\ln \sigma$ versus $\ln \rho/\rho_0$ were linear ($R^2 = 0.99$) with slopes of $m = 1.28$ and $n = 1.12$, respectively.

1.6.3. Cell Walls

It has been commonly known that mechanical properties of cellular materials are strongly influenced by the properties of cell walls. In addition to the mechanical properties of the material forming the cell walls, cell wall thickness, cell wall thickness distribution, and the presence of defects in cell walls were shown to affect the overall mechanical properties of cellular materials (Gibson and Ashby 1997). Cellular materials with thicker cell walls were anticipated to have a higher mechanical strength because cell wall thickness is associated with higher bulk density (Barrett et al 1994). A more comprehensive relationship between density and cell wall thickness was provided by Gibson and Ashby (1997). They reported that the ratio of cell wall thickness (t) to cell edge-length (l) of open- and closed-cell cellular materials are closely related to relative density:

for open-cell foams: $\rho/\rho_s = C_1 \times (t/l)^2$, (6)

for closed cell foams $\rho/\rho_s = C_2 \times t/l$ (7)

where C_1 and C_2 are constants depending on cell shape.

Defects in the cell walls (missing or ruptured cell walls as a results of cell coalescence) and cell wall thickness distribution are relevant for non-ideal cellular materials found in food foams and sponges. From numerical simulation of the stress-strain behaviour of honeycombs, it was shown that both Young's modulus (Silva et al 1995) and compressive strength (Silva and Gibson 1997) significantly decreased with increasing number of missing cell walls. The loss of 5% of the cell walls resulted in over a 30% decrease in modulus and strength, and the removal of 35% of cell walls completely degraded both the modulus and the strength (Silva et al 1995; Silva and Gibson 1997).

Distance to failure, which is a measure of flexibility, was shown to be dependent on properties of cell wall materials, since thinner cell walls can flex more easily without breaking than thicker ones, and therefore, result in greater deflection at break (Shogren et al 1998).

1.6.4. Porosity

Porosity ($1-\rho/\rho_s$), which is the fraction of pore space in cellular materials, is an important structural characteristic that affects the mechanical properties of cellular materials. The relationship between porosity and mechanical properties is expected to be strong since porosity is related to density. Bhatnagar and Hanna (1997) studied the effect of various lipids on the microstructure and texture of extruded starch. They showed that different types of lipids resulted in large variation in the microstructure (bulk density, solid density, cell size, open vs closed cells, and cell wall thickness) and the shear strength of the extrudate. They found that shear strength decreased logarithmically with increasing porosity ($R^2 = 0.94$).

1.6.5. Anisotropy

Anisotropy of cellular materials and its influence on mechanical properties were extensively reviewed by Gibson and Ashby (1997). They described anisotropy as the tendency of cells to be elongated or flattened or to have walls of unequal thickness Anisotropy was classified into two categories which are direction-dependent: structural anisotropy and material anisotropy. The former is a measure of cell shape, while the latter refers to properties of cell walls. For axisymmetric cellular structure, the structural anisotropy is characterized by a shape anisotropy ratio (R), which is measured by the ratio of the largest cell dimension to the smallest. It was indicated that mechanical properties of cellular materials depend on shape anisotropy ratio R and direction of cell elongation. Young's modulus and strength of cellular materials are lower in the direction of cell elongation by an order of magnitude of R^2 and R, respectively. On the other hand, in an orthotropic cellular structure, where cells sizes differ in all three dimensions, two values of R are used to characterise the structural anisotropy.

Hibberd and Parker (1985) investigated the effects of various factors on different measures of firmness. Their results showed a very highly significant dependence of crumb mechanical properties on the direction of measurement. The force required to compress bread crumb by 30% in the direction parallel to the long axis of the loaf was twice that needed to deform the bread in the other two directions. The compression force in the direction parallel to the vertical axis of the loaf was the lowest. For the stiffness, similar trends to that of compression force were observed. Persaud et al (1990), who used dynamic stress-strain measurements to characterize the properties of freshly baked and aged bread crumb, contradicted the results reported by Hibberd and Parker (1985). Persaud et al (1990) found that the shear storage modulus G' was the same in all three planes (or directions) of shear, and therefore, concluded that the bread crumb taken from the center of loaves lacked anisotropy. The isotropy in the rheological properties was attributed to the small size of crumb sample taken from the center of the bread loaves, which consisted of small round cells (uniform grain). Although this result seems reasonable, it does not reflect the true properties of bread crumb in general because the sample size was small. In more recent publications, comprehensive discussions clearly showed that both the structural and the material anisotropy are responsible for the dependence of the mechanical properties of bread crumb on the direction of measurement (Levine 1998; Whitworth and Alava 1999).

1.6.6. Cell Size

It is a common perception that cell size of bread crumb (or crumb fineness) has a significant effect on its physical texture (Kamman 1970; Pyler 1988). Gibson and Ashby (1997) pointed out that the mechanical properties of cellular materials are weakly dependent on cell size, and that cell size distribution has a greater influence. Barrett et al (1994) studied the relationship between cellular structure and mechanical properties of corn meal extrudates. They found that plateau and peak stresses are strongly related ($R^2 \geq 0.91$) to a combined effect of cell area and density. The values of these stresses decreased as the cell size increased and bulk density decreased. It was indicated by the same authors that the effects of mean cell area on the strength of the extrudate is not obvious because of the other changes that occurred in structure such as cell wall thickness and shape.

1.7. Conclusions and Objectives

The visual and physical texture of bread crumb, which are interrelated attributes, are considered by bread technologists to be key factors in evaluating the quality of white bread. Both of these attributes are influenced by bread formulation and baking processes. Digital image analysis (DIA) has proven to be a valuable tool for inspecting and measuring the visual texture of bread crumb and loaf characteristics, as well as differentiating breads made with different ingredients and processing steps. The theoretical and experimental evidence presented by Gibson and Ashby (1997) suggested that visual texture and physical texture of cellular materials are strongly related. Since bread crumb has physical properties similar to that of cellular materials, it is conceivable that the physical texture of bread crumb is also related to its visual texture. Therefore, using DIA and confirming the existence of this relationship can extend DIA's application from evaluating and measuring the visual texture of bread crumb to also estimating the physical texture.

The objectives of this thesis project were:

1. To validate the use of a DIA system to accurately measure the visual texture of bread crumb by predicting its density.

2. To determine the effects of flour type, water absorption, number of sheeting passes, and proof time on the density, crumb visual texture, and mechanical properties of bread crumb (measured in tension).
3. To evaluate the influence of crumb cellular structure (density and visual texture determined by DIA) on the mechanical properties of bread crumb (measured in tension).

2. Prediction of Bread Crumb Density by Digital Image Analysis

ABSTRACT

The cellular structure of bread crumb (i.e., crumb grain and density) is an important factor that contributes to the textural properties of fresh bread. The accuracy of a digital image analysis (DIA) system for crumb grain measurement was evaluated, based on its capability to predict bread crumb density from directly computed structural parameters. Bread was prepared from representative flour samples of two different wheat classes, Canada Western Red Spring (CWRS) and Canada Prairie Spring (CPS). Dough mixing and proofing conditions were varied to manipulate loaf volume and crumb density. Sliced bread was subjected to DIA immediately after physical density measurement. The experiments were repeated for the same bread samples after drying to three different moisture contents. Five computed crumb grain parameters were assessed, viz. crumb brightness, cell wall thickness (CWT), void fraction (VF), mean cell area (MCA), and crumb fineness (measured as number of cells/cm^2). Crumb density ranged from 0.088 to 0.252 g/cm^3 depending on proofing and mixing treatments, and was predominantly affected by the former. With increasing crumb density, bread crumb became finer and brighter in appearance, while CWT, MCA, and VF values decreased. Approximately 80% of the variation in fresh or dried crumb density could be predicted using a linear regression model comprising two variables, CWT and VF. Results indicated that DIA of directly computed crumb grain could accurately predict bread crumb density after images had been correctly classified into cells and background.

2.1. INTRODUCTION

Analysis of product appearance by digital image processing has been shown to be a very effective and reliable method for inspecting and grading food and agricultural products (Chan and Batchelor 1993; Gunasekaran and Ding 1994; Tao et al 1995; Gerrard et al 1996). In the cereals industry it has been applied in widely different ways for objective assessment of the quality of the crumb grain of bread or cake (Bertrand et al 1992; Sapirstein et al 1992; Wang and Coles 1993; Zayas 1993; Sapirstein et al 1994; Wang and Coles 1994; Rogers et al 1995; Sapirstein 1995; Zayas et al 1995, Sapirstein 1999). In addition to crumb grain appearance, physical texture is also an important quality factor for baked products. Kamman (1970) concluded that texture of bread crumb is affected by the character of the grain. He speculated that cell wall thickness, cell size, and uniformity are factors that can influence the texture of bread crumb. This view is supported by materials science which provides strong evidence relating the mechanical properties of cellular materials to their structural characteristics (Gibson and Ashby 1988). Therefore, it is conceivable that digital image analysis (DIA), which can provide an assessment of the structural appearance of the bread crumb, can also be used to estimate the physical texture (or mechanical properties) of this cellular solid.

To establish a relationship between the structural and textural properties in bread crumb, the technique for measuring crumb grain must be accurate and precise. Validating the method for measuring crumb grain is therefore a critical step that must be performed. The objective of this study, which is an extension of previous work (Sapirstein et al 1994; Sapirstein 1999), was to determine the accuracy of the DIA system by means of crumb density prediction based on computed crumb grain features. Density was chosen because it is an important physical property that contributes to the texture of foods of cereal origin possessing a porous structure (Ponte et al 1962; Attenburrow et al 1989; Barrett et al 1994; Bhatnagar and Hanna 1997), and it can be easily measured. To generate a range of densities in the bread crumb, various mixing and proofing times were used in the breadmaking procedure.

2.2. MATERIALS AND METHODS

2.2.1. Flour

Representative samples of sound wheat of two wheat classes, Canada Western Red Spring (CWRS) and Canada Prairie Spring White (CPS) were milled to straight grade flour on a pilot mill (Canadian International Grains Institute, Winnipeg). The CWRS and CPS flours contained 13.5 and 10.4% protein (14% mb), and had farinograph absorptions of 65 and 57%, respectively.

2.2.2. Baking

Bread (100 g flour basis) was baked using a straight dough, short time process (Yamada and Preston 1992) with ascorbic acid added at a level of 150 ppm. Baking absorption, which was optimized based on the handling properties of the doughs at panning, was 68 and 60%, for the CWRS and CPS flours, respectively (Tipples et al 1994). Five mixing times and three proofing times were used to obtain a wide range of crumb density. Doughs were prepared by mixing 10% past peak dough resistance on a GRL 200 mixer (Hlynka and Anderson 1955; Kilborn and Dempster 1965). This level of mixing is commonly used for the GRL 200 mixer (Kilborn and Tipples 1981b; Yamada and Preston 1992); for the CWRS and CPS flours, these dough mixing times were 8.3 and 5.5 min, respectively. Mixing times were chosen so that doughs were under- and over-mixed by 20 and 40% of the selected mixing times. The selected mixing times are hereafter refer to as optimum. After mixing, doughs were processed as described by Yamada and Preston (1992), proofed, and baked for 30 min at 204°C. The three proofing times were 35, 70 and 105 min. Loaves were allowed to cool for 25 min prior to loaf volume measurement by rapeseed displacement. Bread loaves were sealed in double bags of 2 mil (51 µm) polyethylene (Scienceware), and stored overnight at 21°C to allow for moisture equilibration. For each flour, the 15 mixing and proofing time treatments were randomly applied, and breadmaking was replicated three times over a six week period using a different batch of compressed yeast (Fleischmann's, Calgary, AB) for each replication.

2.2.3. Density Measurement

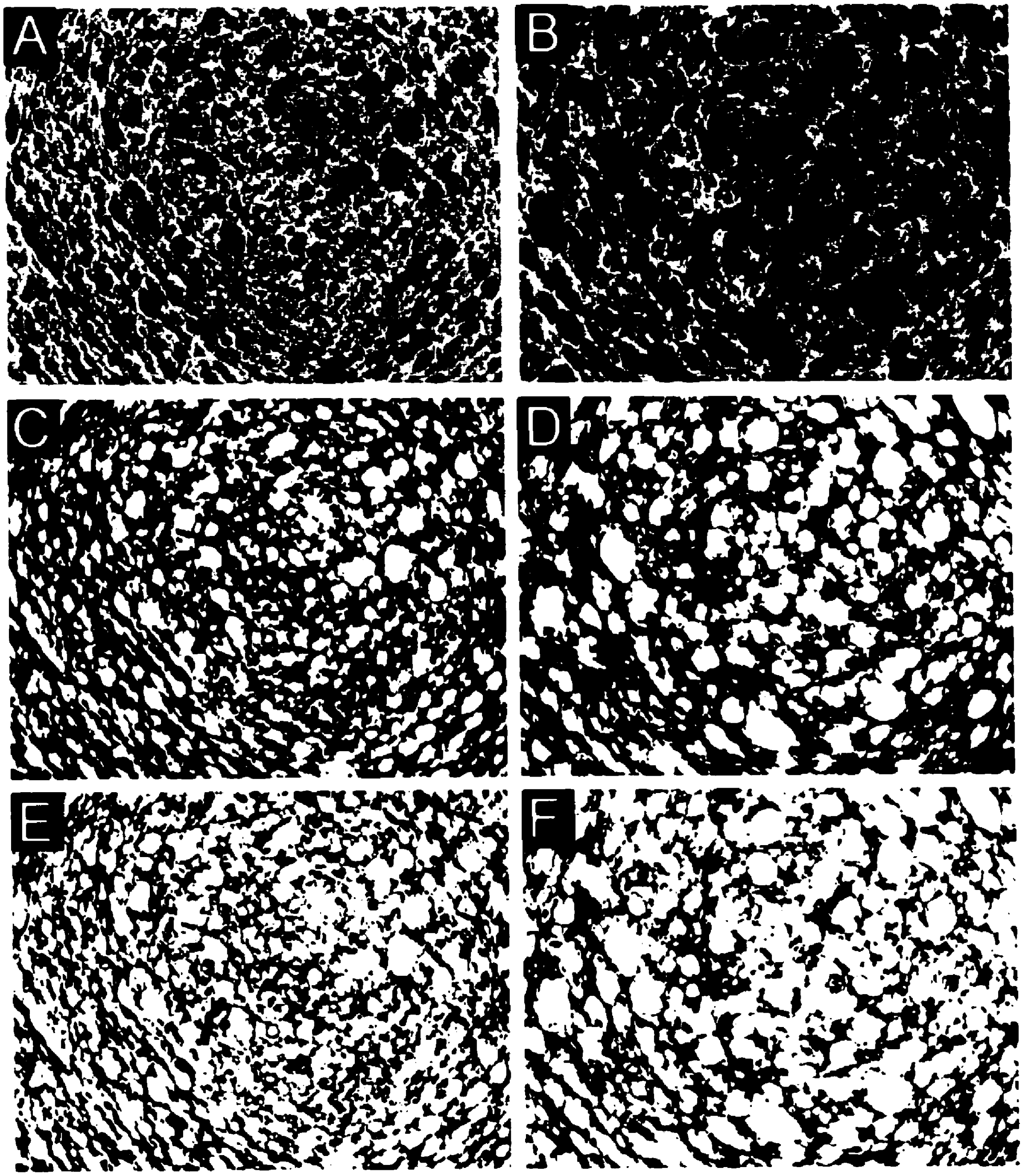
Bread loaves were sliced transversely (12 mm in thickness) using a mechanical bread slicer (Oliver model 697, Grand Rapids, MI). After slicing, the bread was re-bagged to prevent moisture loss. For each loaf, five central slices were selected. For each slice, one rectangular specimen of crumb was extracted in a central region as previously indicated (Fig. 1, Sapirstein et al 1994). The crumb specimen was carefully excised with a pathology trimming blade cutting around a 60 x 80 mm wooden template; a sawing motion was used to prevent crumb compression. The crumb specimens were kept in covered petri dishes throughout the experiment to reduce moisture loss. The volume of each specimen was determined by taking four measurements along the length (two per slice face), six along the width (three per slice face), and two measurements of thickness using digital callipers (Mitutoyo Corporation, Minato-ku, Tokyo). Just prior to acquiring digital images, crumb specimens were weighed.

2.2.4. Image Analysis

Images of bread slices were acquired using a custom built digital image analysis (DIA) system described by Sapirstein et al (1994). The monochrome CCD camera was fitted with a 50-mm *f*-1.4 fixed-focus C-mount lens (Fuji-non Inc.) using 11.5 mm of extension. The image segmentation method, based on the *K*-means algorithm, was used for classifying digitized images into cells and background (Sapirstein et al 1994). This algorithm adapts the gray level thresholding of each bread slice image depending on the overall brightness of the crumb image and the distribution of constituent pixel gray levels, both of which can be affected by the crumb structure itself. Figure 1 (A-D) illustrates the performance of this approach using representative slices of under- (Fig. 1A) and over-proofed (Fig. 1B) bread. The corresponding segmented images (Figs. 1C and 1D, respectively) appear to provide an accurate binary representation of the complex cellular structure seen in the original gray-scale images. Aspects related to the accuracy of this algorithm compared to an alternate approach to image segmentation has been recently discussed (Sapirstein 1999).

The uniformity and precision of the imaging system's gray level (GL) response was calibrated using a white opal acrylic plastic working standard (Chemacryl Plastic Ltd., Rexdale, ON) with a nominal reflectance of 81%. The lens aperture was manually adjusted until the computed mean GL corresponded to a target GL value of 160; the latter was predetermined to provide an optimal dynamic range of GL reflectance for bread crumb. GL calibration was then confirmed using three gray levels of a 12 step reflectance calibrated paper gray scale (cat. 152 2267, Kodak, Rochester, NY). The gray level calibration of the imaging system was performed prior to each imaging session. Bread

Figure 1. Original (A and B) and processed digital images showing computed cells (C and D) and cell wall structures (E and F) of typical slices of under- and over-proofed CWRS bread, respectively.


A
B
C
D
E
F

slices were examined from a working distance (lens to face of the bread slice) of 27.2 cm. The field of view (FOV) was 45 x 34 mm, with a spatial resolution of approximately 70 µm of crumb per pixel length. Digital images of both sides of the crumb specimens were acquired against a black cardboard background. Subsequently, crumb specimens were placed into covered petri dishes for the drying experiment (see below). The following crumb grain parameters were automatically determined as previously described (Sapirstein et al 1994): crumb brightness (average gray level), cell wall thickness (CWT), mean cell area (MCA), median cell area, crumb fineness (measured as the number of cells/cm^2), and void fraction (VF) which measures the proportion of the cross-sectional area of the crumb FOV comprising gas cells. The latter was previously (Sapirstein et al 1994) denoted as the cell-to-total area ratio.

2.2.5. Drying

Once all the fresh crumb specimens were imaged, they were exposed to ambient temperature and humidity conditions for three drying periods to achieve approximately 8% moisture loss each time. The drying times, determined from preliminary experiments, were 30, 40 and 60 min; increasing times were required since the bread tended to lose moisture at a slower rate after each drying treatment. Specimens were inverted at the mid-point of each drying period to minimize physical distortion of the crumb pieces and achieve uniform moisture loss. At the end of each drying period, the samples were kept in covered petri plates for 2 hr to permit moisture equilibration. The density and crumb grain of the specimens were then determined as described above for the fresh specimens.

2.2.6. Statistical Analysis

Data were analyzed by SAS Version 6.12 (SAS Institute Inc., Cary, NC). Computed crumb grain features taken from opposite sides of each specimen were averaged. Correlation analysis between crumb density and each crumb grain feature was carried out. Stepwise linear regression analysis (procedure: Stepwise) was used to determine the model for estimation of bread crumb density. Analysis of variance for various processing conditions was performed using the General Linear Models (GLM) procedure. Differences between dough mixing and proofing times were compared using Duncan's multiple range test.

2.3. RESULTS AND DISCUSSION

2.3.1. Baking Results

Loaf volumes and crumb densities as a function of dough mixing and proofing times are shown in Tables 1 and 2, respectively. The loaf volumes ranged from 570 to 1260 cm^3 and 540 to 1150 cm^3 for the CWRS and CPS bread, respectively. Crumb densities ranged from 0.09 to 0.248 g/cm^3 and from 0.088 to 0.252 g/cm^3 for the CWRS and CPS bread, respectively. These values are substantially lower than densities of bread (based on loaf volume and weight) reported by Whitworth and Alava (1999) for optimally processed bread mixed on different mixers. The lower crumb density obtained in this study likely arises as a result of selecting relatively small crumb sections located centrally in the loaf where bread density appears to be lower (Ponte et al 1962; Short and Roberts 1971).

Table 1. Loaf Volume (cm^3) as a Function of Mixing and Proof Time[a].

Proof time	Dough Mixing Time Relative to Optimum				
(min)	- 40%	- 20%	Optimum	+ 20%	+ 40%
<u>CWRS</u>					
35	596d	660ab	666a	650bc	643c
70	826c	936ab	958a	933b	926b
105	1030c	1146a	1166a	1106b	1076b
<u>CPS</u>					
35	556c	600a	610a	600a	580b
70	780d	830b	902a	836ab	806c
105	957c	1106a	1040b	1060b	1060b

[a] Statistical analysis was performed separately for each type of flour. Means with different letters across each row are significantly different ($P < 0.05$). Means in each column are significantly different ($P < 0.05$).

Table 2. Crumb Density (g/cm^3) as a Function of Dough Mixing and Proof Time[a].

Proof time	Dough Mixing Time Relative to Optimum				
(min)	- 40%	- 20%	Optimum	+ 20%	+ 40%
<u>CWRS</u>					
35	0.215a	0.190b	0.190b	0.196b	0.197b
70	0.142a	0.132b	0.131b	0.129b	0.129b
105	0.111a	0.108ab	0.101c	0.105bc	0.103c
<u>CPS</u>					
35	0.233a	0.215b	0.213b	0.209b	0.216b
70	0.145a	0.141a	0.145a	0.143a	0.142a
105	0.120a	0.107bc	0.108b	0.103c	0.103c

[a] Statistical analysis was performed separately for each type of flour. Means with different letters across each row are significantly different ($P < 0.05$). Means in each column are significantly different ($P < 0.05$).

Dough mixing and proofing times significantly ($P < 0.05$) affected loaf volumes (Table 1) and crumb densities (Table 2) of CWRS. Similar results were obtained for CPS bread, except for 70 min proof time, where dough mixing time had no significant effect on the mean density of bread crumb (Table 2, $P = 0.38$). Varying proofing time had a more pronounced effect on loaf volume and bread crumb density than variation in dough mixing time. Altering the proofing time resulted in significant differences in loaf volumes and crumb densities ($P < 0.05$) for all dough mixing times and for both types of flours.

This experiment also showed that there was a strong negative correlation between loaf volume and bread crumb density ($R = -0.96$) for both types of flours. The strength of this result is important, since by predicting or determining the density, one can accurately estimate loaf volume.

2.3.2. Effects of Dough Proofing on Crumb Grain

Both dough mixing and proofing are known to have major effects on bread quality including crumb grain (Kamman 1970). The purpose of the final proof is to allow the dough after panning to regain an extensible character and a high level of aeration to subsequently yield a loaf with a desired volume and crumb grain (Pyler 1988). As expected, different dough proofing times had a significant effect on the crumb grain of CWRS and CPS bread (Table 3).

Compared to 70 min, the 35 min proof time of CWRS dough resulted in bread crumb with a 3% brighter crumb, 10% smaller cells, 18% more cells/cm^2, 5.5% lower void fraction, and 6.4% thinner cell walls. For CPS bread crumb, the effect of under-

Table 3. Effect of Proof Time on Crumb Grain of Bread Prepared Using Optimally Mixed Dough[a].

Grain Features	Proof Time (min)		
	35	70	105
CWRS			
Average Gray Level	175.0a	168.8b	158.0c
Void fraction	0.4852c	0.5132b	0.5157a
Number of cells/cm^2	113a	96b	80c
Mean cell size (mm)	0.712c	0.795b	0.885a
Mean cell area (mm^2)	0.400c	0.500b	0.622a
Median cell area (mm^2)	0.033b	0.034b	0.041a
CWT (mm)	0.647c	0.792b	0.813a
CPS			
Average Gray Level	177.4a	166.3b	158.2c
Void fraction	0.4741c	0.4974b	0.5163a
Number of cells/cm^2	103a	77b	64c
Mean cell size (mm)	0.725c	0.888b	0.967a
Mean cell area (mm^2)	0.419c	0.623b	0.738a
Median cell area (mm^2)	0.040b	0.048a	0.051a
CWT (mm)	0.736c	0.828b	0.895a

[a] Statistical analysis was performed separately for each type of flour. Means with different letters across each row are significantly different ($P < 0.05$). CWT = cell wall thickness.

proofing on crumb grain features was larger on average. The 35 min proof time of CPS dough resulted in 6.3% brighter crumb, 18.4% smaller cell size, 34% more cells/cm^2, 4.6% lower void fraction, and 11% thinner cell walls. The effects of under-proofing on crumb grain as determined by DIA, were consistent with observations made by Kamman (1970) except for the parameter CWT; Kamman (1970) observed thicker cell walls for under-proofed bread. The results of this study indicated that upon increasing proofing time from 35 to 70 min, a greater degree of gas cell coalescence had occurred for the CPS dough compared to CWRS dough, resulting in a coarser crumb grain (Baker 1941). This result is consistent with the relative strengths of the two flours; CPS dough was weaker with ~ 34% lower dough mixing requirements.

For both types of flour, extending the proofing time to 105 min resulted in lower crumb brightness, larger cells, higher void fraction, coarser crumb (fewer cells/cm^2), and thicker cell walls, compared to samples that have been proofed for 70 min. These results were also attributed to greater degree of gas cell coalescence as proofing time was increased. The effect of increasing proof time on increasing average cell wall thickness was interesting as it appears to run counter to expectations; i.e., it is plausible that gas cell coalescence during over-extended proofing should result in larger cells on average (as was found) with thinner cell walls (which was not seen). In order to more fully explore the nature of this result, careful examination of all the digital images of bread crumb grain was performed, as well as their corresponding images segmented by the *K*-means algorithm into three partitions (Sapirstein et al 1994). Use of three partitions permits isolation of cell wall structures in the images, hence reducing the complexity of the crumb grain. A clear distinction in cell wall structure between under- and over-proofed bread was revealed which supports the computed results for CWT (Table 3). A typical result is shown in Figures 1E and 1F for isolated cell walls of under- and over-proofed bread, respectively. In accordance with Gibson and Ashby (1997), the structure of cellular solids can be classified into cell faces and cell edges (vertices where cell faces meet). For the underproofed slice (Fig. 1E), it is clear that the cell walls comprising both cell faces and edges are distributed much more evenly than that for over-proofed bread. By comparison, over-proofed bread (Fig. 1F) has noticeably thicker cell edges and a much less uniform cell wall thickness distribution than that of under-proofed bread. Accordingly, it is possible that this would contribute to larger CWT values on average for over-proofed bread compared to under-proofed counterparts. While over-proofed bread may have thinner cell faces compared to that of under-proofed bread, the perception that over-proofed bread has relatively thinner cell walls on average compared to that of under-proofed bread may not be correct.

2.3.3. Effects of Dough Mixing on Crumb Grain

Dough mixing is an important process that significantly affects the baking process, and consequently the quality of the bread. Mixing has many functions: it serves to incorporate various ingredients into a dough mass, occlude air, and develop the gluten. The effects of dough mixing time on crumb grain of CWRS and CPS bread are shown in Table 4. Our expectation was that mixing to optimum would produce bread with the finest grain and brightest crumb. Results indicated that this expectation was met only for the CWRS bread.

CWRS dough under-mixed by 40% resulted in bread crumb with very poor grain (coarser) characteristics that were significantly different from those of optimally mixed.

Table 4. Effect of Mixing on Crumb Grain of Bread Prepared with 70 min Proofing[a].

Grain Features	Dough Mixing Time Relative to Optimum				
	- 40%	- 20%	Optimum	+ 20%	+ 40%
CWRS					
Average Gray Level	163.7b	167.9a	168.8a	169.3a	169.1a
Void fraction	0.4980b	0.5014b	0.5132a	0.4986b	0.4963b
Number of cells/cm^2	82b	95a	96a	88ab	93a
Mean cell size (mm)	0.864a	0.797b	0.795b	0.824ab	0.803b
Mean cell area (mm^2)	0.595a	0.505b	0.500b	0.539ab	0.509b
Median cell area (mm^2)	0.045a	0.040ab	0.034b	0.046a	0.041ab
CWT (mm)	0.847a	0.736bc	0.692c	0751b	0.749b
CPS					
Average Gray Level	165.1c	169.0b	166.3c	170.4a	165.8c
Void fraction	0.5034a	0.5033a	0.4974a	0.5017a	0.5022a
Number of cells/cm^2	76c	89a	77c	79bc	83ab
Mean cell size (mm)	0.897a	0.806b	0.888a	0.872a	0.837b
Mean cell area (mm^2)	0.637a	0.514c	0.623a	0.600ab	0.553bc
Median cell area (mm^2)	0.0395b	0.0394b	0.0477a	0.04927a	0.0395b
CWT (mm)	0.828a	0.772b	0.828a	0.776b	0.803ab

[a] Statistical analysis was performed separately for each type of flour. Means with different letters across each row are significantly different ($P < 0.05$). CWT = cell wall thickness.

The crumb of the 40% under-mixed dough had lower crumb brightness, fewer cells/cm^2, thicker cell walls, and larger gas cells when compared to optimally mixed dough (Table 4). These objectively determined results by DIA were similar to those observed by Kamman (1970), who reported that under-mixed dough produced a crumb with thick cell walls, large cells and a dull color. The effect of under-mixing is believed to be due to the failure of the dough to exhibit good sheet-forming and gas retention properties (Tipples and Kilborn 1974).

Over-mixing dough made from CWRS flour by 40% had significant effects on both void fraction and cell wall thickness. No effects were observed for the other crumb grain features. The changes in crumb character as a result of over-mixing is presumably due to the disruption of the continuous membrane structure of gluten in an optimally mixed dough (Paredes-Lopez and Bushuk 1983). It was noteworthy that the DIA results confirmed what is generally known about under- and over-mixing doughs, i.e., under-mixing produces the larger negative effect (Tipples and Kilborn 1974). Optimally mixed dough yielded crumb with the highest degree of brightness, thinnest cell walls, smallest average area, and highest number of cells per unit area. The higher crumb brightness of optimally mixed CWRS dough can be partly attributed to the finer cellular structure of the bread, and to the shiny appearance of the thin film of gluten lining the surface of the cell (Baker 1941).

It was unclear why the CPS bread did not show any consistent trend related to dough mixing treatments, as was observed for the CWRS bread. It should be noted that the CPS flour, and CPS wheat in general, was not optimally suited for breadmaking because of its intrinsically lower protein content and protein quality, as reflected in its lower absorption and weaker dough mixing properties. Presumably, the equivocal response of this flour to varying dough mixing conditions in the short-time test baking procedure that was used, reflects this intrinsic difference in the protein component of the CPS flour compared to the CWRS counterpart.

2.3.4. Relationship Between Crumb Density and Crumb Grain

The response of computed crumb grain features in the experiments described above were examined for their relationships to crumb density (Table 5). Correlation analysis showed that crumb brightness (or average GL) was the grain characteristic most strongly related to crumb density. This was expected, since bread crumb with higher density had a finer structure, i.e., a larger number of cells per unit area with a smaller average cell size, resulting in greater reflectance into the imaging system. Sapirstein et al (1994) also observed that oxidant formula bread crumb, having a higher average GL compared to control formula bread, had a larger number of cells and smaller mean cell area. All these results are in agreement with the observation of Burhans and Clapp (1942) who found that the whiteness in bread crumb was enhanced by the presence of a large number of small cells.

The computed void fraction of crumb also had a relatively high (negative) correlation with crumb density. The void fraction values ranged from 0.438 to 0.539% for CWRS and from 0.443 to 0.534% for CPS bread crumb. On the expectation that surface density is an accurate representation of volume density (Underwood 1970), the void fraction was expected to yield the best estimate of density because *1-VF* represents the surface density (the ratio of the area of all cell wall material to the area of the field of

Table 5. Correlation Coefficients Between Crumb Grain Parameters and Crumb Density.

	Correlation Coefficients	
Grain Features	CWRS	CPS
Average GL	0.77	0.84
Void fraction	-0.71	-0.82
Number of cells/cm^2	0.70	0.73
Mean cell size (mm)	-0.68	-0.69
Mean cell area (mm^2)	-0.65	-0.68
CWT (mm)	-0.58	-0.59

view). However, this was not the case. It is evident that void fraction values have been significantly underestimated based on the difference between typical volumes of baked bread (e.g. 950 cm^3) and typical volumes of the corresponding "degassed" dough cylinders after sheeting (e.g. 200 cm^3); the void fraction in this case should be 0.79.

There are at least two possible explanations for underestimating the void fraction values. First, there are intramural cells or pockets surrounding the larger cells in cell walls (Burhans and Clapp 1942). These intramural cells could not be detected by the DIA system because of the limiting spatial resolution of the system; the smallest cells that were detected are 70 μm in diameter. Although these cells are small in size, they could be present in large numbers (Campbell et al 1991). In fact, it was previously observed (Sapirstein et al 1994) by DIA that the largest fraction of cells in bread crumb were those of smallest size. Therefore, not being able to detect cells smaller than the limiting resolution of the DIA system can result in an underestimation of the void fraction value. This limitation could be overcome by increasing the resolution of the DIA system.

The second reason for the lower void fraction values is that, on average, the gas cell size observed by DIA at the surface of the bread slice is lower than the actual cell size (see Appendix I). Assuming that gas cells are spherical in shape and slicing is random, the cell size observed at the surface is always smaller than the actual diameter of the cell because of the impossibility that all cells are precisely bisected when bread is sliced. This view was previously expressed (Sapirstein et al 1994) for a related concept in regard to the accuracy of CWT computation by the DIA system. It was observed that the two-dimensional image analysis approach used in that (and the present) study most probably overestimates the actual wall thickness of cells in uncut bread. The overestimation derives from the likelihood that only a small proportion of neighboring crumb cells, exposed on the cut surface of a slice of bread, are actually bisected. Therefore, to correct for this underestimation of the void fraction, the average area of gas cell and void fraction values must be multiplied by a factor of 1.5 (Appendix I). If void fraction values are to be used as a means of estimating the density of the slice, then they must be multiplied by a factor of 1.7. This is because, on average, cell volume based on cell size observations of the surface of the slice is 41% lower than the actual cell volume, assuming that cells are spherical in shape and sectioned randomly to give cells with a uniform size distribution. The mathematical explanation of this interpretation is presented in Appendix II.

Compared to crumb brightness and the void fraction, the remaining crumb grain parameters including number of cells/cm^2, average cell size, average cell area, cell wall thickness (CWT) and median cell size were correlated with crumb density to a lesser extent in the range $|R|$ = 0.58 to 0.73 (Table 5).

2.3.5. Model for Prediction of Bread Crumb Density

Despite the relatively high correlations between average GL and the void fraction to crumb density, these two parameters could account for no more than 50 to 70% of the variation in crumb density, depending on bread type. To establish a more robust estimate of crumb density, a combination of two or more crumb grain features was considered and evaluated. Stepwise linear regression analysis indicated that a two-variable model, comprising the VF and CWT, was the best two-variable model (yielding the highest R^2) for predicting bread crumb density of fresh bread samples. This model (VF and CWT) also provided a plausible and relatively simple representation of bread crumb structure. In addition, models with more than two variables did not yield significantly higher R^2 values for predicting crumb density. The two-variable multiple correlation coefficients for prediction of CWRS and CPS bread crumb densities by DIA of crumb grain were R = 0.90 and 0.92, respectively. The pertinent linear regression equations were:

$$\text{CWRS},\quad Density = 1.05 - (1.52 * VF) - (2.04 * CWT) \qquad (P < 0.0001) \qquad (8)$$

$$\text{CPS},\quad Density = 1.12 - (1.67 * VF) - (1.59 * CWT) \qquad (P < 0.0001), \qquad (9)$$

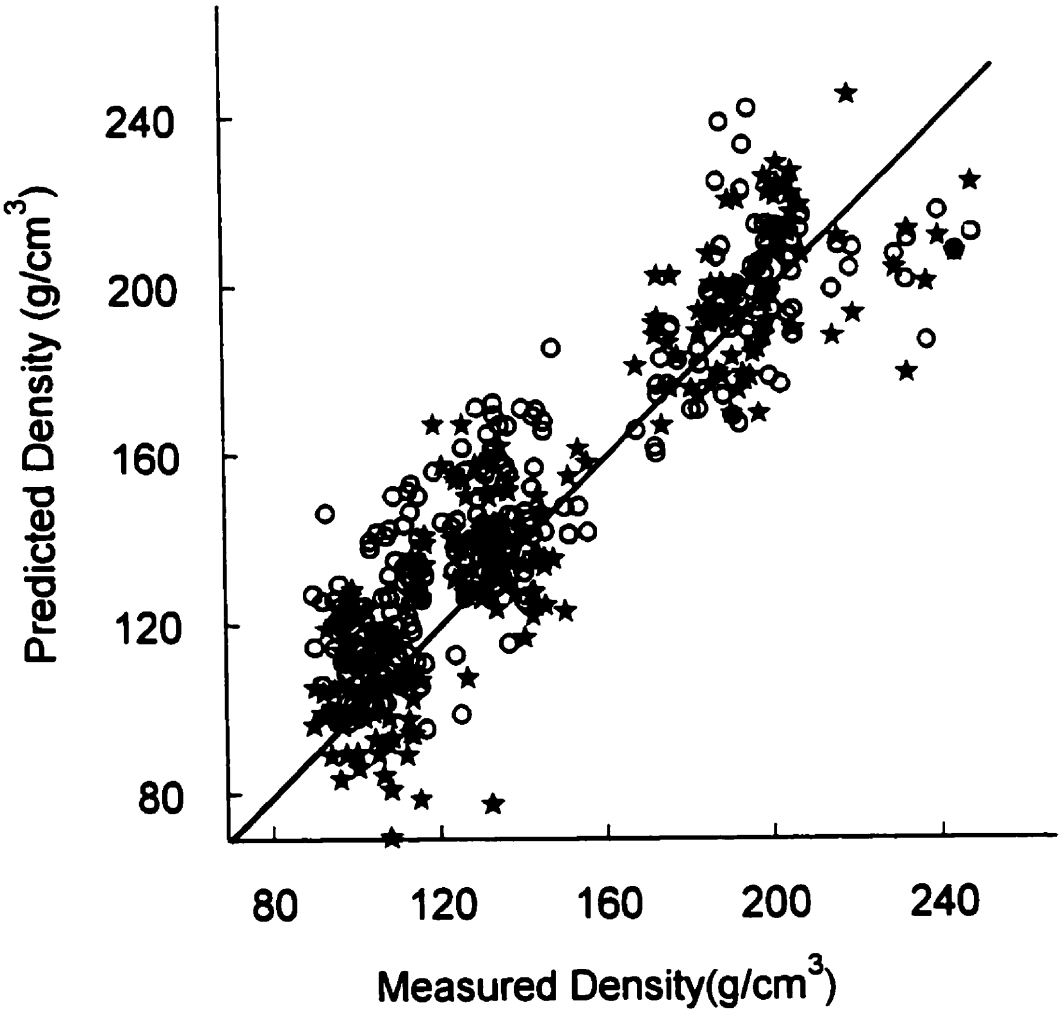
where density is expressed in g/cm^3, CWT in cm, and the coefficients have units of g/cm^3, except for the CWT coefficient which has units of g/cm^4.

In order to evaluate the predictive capacity of these equations for determining density from image analysis of bread crumb, equation 8, which had been developed from images of CWRS bread crumb, was tested on images of CPS bread crumb. A good fit with an R value of 0.90 was obtained. Similarly, using equation 9 on the CWRS bread crumb images gave R = 0.89. Therefore, based on this result and on the similarity in image parameters and coefficients in Equations 8 and 9, stepwise linear regression analysis was used to develop an equation from both flour types. Again, it indicated that the same two crumb grain parameters (VF, CWT) were the best two variable model for crumb density prediction:

$$Density = 1.08 - (1.62 * VF) - (1.59 * CWT) \qquad (P < 0.0001) \qquad (10)$$

The relationship between measured and predicted density of crumb using Equation 10 for the two types of bread is shown in Figure 2. The multiple correlation coefficient for the combined data model (R = 0.89) was comparable to that obtained for CWRS or CPS bread individually.

Figure 2. Relationship between measured and predicted density of CWRS (○) and CPS (★) bread using Equation 10 (refer to text).

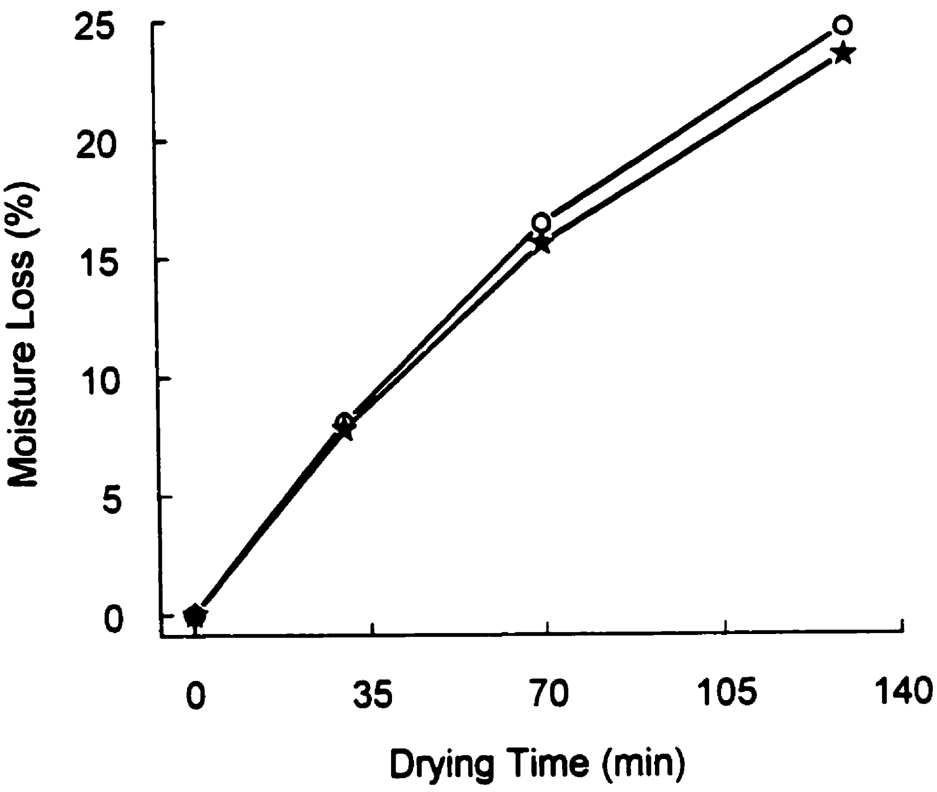

Predicted Density (g/cm^3)
240
200
160
120
80
80
120
160
200
240
Measured Density(g/cm^3)

In all three density prediction equations, the void fraction had a negative partial correlation coefficient because surface density (1-VF) is positively correlated with crumb density. The rationale for CWT as a predictor of crumb density is straightforward: it represents the quantity of material surrounding the gas cells, whose density appears to vary with processing conditions, such as dough mixing and proofing, rather than being constant. Variation in cell wall density has been reported for extruded cereal products (Donald 1994, and references therein). In addition, it is conceivable that CWT may account for the undetected intramural cells which, as mentioned above, are located in the cell walls (Burhans and Clapp 1942), and that these may vary with processing conditions. Therefore, these results clearly indicate that the DIA approach used in this study can accurately predict bread crumb density based on crumb grain structure.

2.3.6. Effect of Drying on Density and Grain of Bread Crumb

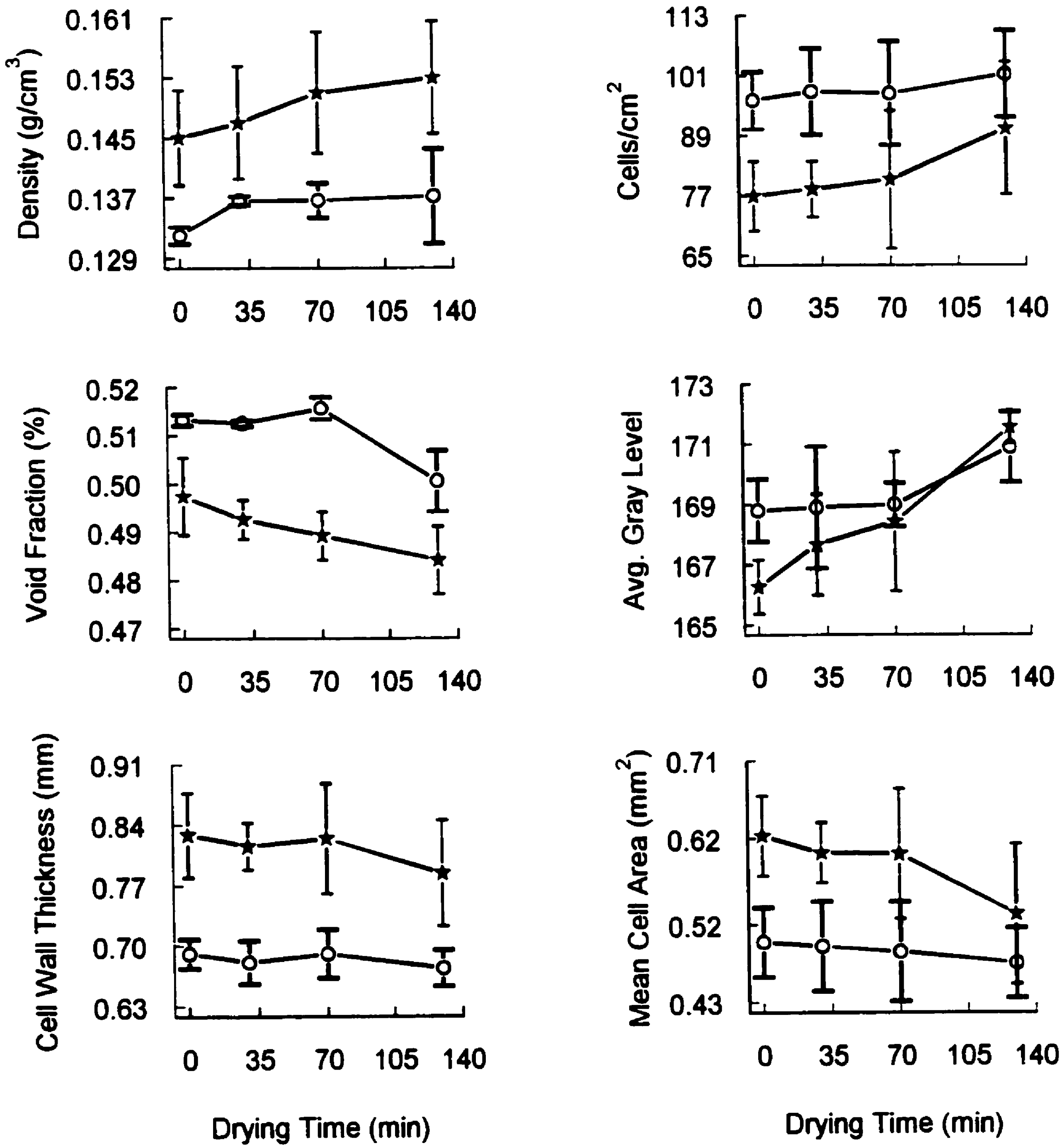
To further assess the ability of image analysis to predict bread density, Equation 10 was tested on bread samples whose densities were altered as a result of drying. The percentage moisture loss from bread crumb as a function of drying time is shown in Figure 3. After each drying period, the moisture loss was about 8%. Although the rate of moisture loss was approximately constant for both types of flours, the change in bread crumb density with increasing drying time appeared to be different. For CPS bread, the change in crumb density as a function of drying time was linear ($R = 0.97$), whereas, for CWRS bread, crumb density increased rapidly during the first 30 min (first drying period), and then leveled off (Fig. 4). The initial rapid increase in density of CWRS bread crumb was due to a larger reduction in the volume of the specimen, since the crumb was soft and deformed easily in the early stage of drying (Steller and Bailey

Figure 3. Percentage moisture loss of CWRS (○) and CPS (★) bread crumb as a function of drying time.



25
20
15
10
5
0
Moisture Loss (%)
0
35
70
105
140
Drying Time (min)

Figure 4. Effect of drying time on density, void fraction, cell wall thickness, cells/ cm^2, average gray level, and average cell area of optimally baked CWRS (○) and CPS (★) bread.


Density (g/cm^3)
0.161
0.153
0.145
0.137
0.129
0
35
70
105
140
Cells/cm^2
113
101
89
77
65
0
35
70
105
140
Void Fraction (%)
0.52
0.51
0.50
0.49
0.48
0.47
0
35
70
105
140
Avg. Gray Level
173
171
169
167
165
0
35
70
105
140
Cell Wall Thickness (mm)
0.91
0.84
0.77
0.70
0.63
0
35
70
105
140
Mean Cell Area (mm^2)
0.71
0.62
0.52
0.43
0
35
70
105
140
Drying Time (min)
Drying Time (min)

1938). For other drying times, the change in CWRS crumb specimen volume was almost equal to the change in weight, as the crumb structure became more rigid and resistant to shrinking. This effect may arise as a result of a relatively more continuous protein-starch matrix in the dough contributed by the higher protein content of the CWRS flour (Paredes-Lopez and Bushuk 1983), which caused a relatively slower decrease in volume upon further drying. The lower protein content of CPS bread that resulted in a weaker crumb structure permitted a constant shrinkage of specimens as they were subjected to drying.

Since the volume of bread crumb decreases as moisture is lost, it can be assumed that drying is accompanied by changes in crumb structure. Because the density of bread crumb made from the CWRS and CPS flours changed in different ways, the change in structure was also expected to be different. Upon drying, it was expected that cell size, VF and CWT would decrease, and that crumb brightness and the number of cells/cm^2 would increase. These expected effects were observed in the structure of the drying crumb as measured by DIA (Fig. 4).

Regression analysis for measured density and grain features of dried bread samples was also performed. The same two variables, VF and CWT, were highly correlated with crumb density. For the various drying times, the multiple correlation coefficients ranged from $R = 0.89$ to 0.91, and $R = 0.91$ to 0.92 for CWRS and CPS bread, respectively. If the regression model (Equation 10) for crumb density prediction by image analysis is robust, then changes in density that result from drying of the bread crumb should also be accurately predicted by the same model. Multiple correlation coefficients (Table 6) for the relationship between measured and predicted crumb density for dried bread crumb,

Table 6. Correlation Coefficients for Measured and Predicted Density of Dried Crumb Grain Using a Two-Variable Linear Regression Model[a].

Drying Time (min)	Flour Type CWRS	CPS
0	0.91	0.92
30	0.89	0.90
70	0.91	0.91
130	0.88	0.91

[a] Equation 10 (see text)

confirmed that DIA prediction of density by Equation 10 was sufficiently robust that the density of dried bread could also be accurately predicted on the basis of crumb structure.

2.4. CONCLUSIONS

In this study, the relationship between bread crumb density and bread crumb grain was assessed to test the validity and accuracy of a digital imaging system for direct determination of crumb grain parameters. For two widely different flour types, various dough mixing and proofing times were used to create a range of loaf volumes and corresponding bread crumb densities. Compared to dough mixing, varying proofing time had a more pronounced effect on crumb density and crumb grain parameters for both flours. Average gray level and void fraction of crumb were most strongly correlated with crumb density. A two-variable model using void fraction and cell wall thickness permitted very good prediction of the density of fresh and dried bread crumb samples. This result indicates successful validation of the imaging system to accurately measure crumb grain features. Therefore, the assessment of the relationship between structure and textural properties in bread crumb by DIA would seem feasible.

3. Effects of Dough Ingredients and Processing Conditions on Density, Crumb Grain and Mechanical Properties of Bread Crumb

ABSTRACT

The objective of this study was to determine the effects of ingredients and processing conditions on the density, grain features, and mechanical properties of bread crumb. Bread loaves were prepared by a short time breadmaking process using four spring wheat flours of varying strength. For two of the flours (CWRS and CWES), the effects of varying water absorption (WA) between 60 and 65% were also assessed. Processing treatments included variation in proof time (PT) and in the number sheeting passes (SP). After crumb density measurement, crumb grain features were measured by digital image analysis (DIA). Tensile tests were performed on bone shaped specimens cut from the same bread slices used for DIA. Tensile parameters included Young's modulus, fracture stress, fracture strain, and fracture energy. Structural and mechanical properties were significantly affected by flour type, with CWES bread having the lowest density, more uniform grain, and greater mechanical strength. WA only affected the mechanical strength and the brightness of bread crumb, which generally decreased with increasing WA. Number of SP only had a small influence on crumb structure. With increasing PT, the effect of the two extra SP has decreased for crumb density and void fraction, suggesting that the extra SP did not alter the gas retention properties of the dough. Increasing PT decreased crumb density, produced a coarser grain and reduced the overall mechanical strength. The decrease in mechanical strength was not observed for all PT despite the changes in density and grain features. This indicated that the mechanical properties of the cell walls were been enhanced with increasing PT.

3.1. INTRODUCTION

The assessment of the visual texture (or crumb grain) and physical texture (or mechanical properties) of bread crumb is important for both bakers and researchers as these two quality attributes determine consumers' acceptability of the products (Pyler 1988). The traditional method for evaluating the visual texture of bread crumb relies on human vision, and is qualitative and subjective in nature. In the past few years, bread technologists have successfully adapted digital image analysis for quantitative and objective measurement of crumb grain (Sapirstein et al 1994; Rogers et al 1995). The physical texture of bread crumb has been extensively studied and related to quality attributes (Elton 1969; Brady and Mayer 1985). Although compression testing of bread crumb has been the method of choice for many years because of its simplicity, recently cereal scientists have become interested in using tensile testing (Nussinovitch et al 1990; Chen et al 1994; Scanlon et al 1997). Despite some limitations of the latter (gripping problems and sample dimensions requirements), it has been chosen since it provides parameters that can be easily interpreted (Nussinovitch et al 1990). In addition, tensile testing offers additional information such as energy to fracture which is a measure of crumb coherence (Scanlon et al 1997) as well as crumb extensibility. Furthermore, this method was shown to be highly sensitive for detecting defects in food products (Luyten et al 1992), such as structural defects, which are of particular importance in determining the quality of bread crumb.

The visual and the physical texture of bread crumb are known to be influenced by both the ingredients of the dough and the processing conditions employed in making the bread. Examples of bread ingredients would include flour strength or protein content

(Ponte et al 1962; Pyler 1988; Sapirstein et al 1994; Scanlon et al 1997), baking absorption (Larsen and Greenwood 1991; Piazza and Masi 1995), and shortening (Lasztity 1980). On the other hand, 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) were also reported to influence the visual and physical texture of bread crumb. The objective of this study was to determine the effects of flour type, water absorption, sheeting, and proof time on the density, crumb grain features (measured by DIA), and the mechanical properties of bread crumb (determined by tensile testing).

3.2. MATERIALS AND METHODS

3.2.1. Flour

Flour of three wheat classes and a flour blend (all grown in 1998) were used in this study. These flour samples, which represent a wide range of inherent strength, included Canada Western Extra Strong (CWES), Canada Western Red Spring (CWRS) and Canada Prairie Spring (CPS), and a 50% blend of CWES and CPS wheats. Wheat was milled to straight grade flour on a pilot mill at the Canadian International Grains Institute (CIGI), Winnipeg.

3.2.2. Chemical Analysis of Flour Samples

Moisture, ash, and protein (5.7 x N) contents of wheat flour samples were determined in duplicate according to AACC approved methods 44-15A, 08-01, and 46-13 (AACC 1983), respectively. Starch damage of flour samples, expressed in Farrand units, was determined using a modified AACC approved method 76-30A (Farrand 1964). Falling Number (in seconds) and amylograph properties of the flour samples were determined using AACC approved methods 56-81B and 22-10, respectively (AACC 1983).

3.2.3. Technological Characterization of Flour Samples

3.2.3.1. Farinograph Test

Flour samples (50 g, 14% moisture basis) were mixed with water in a temperature controlled Brabender farinograph (FA-MV 100, South Hackensack, NJ) bowl (30°C) at 63 rpm. The farinograph water absorption (FWA) corresponded to the amount of water added to the flour so that peak dough consistency of the curve was centered at the 500 BU line according to AACC approved method 54-21 (AACC 1983). Other farinograph parameters derived from the curve included dough development time (DDT, min) and mixing tolerance index (MTI, BU). The DDT is the time required to reach the peak dough consistency. On the other hand, the MTI, which is the difference in dough consistency between the peak and the peak + 5 min, is a measure of the ability of the dough to withstand over-mixing (a dough with a small MTI value can tolerate over-mixing, while a dough with a large MTI value is very susceptible to breakdown upon over-mixing).

3.2.3.2. Extensigraph Test

The extensigraph provides information about the resistance of dough to stretching and extensibility by measuring the force required to pull a hook through a rod-shaped piece of dough. Extensigraph parameters of flour samples were determined according to AACC approved method 54-10 (AACC 1983). Doughs were mixed in a large Brabender farinograph bowl using 300 g flour, 2% salt, and the appropriate amount of distilled water (to obtain a peak resistance centered at 500 BU line). The reported measurements included maximum resistance (RMAX, the height of the curve at the peak expressed in BU), extensibility (EXT, the length of the curve between the start of stretching and the breaking of the dough expressed in cm), area under the curve (in cm^2 which is equivalent to 65.2 BU . cm), and the ratio of maximum resistance to extensibility (RMAX/EXT, BU cm^{-1}). All these measurements were determined in duplicate from the extensigraph curves, which were obtained 135 min after mixing (Holas and Tipples 1978).

3.2.3.3. Mixograph Test

Mixograph data were determined using a 2 g computerized direct drive mixograph (National Manufacturing, Lincoln, NE). All flour samples were mixed in duplicate at 88 rpm and at 25°C using 2 g of flour (14% m.b.) and constant water absorption (60%). In addition, CWES and CWRS flours were tested at 63 and 65% water absorption, respectively, which corresponded to their optimal baking absorption. 'Mixsmart' software (Version 3.4, filter value of 160) was used to analyze mixograph data. Mixograph development time (MDT, min) was determined from the top-line mixogram curve since the peak was better defined than that of the mid-line curve, especially for CWES flour. Based on the MDT, the other parameters were measured by the software from the mid-line curve of the mixogram. These parameters included peak dough resistance (PDR, the height of mixing curve expressed in % of full-scale torque), bandwidth at peak dough resistance (BWPR, % torque), resistance breakdown (RBD, change in dough resistance two min after PDR), bandwidth breakdown (BWBD, change in bandwidth two min after PDR), and work input to PDR (WIP, % Tq.min).

3.2.4. Baking

Bread of each type of flour (CWES, CWRS, CPS, and 50% blend of CWES and CPS) was baked using a straight dough short time process. Bread loaves (225 g flour, 14% m.b.) were prepared using the GRL-Chorleywood baking procedure (Kilborn and Tipples 1981b). Shortening and salt levels in the bread formulation were increased to 3% and 1.8%, respectively, for optimizing the baking procedure (on the basis of loaf volume and crumb grain fineness as measured by DIA). To investigate the effect of water absorption (WA) on bread characteristics, two levels of WA were used: fixed (60%) and optimum WA. The optimum WA, which was determined on the basis of the farinograph absorption and the handling properties of the dough at panning stage, was 65, 63, 61 and 59 % for CWRS, CWES, blend and CPS flours, respectively (Tipples et al 1994). Because the optimum WA of the blend and CPS flours were close to 60%, both flour samples were baked at 60% WA only. This level of WA was considered optimum for these two flours. Dough development was achieved by mixing to 10% past the peak dough resistance on a GRL 200 mixer (Kilborn and Tipples 1981b). After an intermediate proof for 20 min, dough sheeting (3 sheeting passes) was carried out as described by Kilborn and Tipples (1981a). In addition, doughs were processed with two additional sheeting passes (SP) through the smallest roll gap of 1/8" (5 SP in total). The number of SP was varied to create differences in the cellular structure of bread crumb. The molded dough pieces were placed in aluminized steel pans with internal dimensions: bottom, 166 x 72 mm; top, 187 x 90 mm; and height, 55 mm. Four final proofing times were used to create a wide range of density and structure in the bread crumb. These four proofing times (35, 45, 60 and 85 min) were selected so that the densities of bread crumb were approximately evenly distributed. The panned and proofed dough was baked for 27 min at 223°C. After baking, loaves were allowed to cool for 30 min prior to loaf volume measurements by the rapeseed displacement method. The bread loaves were immediately weighed and double bagged in plastic bags (Polyethylene bags 1.7 mil (43 μm) wall thickness, Topsyn Flexible Packaging Ltd. Winnipeg, MB) and stored at 21°C overnight to allow for moisture equilibration. Loaves of a given proof time (including all other treatments: flour type, water absorption, and sheeting) were prepared randomly in one bake day. Three replicate bakes were performed for all the treatments. In this experiment, the number of baked loaves was 144, yielding 720 bread samples in total (5 slices per loaf).

3.2.5. Density Measurement

The bread loaves were sliced transversely as indicated above (2.2.3), yielding 11 slices per loaf. From each loaf, five central slices were selected and manually cut by a slow sawing motion (to prevent crumb compression and structural damage) around a template (40 mm by 110 mm) with a pathology trimming blade. Each set of five cut bread samples from a given loaf were then kept side by side in an air-tight plastic container (946 ml, Rubbermaid Inc. Wooster, OH) throughout the experiment to prevent moisture loss. Three slices from each loaf-end were trimmed so that they fully covered the surface area of the container, and three each were placed under and above the five bread samples. This was done to eliminate the head space in the container and reduce the moisture loss that takes place while the container was opened to remove or return specimens. Density measurements of individual bread samples were performed as described in 2.2.3.

3.2.6. Image Analysis

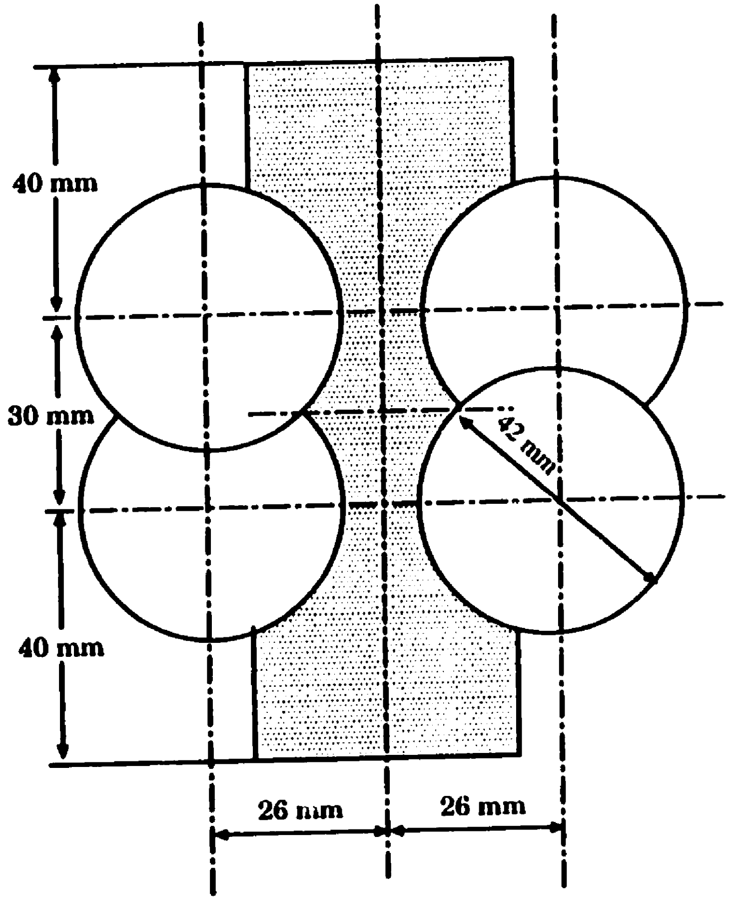
Image acquisition and analysis was performed after measuring bread crumb density as described in 2.2.4. The field of view was slightly reduced by lowering the camera to a distance of 26.2 cm from the surface of bread samples to ensure that bread crumb fully covered the field of view (42 x 32 mm). The crumb grain features that were determined by 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/cm^2, and small-to-large cell count (SLCC, a ratio of cells with areas above and below 4 mm^2). The SLCC is a measure of crumb uniformity within a slice, with higher values indicating greater uniformity of crumb grain.

3.2.7. Tensile Testing

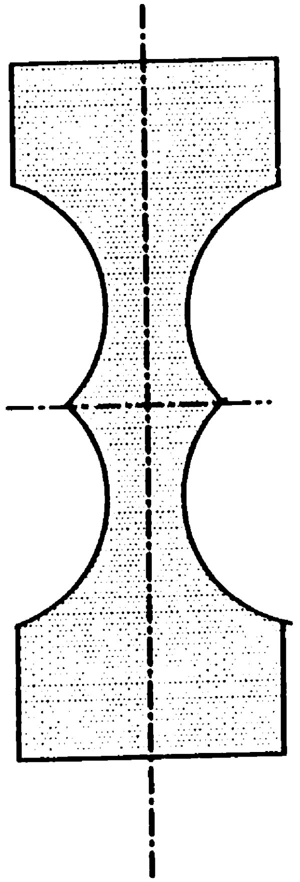
The same bread samples that were used for imaging and density measurement were cut into bone shaped-specimens for tensile testing. The bread specimens were prepared using a sharp stainless steel hole circular cutter (42 mm in diameter) mounted on a drill (Delta International Machinery Corp. Guelph, ON) to cut four circles: two from each side of the bread specimen width (see Fig. 5 A & B). The remaining bread material between the two half-circle cuts was then trimmed manually with a high speed drill (Dremel, Racine, WI) to give the bone shaped specimen shown in Fig. 5C. The preparation time for a bread specimen was approximately 2 min. The gauge length and width of the specimens were 30 and 10 mm, respectively, with a cross sectional area of 1.25×10^{-4} m^2 (10 x 12.5 mm). Bread samples were allowed to rest for four hours in an air-tight container to permit moisture equilibration before performing the tensile tests. The bread specimens were then attached by a diamond shaped four-pin fixture to a TA.XT2i

Figure 5. Schematic representation of the preparation of the bread specimen used in tensile testing: (A and B) cutting the two half-circles from each side of the bread specimen with hole cutter, and (C) a bone shaped specimen obtained after the remaining material between the two cuts was trimmed

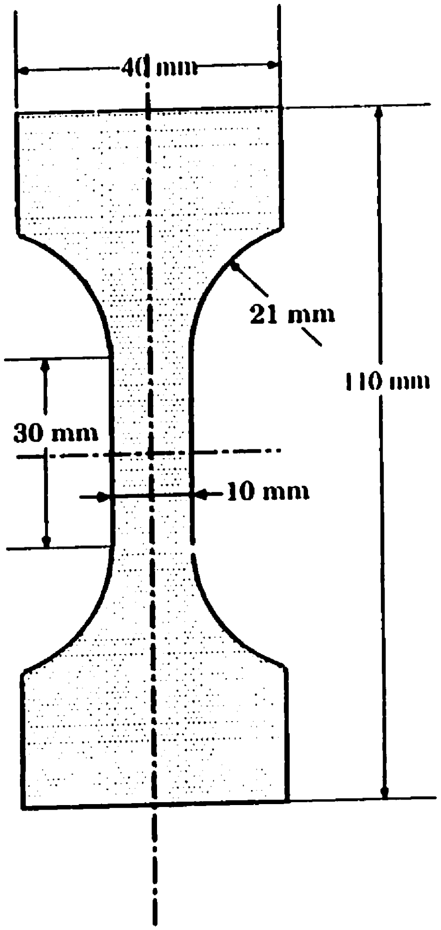
A



B



C



Texture Analyzer (Texture Technology Corp. Scarsdale, NY) equipped with a 5 kgf load cell. The specimens were subjected to tensile loading until failure at a crosshead speed of 0.2 mm s^{-1}, which corresponds to a strain rate of 6.66 • 10^{-3} s^{-1}. The mechanical properties of bread crumb 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/gauge 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 hours (Fontanet et al 1997). Room temperature was monitored during the experiment, and its effect on the mechanical properties was evaluated.

3.2.8. Statistical Analysis

Data were analyzed by SAS Version 6.12 (SAS Institute Inc., Cary, NC). All results including density, crumb grain features, and mechanical properties were averaged on loaf basis to reduce the effects of inherent variation in bread crumb within each loaf as well as the variation in sampling from bread slices. Analysis of variance for various ingredients and processing conditions was performed using the General Linear Models (GLM procedure). Significant differences among the main treatments and interactions effects were established using $\alpha = 0.05$ with type III sum of squares (SS) in an analysis which included the effects of replication. The type III SS was used since the hypotheses to be tested are invariant to the ordering of treatments or the presence of covariates in the model. Effects of the variation in room temperature and moisture content of bread crumb on the mechanical properties were assessed by including these two factors in the GLM model as covariates.

3.3. RESULTS AND DISCUSSION

The results of this study are presented and discussed in two sections. Section 3.3.1 deals with technological quality characteristics of flour samples. In section 3.3.2, the effects of dough ingredients and processing conditions on loaf volume, density, structural properties (determined by DIA) and mechanical properties (determined by tensile testing) are presented and discussed.

3.3.1. Technological Quality Characteristics of Flour Samples

3.3.1.1. Chemical Analysis

Table 7 shows the analytical results for the flour samples used in this study. The protein contents of flour samples ranged from 10.0 to 12.9%. The ash content ranged from 0.46 to 0.57%. Amylograph and Falling Number results indicated that all flours samples used in this experiment were sound. Starch damage of flour samples ranged from 27 to 55 Farrand units (FU), with the highest and lowest values for the CWES and CPS flour, respectively. As expected, the starch damage was lower for the softer wheat flour, but the starch damage values were about 10-15 FU higher than those reported in the Wheat, Rye & Triticale Subcommittee Report for similar flour samples (Anonymous 1997). These high values of starch damage are likely to be due to the greater degree of mechanical damage of starch during flour milling since the high ash content, 10-25% higher than normal, is an indication that the flours were milled to a higher extraction rate (Dexter et al 1994).

Table 7. Means and Standard Deviations of Analytical, Farinograph[a], and Extensigraph Results of Flour Samples.

Flour	CWRS	CWES	CPS	Blend[b]
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
Starch Damage (FU)	40 ±1	55 ±1	27 ±1	41
Amylograph (BU)	965 ±7	428 ±11	755 ±7	625 ±7
Falling Number (sec)	739 ±33	447 ±10	526 ±18	467 ±5
Farinograph				
FWA (%)	64.0	62.2	57.9	60.4
DDT (min)	6.0	11.8	4.5	7.0
ST (min)	12.0	31.0	6.5	13.5
MTI (BU)	30	15	68	40
Extensigraph				
WA (%)	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
A (cm^2)	130 ±1	172 ±0	116 ±2	154 ±6
RMAX/EXT ($BU.cm^{-1}$)	27.9	62.0	26.9	40.8

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[a] The reported results are means of two replicates except those of farinograph where only one replication was performed.

[b] Values for moisture, protein, ash and starch damage of blend flour are means of CWES and CPS flours. FAW, farinograph water absorption; DDT, dough development time; ST, stability time; MTI, mixing tolerance index; WA, water absorption; RMAX, maximum resistance; EXT, extensibility; A, area under the curve.

3.3.1.2. Rheological Properties

It has long been established that dough rheological properties are related to flour strength and breadmaking performance. The rheological properties of flour samples measured by farinograph, extensigraph and mixograph are summarized in Tables 7 and 8. Farinograph water absorption (FWA) of the flour samples used in this study showed a wide range: 57.9, 60.4, 62.2, and 64.0% for CPS, Blend (50% CWES and CPS), CWES, and CWRS flours, respectively. The FWA of flour samples generally appeared to be affected by starch damage and protein content as was indicated by Bushuk and Hlynka (1964), except the FWA of CWES flour. The latter had a comparable protein content to CWRS flour but its FWA was lower than that of CWRS flour despite its higher starch damage. The finer particle size (Williams 1993) and possibly the higher pentosan content (Bushuk 1966) of CWRS flour as compared to CWES flour may account for the higher water absorption observed for the CWRS flour. These results suggested that although FWA is known to be dependent on protein content and quality, it does not necessarily reflect flour strength since the results of this study showed that CWES flour had lower FWA than CWRS, despite its higher inherent strength (discussed below).

Dough development time (DDT, min) of flour samples determined by either farinograph or mixograph (see Tables 7 & 8) was strongly related to mixing time on the GRL 200 mixer ($R^2 > 0.95$). In general, the dough development times of the flour samples, which are positively related to flour strength (Tipples et al 1982), increased in this order: CPS, CWRS, Blend, and CWES. The ratio of RMAX/EXT was considered to be an indicator of the dough mixing requirement and breadmaking quality, with doughs

Table 8. Means and Standard Deviations (*n* = 2) of Mixing Quality Characteristics as a Function of Flour Type and Water Absorption.

Flour	CWRS		CWES		CPS	Blend
WA(%)	60	65	60	63	60	60
GRL 200 mixer						
MT (min)	4.7 ±0.4	5.1 ±0.2	7.2 ±0.5	7.7 ±0.8	4.0 ±0.1	5.5 ±0.3
WI (Whr kg^{-1})	14.8 ±1.4	13.7 ±2.7	22.3 ±1.8	22.6 ±2.0	10.0 ±0.8	15.6 ±1.1
Mixograph						
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 (% Tq.min)	85 ±2	88 ±4	145 ±0	144 ±12	64 ±3	105 ±1

WA, water absorption; MT, mixing time; WI, work input (GRL 200 mixer); MDT, mixograph development time; PDR, peak dough resistance; BWPR, bandwidth at peak dough resistance; BWBD, bandwidth breakdown; RBD, resistance breakdown; WIP, work input to PDR (mixograph).

having high RMAX/EXT ratios being considered stronger flours (Uthayakumaran et al 1999). Results of this study also showed that the RMAX/EXT ratio was closely related to mixing time on the GRL 200 mixer ($R^2 = 0.92$) and therefore it could be used as an indication of flour strength.

Peak dough resistance (PDR), which is the height of the mixograph curve at the peak, is a measure of dough resistance to extension (Spies 1990). PDR was found to be highly correlated to protein quality and breadmaking performance (Khatkar et al 1996). The results of this study showed that PDR and RMAX which were highly correlated ($R^2 = 0.94$), decreased in the same order of flour as was observed for DDT.

The area under the extensigraph curve (A), which is a measure of the energy needed to stretch the dough piece to its breaking point, is also a measure of dough strength (Tipples et al 1982; Preston and Hoseney 1991). Mixograph work input (WIP) and A were highly correlated with the work input on the GRL 200 mixer (R^2 values were 0.98 and 0.92 respectively), and they both decreased in the same order of flour samples as was observed for DDT and PDR.

Finney and Shogren (1972) indicated that MTI does not necessarily reflect flour strength since wheat flour with very low protein content had greater mixing tolerance than flour with medium or high protein content. However, for medium and strong wheat flours, the MTI was shown to be significantly correlated with baking performance (Kunerth and D'Appolonia 1987). The MTI of the flour samples used in this study ranged from 15 to 68. The MTI values, which were generally inversely proportional to the DDT values, decreased in the following order of flour samples: CPS, CWRS, Blend, and CWES. This indicated that stronger flour had more tolerance to over-mixing and to variation in processing conditions (Tipples et al 1982). For the various flour samples used in this experiment, resistance breakdown (RBD) which, is a measure of the dough's tolerance to over-mixing, also showed (with the exception of blend) a similar trend to MTI.

Increasing water absorption from 60% to optimum level (63 and 65% for CWES and CWRS, respectively) increased MDT, and decreased PDR and BWPR (Table 8). These results are consistent with those reported by Larsen and Greenwood (1991). The changes in the other mixograph parameters as a function of water absorption were smaller and inconsistent for CWRS and CWES flours. In general, mixograph parameters showed that CWES flour was less sensitive to the increase in water absorption (from 60% to optimum) than was CWRS flour. This could in part be due to the fact that less water was added to the CWES flour. In addition, the higher inherent strength of CWES flour may be responsible for the relatively small variation in its rheological properties when more water was added to the dough.

The results of the rheological tests including DDT, RMAX/EXT, PDR, WIP, A and RBD clearly reflected the wide range of the inherent strength of the four flour samples. It can be concluded from these results that CWES flour was very strong, CWRS and blend (CWES and CPS, 50%) flours were moderately strong, and CPS flour was relatively weak.

3.3.2. Effects of Dough Ingredients and Processing Conditions

The experimental design of this study, which was an incomplete factorial form, is shown in Table 9. Results of baking, density measurements, grain features, and mechanical properties of bread crumb as a function of the individual experimental treatments are shown in Tables 1-15, Appendix III. The data were subdivided into three categories, each representing a complete factorial set of treatments to simplify the statistical analysis. The effects of experimental treatments on bread crumb characteristics was examined on the basis of fixed water absorption (WA), optimum WA, and optimum versus fixed WA. Therefore, the analysis of variance was performed in three stages to determine the significant differences among various levels of the following treatments and their interactions (Table 9):

1. Four flour samples prepared at fixed WA (60%), two sheeting treatments, and four proof times (statistical results are listed in Tables 16-28, Appendix IV);
2. Four flour samples prepared at optimum WA, two sheeting treatments, and four proof times (statistical results are listed in Tables 29-41, Appendix V);
3. Two flour samples (CWRS and CWES), two WA (fixed and optimum), two sheeting treatments, and four proof times (statistical results are listed in Tables 42-54, Appendix VI).

Replicate effects were seen on the physical properties of bread crumb, and these likely represent slight variations in position when selecting crumb specimens from a bread slice (Appendices IV-VI). The effects of the variation in room temperature (less than 7°C) during tensile testing and variability in moisture content (less than 1%) of bread crumb (among replicates of the same treatment) on the Young's modulus, fracture stress, fracture strain, and energy to fracture of bread crumb were also assessed by incorporating these two factors in the GLM model as covariates. The statistical results (shown in Tables 25-28, Appendix IV; 38-41, Appendix V; 51-54 Appendix VI) indicated that variation in moisture content or room temperature of the bread crumb did not have a significant effect on any mechanical properties.

Table 9. Experimental Design and Statistical Analysis.

Treatments	Levels			
Flours	CWRS	CWES	CPS	Blend
WA (%)	60	65 (CWRS)	63 (CWES)	
SP	3	5		
PT (min)	35	45	60	85
Analysis I: Fixed Water Absorption				
Flours	CWRS	CWES	CPS	Blend
WA (%)	60	60	60	60
SP	3	5		
PT (min)	35	45	60	85
Analysis II: Optimum Water Absorption				
Flours	CWRS	CWES	CPS	Blend
WA (%)	65	63	60	60
SP	3	5		
PT (min)	35	45	60	85
Analysis III: Fixed versus Optimum Water Absorption				
Flours	CWRS	CWRS	CWES	CWES
WA (%)	60	65	60	63
SP	3	5		
PT (min)	35	45	60	85

WA, water absorption; SP, number of sheeting passes; PT, proof time.

3.3.2.1. Fixed Water Absorption

3.3.2.1.1. Flour Strength

Table 10 shows the effects of flour strength on loaf volume, density, grain features, and mechanical properties of bread crumb prepared at 60% water absorption. The flour type had a significant effect on loaf volume which decreased in the same order as flour strength determined by the rheological tests, except for the blend. The latter had lower loaf volume than that of CWRS despite its relatively higher flour strength. These results suggested that the carrying capacity of CWES flour was manifest more in the rheological properties of the dough than in its baking performance. The crumb density was also significantly affected by flour type. It showed the same trend observed for loaf volume, but the crumb density of CWRS bread was not significantly different from that of the blend (Table 10). Unlike crumb density and loaf volume, the visual texture of bread crumb samples which was determined by DIA did not show a large variation across bread samples made from different flours. Cell wall thickness (CWT), number of cells/cm^2, and mean cell area (MCA) were not significantly affected by bread type. However, void fraction, ratio of small-to-large cells count (SLCC), and crumb brightness were significantly influenced by the flour type or flour strength (Tables 19-24, Appendix IV). The void fraction, which is strongly correlated with loaf volume and crumb density (2.3.4), had the largest value in CWES bread. The SLCC showed that CWES bread had the most uniform crumb grain despite its larger loaf volume and void fraction (Table 10). This suggested that the degree of gas-cell coalescence is low in CWES dough, and that CWES flour has a superior breadmaking performance. Since CWES flour produced strong dough, the low rate of gas cell coalescence in this dough is due to its higher rate of

Table 10. Effects of Flour Type on the Characteristics of Bread Crumb Prepared at Fixed Water Absorption[a].

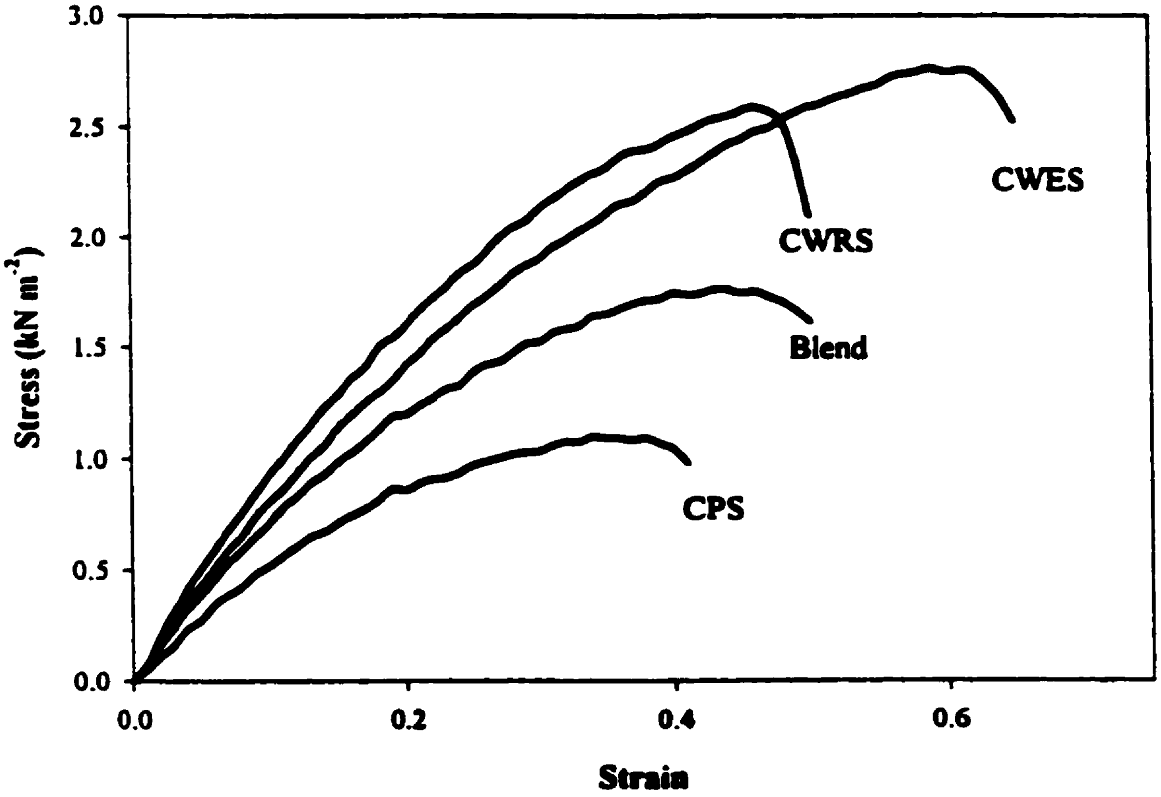
Flour Type	CWES	CWRS	Blend	CPS
Loaf Volume (cm^3)	2240a	2199b	2139c	1967d
Density (g cm^{-3})	0.128c	0.131b	0.132b	0.135a
Crumb Grain				
No. Cells/cm^2	87.7	88.6	88.0	84.5
MCA (mm^2)	0.566	0.555	0.560	0.581
CWT (mm)	0.782	0.785	0.779	0.808
SLCC	40.2a	37.8a	34.1b	33.1b
Crumb Brightness	180.9b	184.5a	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. Means with different letters across each row are significantly different (p <0.05). MCA, mean cell area; CWT, cell wall thickness; SLCC, small-to-large cell count.

strain hardening when subjected to extension such as occurs during proofing (Dobraszczyk and Roberts 1994). This strain hardening phenomenon, which is the increase in the slope of the dough stress-strain curve with increasing extension, is known to limit the growth of the large gas cells permitting the small cells to expand, and thus, leading to a uniform and fine crumb grain (van Vliet et al 1992). The higher the rate of strain hardening, the greater the stability of the dough's cell walls against rupture and the more uniform the bread crumb will be. Dobraszczyk and Roberts (1994) indicated that the mechanism of strain hardening involved molecular orientation and alignment of polymer chains under large deformation, causing greater resistance to further deformation. In contrast to CWES, CPS bread, which was produced from a relatively weak flour, had poor crumb grain characteristics: coarser grain and lower uniformity (small value of SLCC). These results suggested that a higher degree of coalescence had occurred in CPS dough during baking, since weak dough is generally known to exhibit a low rate of strain hardening and a poor gas cell stability (Dobraszczyk and Roberts 1994). Therefore, CPS flour is not optimally suited for breadmaking. The overall crumb grain features of CWRS and blend bread were generally very similar and were considered satisfactory.

Typical stress-strain curves of the four types of bread crumb tested in tension are shown in Fig. 6. The mechanical properties or physical texture of bread crumb, which were determined from the stress-strain curve, included Young's modulus, fracture stress, fracture energy (or fracture resistance, area under stress-strain curve to failure), and fracture strain. All of these mechanical properties were significantly affected by flour type (Tables 25-28, Appendix IV). The fracture strain and energy of bread crumb

Figure 6. Typical stress-strain curves of CWES, CWRS, CPS and blend (50% CWES and CPS) bread crumb prepared at fixed water absorption.


3.0
2.5
2.0
1.5
1.0
0.5
0.0
Stress (kN m^{-2})
0.0
0.2
0.4
0.6
Strain
CWES
CWRS
Blend
CPS

decreased in the following order of flour samples: CWES, CWRS, blend and CPS (Table 10), indicating that flours with higher inherent strength produced bread crumb that has a greater fracture resistance and greater extensibility. The extensibility of dough as measured by the extensigraph did not reflect the extensibility of bread crumb as determined by fracture strain (Tables 7 and 10). From this result it appears that extensibility in dough and bread are governed by different factors. In the dough, extensibility is enhanced by the amount of water added and the gliadin proteins (Spies 1990). However, in proofed dough, extensibility is expected to be mainly a factor of the quantity of HMW glutenin since these oriented and aligned long molecules can slide along each other without affecting the coherence of the dough (Bloksma 1990). Because the large extensibility of the proofed dough is attributed to protein structure (Bloksma 1990; Dobraszczyk and Roberts 1994), and this is expected to carry through the baking process, the greater extensibility of the CWES bread crumb is believed to be due to the higher quantity of HMW glutenin. Although the Young's modulus was significantly affected by flour type, it did not show any clear trend with respect to flour strength. For instance, the average Young's modulus of CWES bread was not significantly different from that of CPS bread (Table 10), despite the large difference in their flour strength. The Young's modulus of these two types of bread being almost equal does not imply that the stiffness of the cell walls are unaffected by flour strength. In fact, these results imply that the stiffness of the cell walls of the CWES bread is higher than that of CPS. This conclusion was reached on the basis that the Young's modulus of cellular materials, including industrial products (Gibson and Ashby 1997), starch bread (Keetels et al 1996b) and starch foams (Shogren et al 1998), are a function of the stiffness of the cell walls and the relative density of the bread crumb (Equation 4, 1.6.2). And because CWES bread had significantly lower crumb density than that of CPS bread even though their moduli were comparable, it is reasonable to suppose that the stiffness of CWES crumb cell walls is higher than CPS. The fracture stresses of CWES and CWRS breads were comparable, but for blend and CPS bread, fracture stresses decreased markedly (on average, by 17% and 40% of the fracture stress of CWES bread, respectively). According to Gibson and Ashby (1997) fracture stress of cellular material is also a function of the fracture stress of the cell walls and the relative density (Equation 5, 1.6.2), meaning that the fracture stress increases with increasing density and/or fracture stress of the cell walls. Since the fracture stress generally decreased in the order of decreasing flour strength (CWES, CWRS, blend, and CPS; 3.3.1.2) despite the increase in density (Table 10), it is evident that the strength of the cell walls has also decreased with decreasing flour strength, but more so than the change in modulus. All these results clearly indicated that the mechanical properties of the cell walls of bread crumb are affected by flour strength.

3.3.2.1.2. Sheeting Passes (SP)

The sheeting process, which is a crucial step in breadmaking, serves many functions. These functions include dough development, protein alignment, gas repulsion, and lamination (Levine 1998). Excessive sheeting beyond optimal levels was reported to have 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 (3.2 mm) of the rollers resulted in small, but significant, changes in both loaf volume and crumb density (Table

11). On average, the loaf volume decreased by 66 cm^3, while crumb density increased by 0.005 g cm^{-3}.

For the crumb grain features, the two additional SP had a significant effect on void fraction and SLCC, decreasing the void fraction and increasing the SLCC. It is interesting to note that the change in the crumb density or loaf volume as a result of varying the number of SP brought about an equivalent change in the void fraction. This confirmed the strong relationship between density and void fraction, which was also observed for various types of flour (3.3.2.1.1). No significant effects were observed for the other imaging parameters, e.g. cells/cm^2, MCA, CWT, and crumb brightness (Tables 19-21 and 23, Appendix IV). Although on average, the MCA and CWT did not vary with the sheeting treatment, the distributions of cells may have been improved (Stenvert et al 1979) since SLCC increased with the two extra SP.

The number of sheeting passes did not produce any significant effect on Young's modulus, fracture stress, fracture strain, or fracture energy (Tables 25-28, Appendix IV) despite the significant increase in crumb density (Table 18, Appendix IV). The mechanical properties of cellular materials generally depend on the structural properties and the physical properties of the cell walls (Chen et al 1994; Gibson and Ashby 1997). Since the effect of the sheeting treatment on the overall mechanical properties and most structural parameters of bread crumb was insignificant, one can speculate that the imposed stresses of the two extra SP did not have any major influence on the properties of the cell walls.

Table 11. Effects of Number of Sheeting Passes on the Characteristics of Bread Crumb Prepared at Fixed Water Absorption[a].

No. of Sheeting Passes:	3	5
Loaf Volume (cm^3)	2169a	2103b
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
SLCC	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. Means with different letters across each row are significantly different ($p < 0.05$). MCA, mean cell area; CWT, cell wall thickness; SLCC, small-to-large cell count.

3.3.2.1.3. Proof Time (PT)

Table 12 shows the effects of PT on average density, grain features and mechanical properties of bread crumb prepared with fixed WA. As was expected, loaf volume significantly increased as proof time was extended from 35 to 85 min (Kamman 1970; Pyler 1988). This trend was observed for all types of flours, and for both sheeting treatments. The density of bread crumb significantly decreased with increasing PT. An interaction effect between PT and number of SP for density showed that the difference in crumb density between 3 and 5 SP decreased with increasing PT and resulted in approximately the same density at 85 min PT (Fig. 7). Likewise, loaf volume showed similar trends as a function of PT and SP, but it was not statistically significant. At 35 min PT, the crumb density was higher when the dough was processed with 5 rather than 3 SP, indicating that the former contained less gas to start with as a result of the two additional SP. In other words, 5 SP caused more degassing of the dough than did 3 SP. But at 85 min proof time, crumb density was the same regardless of the number of SP. Assuming that the density of the cell wall is unaffected by the two extra SP, this means that at 85 min PT, the bread crumb contained the same amount of gas, regardless of the sheeting treatment. Thus, it is evident that the dough which was subjected to 5 SP retained more of the gas that was produced during fermentation. Therefore, it can be concluded that the two additional sheeting passes did not cause any structural damage in the dough system and did not have any negative effect on its gas retention properties.

All crumb grain features were significantly influenced by PT. With increasing PT, MCA, CWT, and void fraction increased, while cells/cm^2, SLCC, and crumb brightness decreased. These results are consistent with those reported in the previous chapter (2.3.2

Table 12. Effects of Proof Time on the Characteristics of Bread Crumb Prepared at Fixed Water Absorption[a].

Proof Time (min)	35	45	60	85
Loaf Volume (cm^3)	1678d	1969c	2270b	2628a
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
SLCC	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

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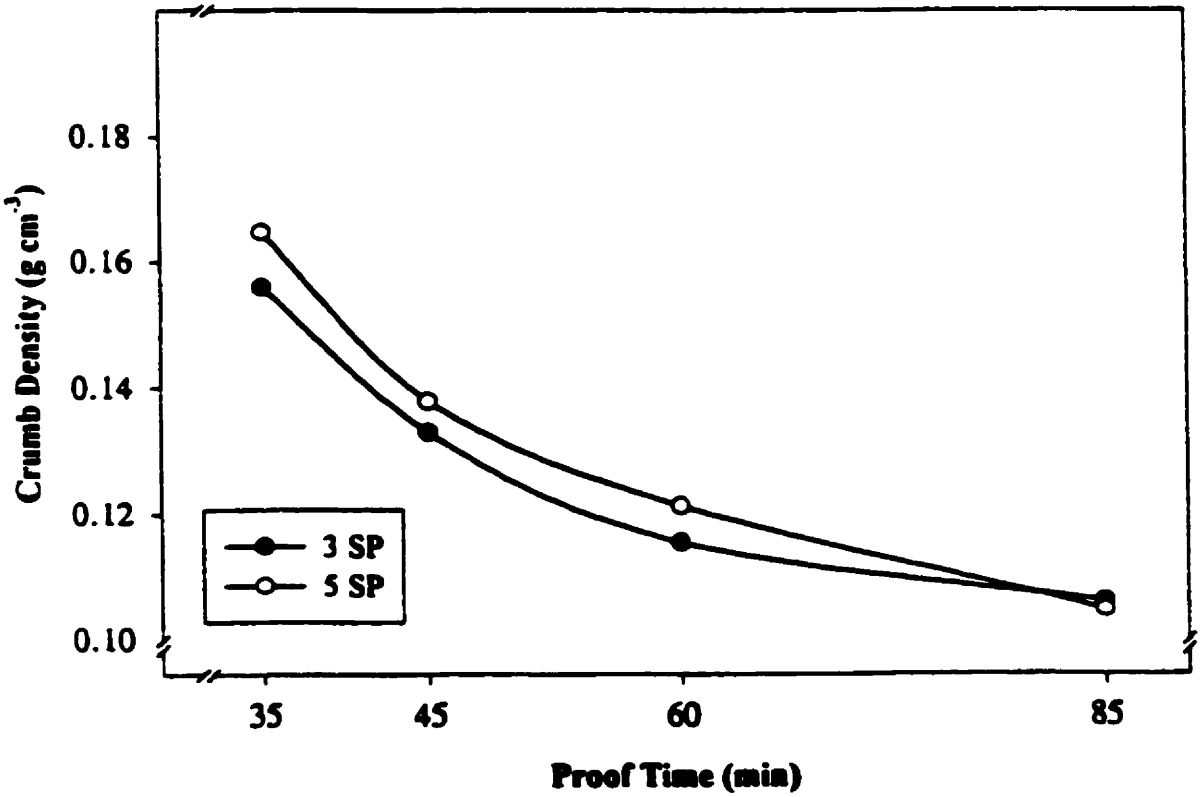
[a] Data of various flour types and sheeting treatments were combined for each proof time. Means with different letters across each row are significantly different ($p < 0.05$). MCA, mean cell area; CWT, cell wall thickness; SLCC, small-to-large cell count.

Figure 7. Changes in mean crumb density (flour types combined) of bread prepared at fixed absorption as a function of proof time and number of sheeting passes.


0.18
0.16
0.14
0.12
0.10
Crumb Density (g cm^{-3})
3 SP
5 SP
35
45
60
85
Proof Time (min)

and references therein). For the SLCC, interaction effects (PT and SP; PT and flour type) were observed. These interactions showed no clear and consistent trends of the SLCC as a function of PT and number of SP or as a function of PT and flour type.

PT was also found to have a major effect on the mechanical properties of bread crumb. On average, as PT was increased from 35 to 85 min, the Young's modulus values decreased by as much as 42%. The fracture stress of bread crumb also significantly decreased with increasing PT (on average, up to 29% reduction). Likewise, energy to fracture (the area under the stress-strain curve) as a function of proof time also showed a similar trend to those of fracture stress and stiffness. The changes in the mechanical properties of bread crumb with increasing PT was believed to be mainly due to the large reduction in bread crumb density (Ponte et al 1962; Wassermann 1979). The resulting changes in the grain features of bread crumb with increasing PT may also explain some of the variation in its mechanical properties (Kamman 1970; Pyler 1988). The fracture strain (or extensibility) of bread crumb significantly increased with increasing PT (and corresponding decrease in density). 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). Although the changes in the mechanical properties of bread crumb with varying PT generally followed the expected trends, exceptions were observed. For example, increasing PT from 35 to 45 min or from 60 to 85 min did not produce any significant effect on the Young's modulus, fracture stress, and fracture strain, while the fracture energy was almost constant between 35 and 60 min PT, but markedly decreased at 85 min PT. As mentioned above, it is known that the mechanical properties of bread crumb in general, but stiffness and fracture stress in particular, depend on the properties of the cell walls and the crumb density (Chen et al 1994; Keetels et al 1996b; Gibson and Ashby 1997). Because the mechanical properties were not significantly affected as PT was increased from 35 to 45 or from 60 to 85 min despite the major decrease in crumb density (Table 12), it is evident that the physical strength of the cell walls has been enhanced by increasing proof time. This appears to be reasonable on the ground that the effect of decreasing crumb density, which would normally cause a reduction in the mechanical strength, was cancelled out by the increase in the strength of the cell walls resulting from increasing PT. This conclusion is in line with the results of van Vliet and co-workers (1992) who indicated that strain hardening occurred in dough cell walls as they are stretched during fermentation, causing higher resistance to extension. Since the strain hardening phenomenon taking place in dough's cell walls upon stretching involves rearrangement of molecular structure of polymers (i.e. orientation and alignment), its effect is expected to carry through the baking operation and influence the properties of the cell walls of bread as well.

3.3.2.2. Optimum Water Absorption

3.3.2.2.1. Flour Strength

The effects of flour strength on loaf volume, density, grain features and mechanical properties of bread crumb prepared at optimum water absorption are illustrated in Table 13. For bread prepared at optimum WA, the effect of flour type on loaf volume and crumb density were very similar to those observed for bread baked at fixed WA. The only exception was the loaf volume of CWES and CWRS breads, which was significantly different at fixed water absorption, but not at optimum WA. The effects of flour strength on the crumb grain features (cells/cm^2, MCA, SLCC, crumb brightness, and void

Table 13. Effects of Flour Type on the Characteristics of Bread Crumb Prepared at Optimum Water Absorption[a].

Flour Type:	CWES	CWRS	Blend	CPS
Loaf Volume (cm^3)	2278a	2259a	2139b	1967c
Density (g cm^{-3})	0.130b	0.130b	0.132ab	0.135a
Crumb Grain				
No. Cells/cm^2	87.9ab	89.6a	88.0ab	84.5b
MCA (mm^2)	0.563ab	0.548b	0.560ab	0.581a
CWT (mm)	0.786	0.801	0.779	0.808
SLCC	38.8a	36.4ab	34.1bc	33.1c
Crumb Brightness	178.7c	182.6ab	183.9a	181.5b
Void Fraction	0.486a	0.479c	0.483b	0.479c
Mechanical Properties				
Modulus (kN m^{-2})	10.54b	10.37b	11.96a	10.46b
Fracture Stress (kN m^{-2})	2.23a	1.98b	1.97b	1.47c
Fracture Strain	0.46a	0.38b	0.36b	0.30c
Fracture Energy (J m^{-3})	649a	480b	462b	283c

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[a] Data of various proof times and sheeting treatments were combined for each type of flour. Means with different letters across each row are significantly different ($p < 0.05$). MCA, mean cell area; CWT, cell wall thickness; SLCC, small-to-large cell count.

fraction) of bread prepared at optimum WA also showed similar trends to those observed for fixed WA, but differences among flour types were more statistically significant. For the mechanical properties of bread crumb, flour type had a significant effect on Young's modulus, fracture stress, fracture strain and energy to fracture. At optimum WA, fracture stress, fracture strain, and energy to fracture of CWRS bread crumb were significantly lower than those of CWES bread, but they were comparable to those of blend bread. As it was observed for bread prepared at fixed WA, the Young's modulus of bread prepared at optimum WA did not show any clear trend with respect to flour strength. On average, CPS, CWES, and CWRS breads had approximately the same Young's modulus despite their different inherent strengths (Table 13). Blend bread showed significantly higher values of Young's modulus than all other flours. The reason for the Young's modulus of CPS, CWES, and CWRS bread crumb being approximately equal is due in part to the plasticizing effect of water (Maleki et al 1980; Piazza and Masi 1995), as bread made from stronger flour had a higher moisture content. But even though these bread samples which were prepared with optimum WA (crumb containing different levels of moisture) had comparable Young's moduli, the Young's moduli of their cell walls is anticipated to decrease with decreasing flour strength. This conclusion was reached by following the same approach (theory by Gibson and Ashby 1997) that was previously discussed in section 3.3.2.1.1. Again, by using the CWES and CPS bread as an example, the lower density of the former (0.130 g cm^{-3}) compared to the latter (0.135 g cm^{-3}) suggested that the modulus of CWES cell walls is higher than that of CPS. Likewise the strength of the cell walls is expected to increase with increasing flour strength (more so than Young's modulus), since the fracture stress of CWES bread crumb was higher than that of CPS in spite of its lower density.

3.3.2.2.3. Sheeting Passes

Both loaf volume and bread crumb density of bread prepared at optimum WA were significantly affected by the number of sheeting passes (Table 14). Among all crumb grain features, the void fraction was the only feature which was affected by the number of SP. Interaction effects between flour type and the number of SP was observed for void fraction (Fig. 8). No effect of number of SP on void fraction was observed for blend flour, but for the other flours the two additional SP decreased the void fraction. The difference in void fraction increased in this order of flour type: CPS, CWRS, and CWES. The reasons for this interaction are unclear.

As was the case for bread prepared with fixed water absorption, the number of sheeting passes did not have a statistically significant effect on the mechanical properties of bread crumb (Table 14).

3.3.2.2.3. Proof Time

For bread prepared with optimum WA, the effects of PT on all bread characteristics including loaf volume, density, physical and visual texture of bread crumb (shown in Table 15), were similar to those observed for bread baked at fixed WA. An interaction effect between PT and flour type was observed for loaf volume of bread prepared at optimum WA (Fig. 9). This interaction, which was very highly significant ($P < 0.001$, Appendix V, Table 30) indicated that the flour with highest inherent strength (CWES) showed more tolerance to over-proofing. This interaction was also observed for bread prepared with fixed water absorption, but it was of borderline significance ($P = 0.057$).

Table 14. Effects of Number of Sheeting Passes on the Characteristics of Bread Crumb Prepared at Optimum Water Absorption[a].

No. of Sheeting Passes:	3	5
Loaf Volume (cm^3)	2194a	2127b
Density ($g\ cm^{-3}$)	0.129b	0.135a
Crumb Grain		
No. Cells/cm^2	87.0	88.0
MCA (mm^2)	0.570	0.556
CWT (mm)	0.789	0.798
SLCC	35.4	35.8
Crumb Brightness	181.1	182.3
Void Fraction	0.484a	0.480b
Mechanical Properties		
Modulus ($kN\ m^{-2}$)	11.53	11.15
Fracture Stress ($kN\ m^{-2}$)	1.87	1.94
Fracture Strain	0.38	0.38
Fracture Energy ($J\ m^{-3}$)	462	475

[a] Data of various flour types and proof times were combined for each sheeting treatment. Means with different letters across each row are significantly different ($p < 0.05$). MCA, mean cell area; CWT, cell wall thickness; SLCC, small-to-large cell count.

Figure 8. Changes in mean void fraction (proof times combined) of bread crumb prepared at optimum water absorption as a function of flour type and number of sheeting passes.

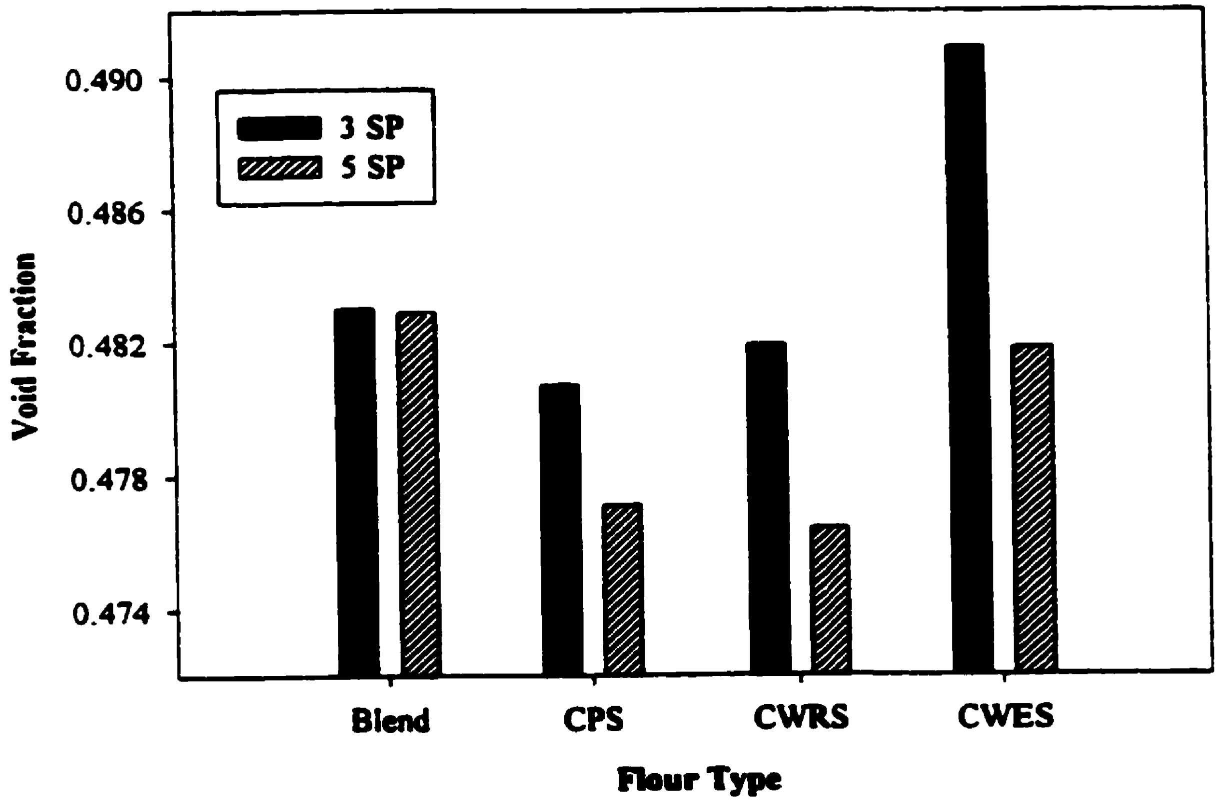
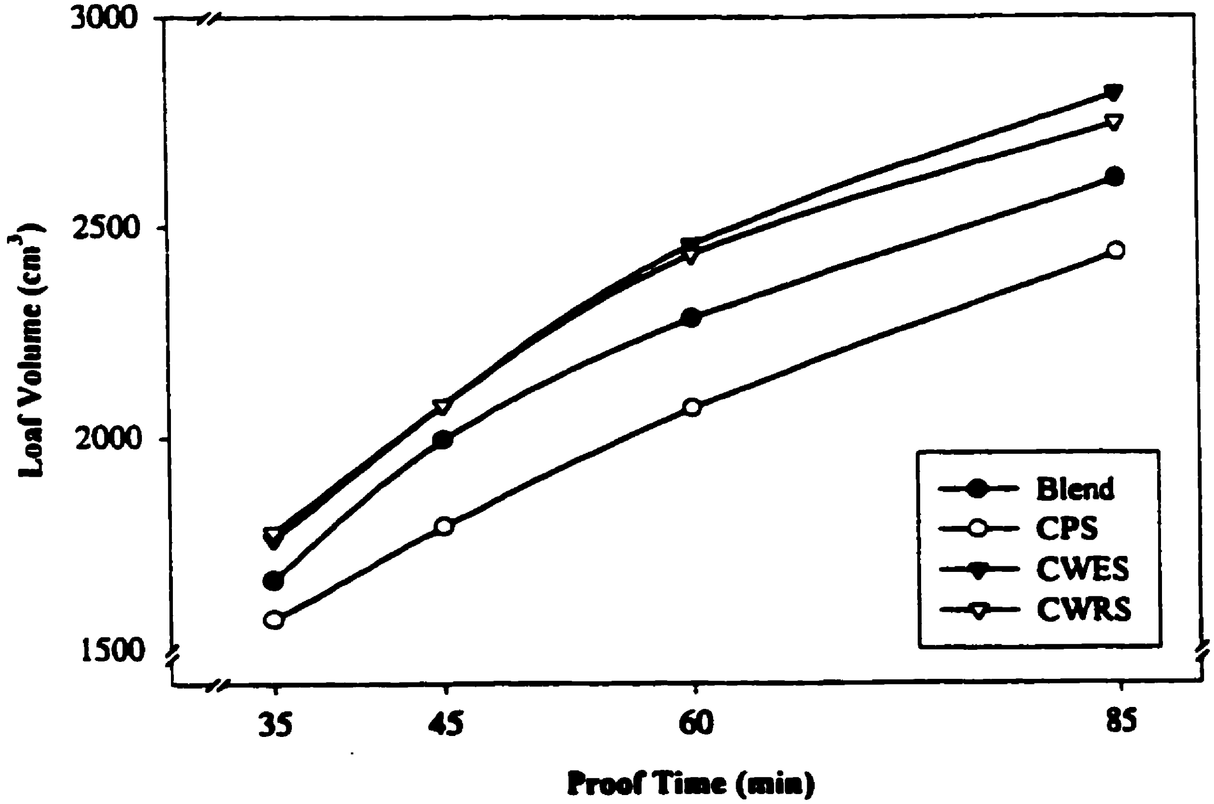

3 SP
5 SP
Void Fraction
0.490
0.486
0.482
0.478
0.474
Blend
CPS
CWRS
CWES
Flour Type

Table 15. Effects of Proof Time on the Characteristics of Bread Crumb Prepared at Optimum Water Absorption[a].

Proof Time (min)	35	45	60	85
Loaf Volume (cm^3)	1692d	1985c	2312b	2653a
Density (g cm^{-3})	0.164a	0.138b	0.120c	0.106d
<u>Crumb Grain</u>				
No. Cells/cm^2	92.6a	90.8ab	88.6b	78.1c
MCA (mm^2)	0.516c	0.535bc	0.556b	0.646a
CWT (mm)	0.769b	0.771b	0.795b	0.839a
SLCC	38.4a	36.8a	36.5a	30.8b
Crumb Brightness	187.6a	184.4b	179.9c	174.8d
Void Fraction	0.468d	0.480c	0.485b	0.494a
<u>Mechanical Properties</u>				
Modulus (kN m^{-2})	14.18a	12.87b	8.11c	8.20c
Fracture Stress (kN m^{-2})	2.25a	2.03b	1.70c	1.65c
Fracture Strain	0.34b	0.34b	0.42a	0.40a
Fracture Energy (J m^{-3})	517	460	465	433

[a] Data of various flour types and sheeting treatments were combined for each proof time. Means with different letters across each row are significantly different ($p < 0.05$). MCA, mean cell area; CWT, cell wall thickness; SLCC, small-to-large cell count.

Figure 9. Changes in mean loaf volume (sheeting treatments combined) of bread prepared at optimum water absorption as a function of proof time and flour type.


3000
2500
2000
1500
Loaf Volume (cm^3)
35
45
60
85
Proof Time (min)
Blend
CPS
CWES
CWRS

Despite the good relationship between loaf volume and density, no interaction between PT and flour type was found for density. The reason that this interaction was not seen could be attributed to sampling of bread crumb. Bread samples were relatively small (taken from the central portion of the slice) and they may not therefore represent the density of the whole slice. In addition, slight variability in selecting the portion of the bread slice from which bread samples were cut may have masked the interaction from being observed, since the density of bread crumb is known to vary across the bread slice (Ponte et al 1962). PT and SP showed an interaction effect (of borderline significance, $P = 0.057$) for crumb density. This interaction which is similar to the one shown in Fig. 7 (fixed WA) further indicated that the gas retention properties of the doughs were not altered by the additional two SP (3.3.2.1.3).

3.3.2.3. Fixed Versus Optimum Water Absorption

Increasing water absorption from 60% to optimum levels (65% and 63% for CWRS and CWES, respectively) generally resulted in a statistically significant increase in loaf volume; on average, there was approximately 50 cm^3 increase in loaf volume (Table 16). This increase in loaf volume can be explained by two mechanisms that are related to dough rheology and its gas retention properties. Firstly, the seam in the dough of higher WA tended to seal better when molded, since the dough was more sticky (Atkins and Larsen 1990), and therefore, less gas escaped through the seam of the dough. Secondly, the increase in dough extensibility with increasing water content (Bloksma 1990; Spies 1990) may have accounted for greater expansion of the dough during final proofing. These two explanations are based on personal observation during the experiment, and on

Table 16. Effects of Water Absorption on the Characteristics of Bread Crumb[a].

Water Absorption	Fixed	Optimum
Loaf Volume (cm^3)	2220b	2269a
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
SLCC	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

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[a] Data of various types of flour (CWES and CWRS), sheeting treatments, and proof times were combined for each level of water Absorption. Means with different letters across each row are significantly different ($p < 0.05$). MCA, mean cell area; CWT, cell wall thickness; SLCC, small-to-large cell count.

the baking results (Tables 1-4, Appendix III) since the height of dough at the end of proofing was greater for optimum WA than its height at 60% WA.

The moisture content of bread specimens was strongly correlated ($R^2 = 0.993$) with the water absorption. The average moisture content was 37.1% for CWRS and CWES bread prepared at 60% WA, 38.1% for CWES bread prepared at 63% WA, and 39.0 % for CWRS bread prepared at 65% WA. On average, the density of bread crumb samples remained unaffected by increasing WA from 60% to optimum, despite the increase in loaf volume (Table 16). The reason that WA did not influence the crumb density is because the weight increase resulting from the higher WA or moisture content was cancelled out by the volume increase.

Interaction effects between PT and number of SP was observed for the density of bread crumb. This interaction, which is similar to that observed for all flour samples baked at 60% WA (Fig. 7) and at optimum WA, confirmed that the two extra SP only expelled air and did not cause any structural breakdown of the dough.

WA also had only minor effects on the cellular structure of bread crumb: on average, cells/cm^2, MCA, CWT, SLCC, and void fraction were not affected (Table 16). The effect of WA on crumb grain features determined by DIA is in agreement with the results reported by Larsen and Greenwood (1991) which indicated that crumb grain score of unlidded loaves was unaffected by WA at levels ranging between 60 and 66%. Unlike the other crumb grain features, average crumb brightness decreased with increasing WA from 60% to optimum levels (Table 16). Although there were very few exceptions, the change in crumb brightness as a function of WA was highly significant ($P < 0.01$, Appendix VI, Table 49). The higher degree of starch gelatinization with increasing water absorption is expected to give a creamy color that appears less bright (A.W. MacGregor, personal communication). Therefore, the lower brightness of bread crumb prepared with higher WA could be explained by a greater degree of gelatinization of starch. Although this argument is plausible, further investigation is required. Interestingly, this result suggested that the DIA is sensitive to changes even at the supramolecular level.

Interaction effects among experimental treatments were observed for crumb brightness (PT, Flour, and WA) void fraction (PT and SP), and SLCC (PT, WA, and SP). Figure 10 illustrates the effect of PT, flour type and WA on crumb brightness. This figure clearly shows that the brightness of CWES and CWRS bread was generally lower for the bread samples which were prepared with the higher (optimum) WA. Since crumb brightness is also a function of crumb fineness as was previously shown (2.3.4 and reference therein), the two exceptions shown in Fig. 10 (CWRS at 35 min PT and CWES at 85 min PT) could be due to differences in crumb structure which overpowered the effect of starch gelatinization on crumb brightness. Figure 11 shows the interaction effect between PT and SP for void fraction. This interaction effect, which is analogous to that observed for crumb density (Fig.7), showed that the difference in void fraction between 3 and 5 SP decreased with increasing PT. This further confirmed that the gas retention properties of the dough were unaffected by the sheeting treatment. The interaction between PT and SP for void fraction of bread crumb was examined by plots (not shown) for all types of bread on the basis of fixed and optimum WA. Similar trends to those shown in Fig. 11 were also found, although they were not statistically significant. The other observed interaction, which were confirmed by plots, showed no consistent and predictable SLCC responses to PT, flour type, or WA.

Figure 10. Changes in mean crumb brightness of CWES and CWRS bread samples as a function of proof time, water absorption and number of sheeting passes.

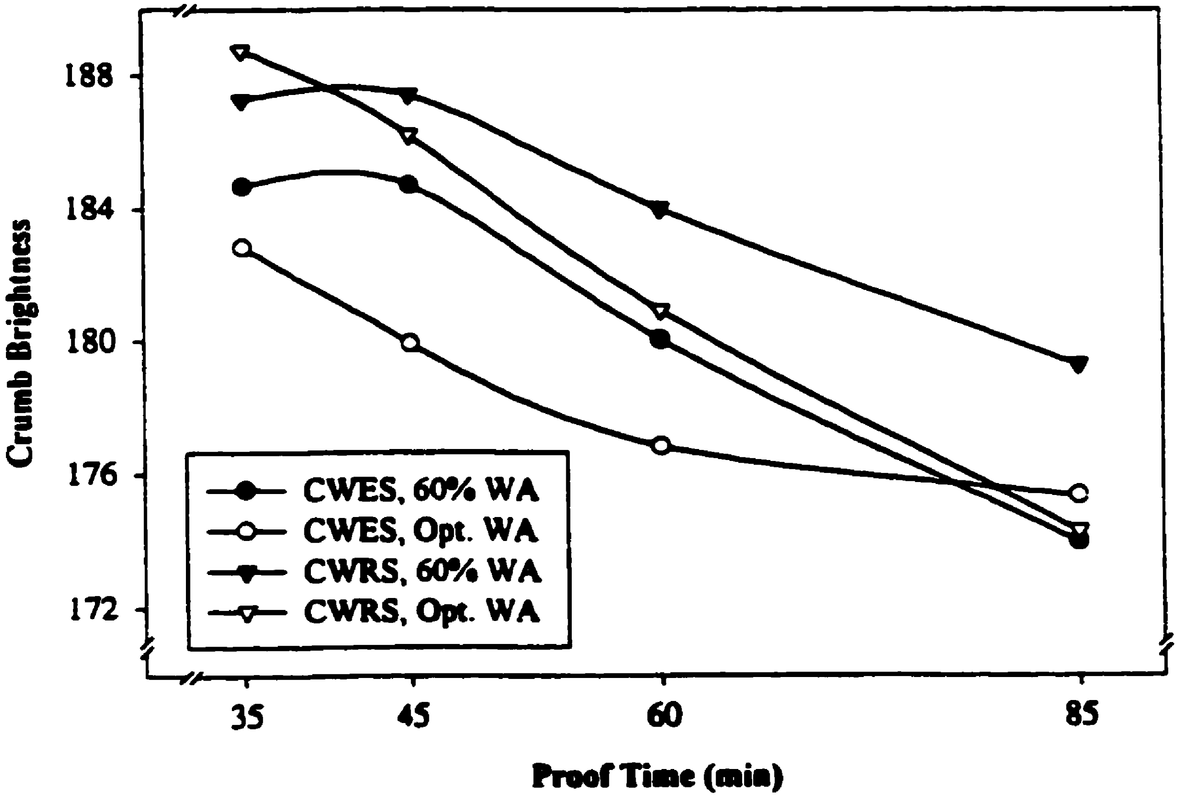
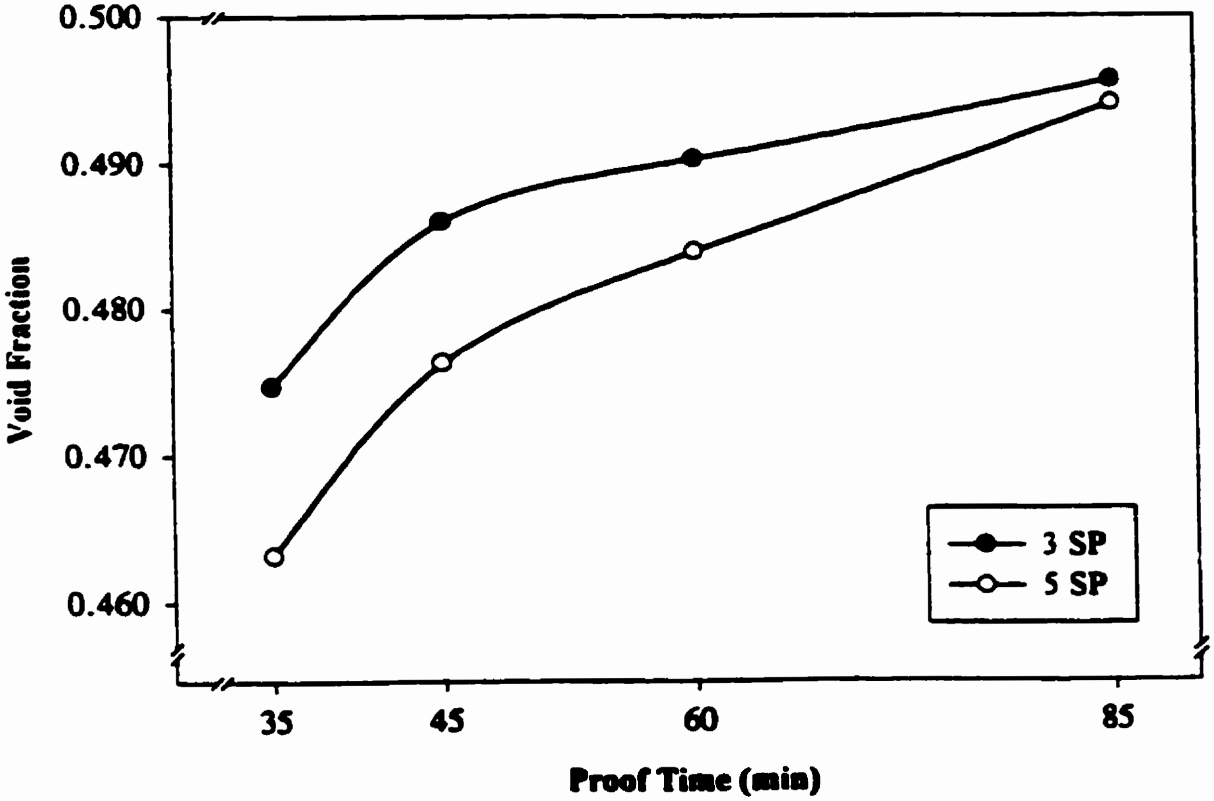

Crumb Brightness
188
184
180
176
172
35
45
60
85
Proof Time (min)
CWES, 60% WA
CWES, Opt. WA
CWRS, 60% WA
CWRS, Opt. WA

Figure 11. Changes in mean void fraction of bread crumb samples (flour types and water absorption combined) as a function of proof time and number of sheeting passes.


0.500
0.490
0.480
0.470
0.460
Void Fraction
35
45
60
85
Proof Time (min)
3 SP
5 SP

In contrast to crumb density and grain features, the mechanical properties of bread crumb were greatly influenced by the moisture content of the bread samples. On average, Young's modulus, fracture stress, and fracture energy of bread crumb significantiy decreased with increasing WA, but fracture strain did not show any clear trend with respect to the change in WA (Table 16). The decrease in the overall mechanical strength of bread crumb (mainly due to CWRS bread, see below) with increasing WA, which is consistent with the results of Maleki et al (1980) and Piazza and Masi (1995), is believed to be due to the plasticizing effect of water. It is obvious that the mechanical properties of crumb cell walls have been dramatically altered with increasing WA, since the structural properties of bread crumb (density and grain features determined by DIA) were not affected. Interaction effects of experimental treatments for fracture stress (Flour and WA; PT, Flour, and WA) and fracture energy (flour and WA; PT, flour, and WA; PT, WA, and SP) of bread crumb were observed.

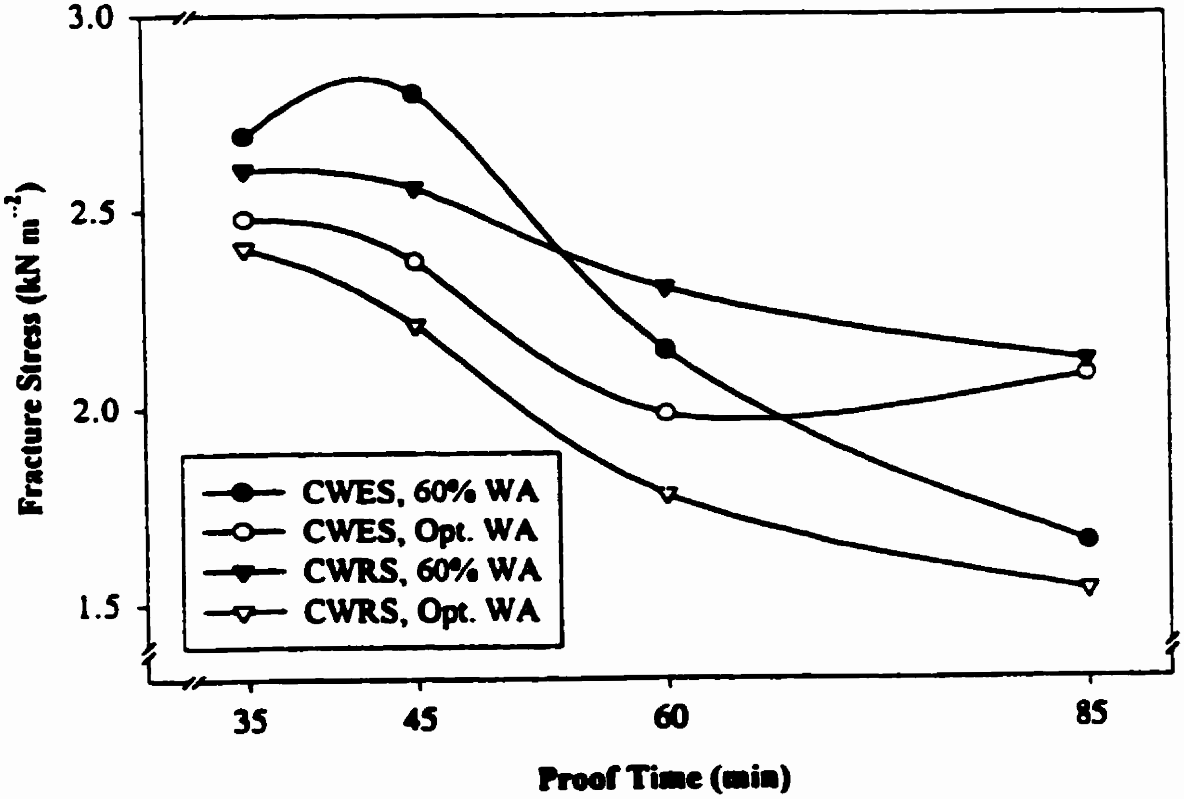
Unlike CWRS bread crumb, the fracture stress of CWES bread crumb was not significantly affected by increasing WA from 60% to optimum (Table 17). The higher water content in CWES bread did not seem to act as a plasticizer. This result is not surprising since the mixograph results (Table 8) showed that the rheological properties of CWES dough were only marginally affected by the water addition. Therefore, it appears that the higher WA did not contribute to additional free water in CWES bread, and consequently its mechanical strength was not affected. Figure 12 shows the variation in fracture stress of bread crumb as a function of PT for the two types of flour and the two WA. For CWRS bread prepared at both optimum and 60% WA, the decrease in the fracture stress as a function of PT was almost linear, with bread prepared at 60% WA

Table 17. Interaction Effect Between Flour Type and Water Absorption for Fracture Stress (kN m^{-2}).

	Flour Type	
WA	CWRS	CWES
Fixed	2.40a, a	2.32a, a
Optimum	1.98b, b	2.23a, a

Data of various sheeting treatments and proof times were combined for each type of flour and water absorption. Means with different letters across each row or column are significantly different ($p < 0.05$).

Figure 12. Changes in mean fracture stress (sheeting treatments combined) of CWRS and CWES bread crumb as a function of proof time, flour type, and water absorption.


3.0
2.5
2.0
1.5
Fracture Stress (kN m⁻²)
35
45
60
85
Proof Time (min)
CWES, 60% WA
CWES, Opt. WA
CWRS, 60% WA
CWRS, Opt. WA

having a smaller slope. The latter result suggests that the rate of strain hardening in the dough cell walls was higher at 60% WA compared to optimum, resulting in much greater strength in the bread cell walls, especially in over-proofed bread. On the other hand, the change in fracture stress of CWES bread with increasing PT also showed a decreasing trend, but bread prepared with optimum water absorption had a smaller slope suggesting that the rate of strain hardening was greater at optimum WA (Fig. 12).

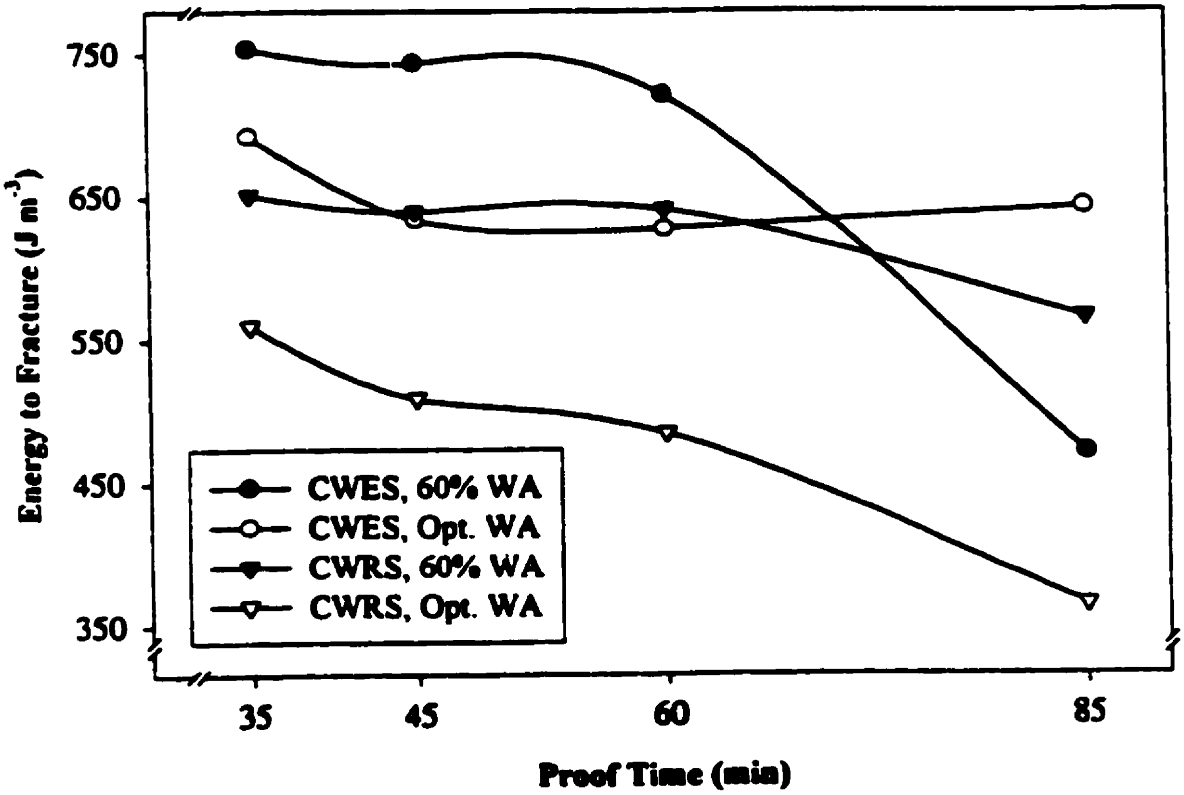
The interaction effects of flour type and WA for energy to fracture (or fracture resistance) is shown in Table 18. For both types of flours, bread baked at lower WA showed higher energy to fracture, but the difference between optimum and 60% WA was much larger in the case of CWRS bread. This is due in part to the fact that optimum WA of CWRS was 2 ml higher than the optimum WA of CWES flour. In addition, as was explained earlier, the higher inherent strength of CWES flour may have reduced or eliminated its sensitivity to higher WA within the range of 60-63%. The interaction effects among PT, flour type, and WA for energy to fracture (Fig. 13) showed very similar trends to the interaction effects observed for fracture stress (Fig. 12). This interaction confirmed that the effect of WA or water content on the mechanical properties varies depending on flour type. Increasing WA from fixed to optimum level caused the fracture energy of CWRS bread to decrease at a higher rate with increasing proof time, but for CWES bread opposite results were observed. Increasing PT did not affect the fracture resistance of CWES bread that was prepared with optimum absorption, but decreased the fracture resistance of CEWS bread which was baked with fixed WA. The interaction effects among PT, WA, and SP for energy to fracture were inconsistent and unclear.

Table 18. Interaction Effect Between Flour Type and Water Absorption for Fracture Energy ($J\ m^{-3}$).

	Flour Type	
WA	CWRS	CWES
Fixed	625a, a	673a, a
Optimum	480b, b	649a, a

Data of various sheeting treatments and proof times were combined for each type of flour and water absorption. Means with different letters across each row or column are significantly different ($p < 0.05$).

Figure 13. Changes in mean fracture energy (sheeting treatments combined) of CWRS and CWES bread crumb samples as a function of proof time, flour type, and water absorption.


750
650
550
450
350
Energy to Fracture (J m^{-3})
35
45
60
85
Proof Time (min)
CWES, 60% WA
CWES, Opt. WA
CWRS, 60% WA
CWRS, Opt. WA

3.4. CONCLUSIONS

Flour type influenced the density, grain features and mechanical properties of bread crumb, with stronger flour producing bread having lower density, finer structure and greater mechanical strength. Young's modulus however, did not show any dependence on flour strength. Water absorption (WA) affected the mechanical properties and the brightness of bread crumb only. Increasing WA decreased the mechanical strength of CWRS bread crumb, but had insignificant effect on the mechanical properties of CWES bread. Because WA did not affect the structural properties of bread crumb, it was concluded that the properties of the cell walls were altered with changing WA. Increasing the number of sheeting passes from 3 to 5 resulted in a minor effect on crumb cellular structure, but no effect was observed for the mechanical properties. Proof time significantly affected all bread characteristics: it increased loaf volume, decreased crumb density and mechanical properties, and yielded bread crumb with coarser grain. However, the decrease in mechanical properties was not observed for all proof times despite the continuous decrease in crumb density and the coarser crumb grain. This suggested that the physical properties of the cell wall of bread crumb were enhanced through a strain hardening phenomenon that occurred during dough proofing. With increasing proof time, the effect of the two extra sheeting passes compared to the control has decreased for crumb density and void fraction, suggesting that the gas retention properties of dough were not altered by the two extra sheeting passes.

4. Structure and its Influence on the Mechanical Properties of Bread Crumb

ABSTRACT

Mechanical properties and cell structure of bread crumb are important factors in bread quality evaluation. The objective of this study was to determine the influence of crumb cellular structure on its mechanical properties and establish models for predicting the mechanical properties of bread crumb from its structural parameters. Variation in structural and mechanical properties were obtained by using different types of flour, water absorptions, sheeting passes, and proof times. The cellular structure was characterized by crumb density and crumb grain features (determined by digital image analysis), while mechanical properties were measured by tensile testing to provide values for Young's modulus, fracture stress, fracture strain, and fracture energy. The structural parameters of bread crumb were closely related to Young's modulus and fracture stress, with crumb density and brightness (separately) showing very highly significant correlations. In addition, Young's modulus and fracture stress were successfully fitted to the power law model proposed by Gibson and Ashby for characterizing the properties of industrial cellular solids. A three-variable model comprising crumb density, crumb brightness and SLCC (small-to-large cell count ratio) permitted the prediction of Young's modulus and fracture strength (R^2 values ranged from 0.76 to 0.97 and from 0.86 to 0.94, respectively). Fracture strain and energy did not show any dependence on crumb structure, and seemed to be influenced by the properties of cell walls. It was concluded that the overall mechanical properties of bread crumb are dependent on the crumb structure and the mechanical properties of the cell walls as influenced by dough ingredients and bread processing conditions.

4.1. INTRODUCTION

Studying and understanding the deformation of porous food materials has become a subject of great interest to many food scientists. It is widely believed that the mechanical properties of bread crumb were affected by its structural properties (Kamman 1970; Pyler 1988; Chen et al 1994; Keetels et al 1996b). However, very little research has been performed to quantify the structural properties of bread crumb and assess their influence on the mechanical properties. For materials (mostly synthetic) having a cellular structure with open cells (as in a sponge) or closed cells (as in a foam), theoretical and experimental results have shown that the mechanical properties are dependent on the geometry of the structure and the properties of the materials forming the cell walls (Gibson and Ashby 1997). Relative density, which is defined as the density of the cellular material (its bulk density) divided by the density of the solid material, was shown to be the dominant structural characteristic that influenced mechanical strength and stiffness (Young's modulus) of synthetic foams (Gibson and Ashby 1997) and cellular food products (Hutchinson et al 1987; Attenburrow et al 1989; Warburton and Donald 1990; Keetels et al 1996b; Shogren et al 1998). But, in addition, other cellular properties such as cell size distribution and cell wall thickness distribution were also anticipated to affect the mechanical properties (Gibson and Ashby 1997). Barrett et al (1994) reported that the compressive strength of extruded corn meals increased with decreasing cell size and increasing bulk density. Shogren et al (1998) speculated that smaller pore size, thinner cell walls, and closed cells would contribute to greater mechanical strength and flexibility of starch foams. Most of the studies that have been reported in the literature focused on the relationship of stiffness and strength versus density or relative density. But no work has been undertaken to quantitatively measure the structural properties of bread crumb and evaluate their influence on the mechanical properties. Determining the relationship between structural and mechanical properties of bread crumb prepared under different conditions is of great importance to bread technologists and to the baking industry for improving the quality of existing baked goods as well as the development of new products.

Therefore, the objective of this study was to determine how the various structural parameters affect the mechanical properties of bread crumb and establish multi-regression models (using structural parameters) for predicting various mechanical properties. The data which were used to assess the relationship between the structural properties and mechanical properties included crumb density, grain features (quantified by DIA), and mechanical properties of the bread crumb (measured by tensile testing). The structural and mechanical properties of bread crumb were altered by varying flour type, water absorption, number of sheeting passes, and proof time.

4.2. MATERIALS AND METHODS

4.2.1. Structural and Mechanical Properties of Bread Crumb

The same data (including structural and mechanical parameters) that have been discussed in the previous chapter were used for assessing the relationship between structural and mechanical properties of bread crumb. The experimental treatments (described in 3.2.1 and 3.2.4) that have been used to create differences in both structural and mechanical properties involved four types of flours of various strength, two levels of water absorption, two sheeting treatments (3 and 5 sheeting passes), and four proof times (35, 45, 60, and 85 min). The two former treatments were utilized mainly to create differences in the properties of the walls, while the two latter treatments were used to manipulate the structural properties of the bread crumb. The structural parameters of bread crumb included density and grain features (cells/cm^2, mean cell area (MCA), cell wall thickness (CWT), small-to-large cell count ratio (SLCC), crumb brightness, and void fraction) which have been quantitatively measured by DIA (2.2.4 and 3.2.6). The mechanical parameters determined by tensile testing (3.2.7) included Young's modulus (E, kN m^{-2}), fracture stress (σ_f, kN m^{-2}), fracture strain (ε_f), and energy to failure (U_f, J m^{-3}).

4.2.2. Solid Density

In a separate study, the effect of proof time on solid (or cell wall) density of bread crumb was investigated. CWRS bread was prepared in duplicate using the Chorleywood baking method as described by Kilborn and Tipples (1981b). Proof times were 30, 55 and 80 min. Bread crumb samples (~ 30 x 15 x 12 mm) were cut from the central portion of a bread slice with a pathology trimming blade and weighed. Solid densities of fresh bread crumb samples were determined using an AccuPyc 1330 pycnometer equipped with a 10 cm^3 sample chamber (Micromeritics, Norcross, GA). Helium was used as the displacement medium to measure the solid volumes of the bread samples. The solid density (in g cm^{-3}) was then calculated as sample weight (or mass) divided by solid volume. The accuracy of the results was assessed by programming the instrument to perform five purges and 10 successive measurements (or runs). The five purges, which were done before each measurement, permit the removal of air and moisture from the sample chamber. To ensure that the five purges did not alter the results of fresh bread samples (i.e. did not remove moisture from the samples), the solid density of freeze-dried bread crumb was measured under the same conditions and compared to that of fresh bread over the ten runs.

4.2.3. Statistical Analysis

Data were analyzed by SAS Version 6.12 (SAS Institute Inc., Cary, NC). All results, including density, crumb grain features, and mechanical properties were averaged on loaf basis to reduce the effects of inherent variation in bread crumb within each loaf as well as the variation in sampling from bread slices. Pearson correlation analysis (Corr procedure) was performed to determine the relationship between structural parameters of bread crumb (density and crumb grain features determined by DIA) and the mechanical properties of bread crumb. Stepwise linear regression analysis (Stepwise procedure) was used to determine the model for estimating the mechanical properties of bread crumb from its structural parameters.

4.3. RESULTS AND DISCUSSION

The assessment of the relationship between structural and mechanical properties of bread crumb was carried out in three sections. Firstly, the relationships among structural (density and crumb grain features) and mechanical properties (Young's modulus, fracture stress, fracture strain and fracture energy) were determined using correlation analysis. Secondly, a theory relating the relative density to Young's modulus and to fracture stress (Gibson and Ashby 1997) was applied to bread crumb. Thirdly, a model based on quantification of structural properties was determined to predict the mechanical properties of bread crumb. In all three sections, the investigation of the relationship between structure and mechanical properties was done for each type of flour and water absorption separately. The reason for separating the data according to flour type and water absorption was to eliminate the differences in the properties of the cell walls imparted by flour strength and moisture content (3.3.2.1.1 and 3.3.2.3), and thus, focus on the effects of the structural features of bread crumb on its mechanical properties. Therefore, the relationship between structural and mechanical properties was based on differences created by SP and PT (same composition of cell walls), with the latter generating the larger variations in both structure and mechanical properties of bread crumb.

4.3.1. Relationship Between Crumb Grain Features and Mechanical Properties

Pearson correlation analysis was performed to determine the relationship between structural and mechanical properties of bread crumb. Tables 19-24 present the correlations among crumb structure and texture parameters for various bread types and WA. Void fraction, which is a measure of the proportion of gas cells in bread crumb, was very highly correlated with crumb density. The correlation coefficient *R* ranged between -0.90 and -0.97 depending on flour type and WA. Bread crumb brightness was the parameter that was second highest in correlation to crumb density ($R = 0.78$ to 0.96). The other crumb grain features correlated with density to a lesser extent, and lacked consistency among different flour types and water absorption. These results are in agreement with the findings previously reported in section 2.3.4.

The Young's modulus of bread crumb was very highly significantly correlated with the density and the brightness of bread crumb, with the ranges of *R* values being 0.78 to

Table 19. The Correlation Coefficients Between Structural and Mechanical Properties for CWRS Bread Prepared at 60% Water Absorption.

	ρ	C/cm^2	MCA	CWT	SLCC	CB	VF	E	σ_f	ε_f	U_f
ρ	1.00										
C/cm^2	0.85**	1.00									
MCA	-0.90**	0.99***	1.00								
CWT	-0.38	-0.66	0.58	1.00							
SLCC	0.89**	0.87**	-0.90**	-0.24	1.00						
CB	0.78*	0.87**	-0.86**	-0.81*	0.61	1.00					
VF	-0.94***	-0.73*	0.80*	0.08	-0.90**	-0.59	1.00				
E	0.85**	0.68	-0.73*	-0.46	0.61	0.85**	-0.75*	1.00			
σ_f	0.82*	0.73*	-0.75*	-0.61	0.60	0.91**	-0.66	0.95***	1.00		
ε_f	-0.77*	-0.50	0.56	0.20	-0.58	-0.59	0.74*	-0.85**	-0.67	1.00	
U_f	0.54	0.63	-0.61	-0.75*	0.36	0.83*	-0.33	0.66	0.86**	-0.20	1.00

ρ, density of bread crumb; C/cm^2, cells/cm^2; MCA, mean cell area; CWT, cell wall thickness; SLCC, small-to-large cell count; CB, crumb brightness; VF, void fraction; E, Young's modulus; σ_f, fracture stress; ε_f, fracture strain; U_f, fracture energy. *, **, and *** indicate that the parameters are significantly, highly significantly, and very highly significantly correlated at 5, 1, and 0.1% probability, respectively.

Table 20. The Correlation Coefficients Between Structural and Mechanical Properties for CWRS Bread Prepared at 65% Water Absorption.

	ρ	C/cm^2	MCA	CWT	SLCC	CB	VF	E	σ_f	ε_f	U_f
ρ	1.00										
C/cm^2	0.60	1.00									
MCA	-0.70	-0.99	1.00								
CWT	-0.43	-0.82*	0.81*	1.00							
SLCC	0.37	0.85**	-0.78*	-0.63	1.00						
CB	0.94***	0.75*	-0.84**	-0.65	0.44	1.00					
VF	-0.96***	-0.71	0.79*	0.43	-0.48	-0.94***	1.00				
E	0.93***	0.46	-0.58	-0.42	0.13	0.92**	-0.86**	1.00			
σ_f	0.94***	0.59	-0.69	-0.52	0.35	0.95***	-0.91**	0.96***	1.00		
ε_f	0.46	0.13	-0.01	-0.12	0.46	-0.38	0.34	-0.62	-0.39	1.00	
U_f	0.79*	0.70	-0.74*	-0.65	0.60	0.83**	-0.79*	0.71*	0.88**	0.09	1.00

ρ, density of bread crumb; C/cm^2, cells/cm^2; MCA, mean cell area; CWT, cell wall thickness; SLCC, small-to-large cell count; CB, crumb brightness; VF, void fraction; E, Young's modulus; σ_f, fracture stress; ε_f, fracture strain; U_f, fracture energy. *, **, and *** indicate that the parameters are significantly, highly significantly, and very highly significantly correlated at 5, 1, and 0.1% probability, respectively.

Table 21. The Correlation Coefficients Between Structural and Mechanical Properties for CWES Bread Prepared at 60% Water Absorption.

	ρ	C/cm^2	MCA	CWT	SLCC	CB	VF	E	σ_f	ε_f	U_f
ρ	1.00										
C/cm^2	0.97***	1.00									
MCA	-0.96***	-0.99***	1.00								
CWT	-0.71*	-0.81	0.80*	1.00							
SLCC	0.83*	0.76*	-0.73*	-0.36	1.00						
CB	0.81*	0.88**	-0.89**	-0.92**	0.39	1.00					
VF	-0.96***	-0.91**	-0.92**	0.52	-0.85**	-0.69	1.00				
E	0.80*	0.80*	-0.80*	-0.84**	0.38	0.89**	-0.66	1.00			
σ_f	0.73*	0.72*	-0.72*	-0.86**	0.29	0.86**	-0.57	0.92***	1.00		
ε_f	-0.45	-0.43	-0.43	0.18	-0.32	-0.37	0.48	-0.52	-0.18	1.00	
U_f	0.50	0.49	0.49	-0.73*	0.14	0.63	-0.32	0.62	0.87**	0.33	1.00

ρ, density of bread crumb; C/cm^2, cells/cm^2; MCA, mean cell area; CWT, cell wall thickness; SLCC, small-to-large cell count; CB, crumb brightness; VF, void fraction; E, Young's modulus; σ_f, fracture stress; ε_f, fracture strain; U_f, fracture energy. *, **, and *** indicate that the parameters are significantly, highly significantly, and very highly significantly correlated at 5, 1, and 0.1% probability, respectively.

Table 22. The Correlation Coefficients Between Structural and Mechanical Properties of CWES Bread Prepared at 63% Water Absorption.

	ρ	C/cm^2	MCA	CWT	SLCC	CB	VF	E	σ_f	ε_f	U_f
ρ	1.00										
C/cm^2	0.73*	1.00									
MCA	-0.77*	-0.99***	1.00								
CWT	-0.31	-0.60	0.52	1.00							
SLCC	0.66	0.84**	-0.85**	-0.35	1.00						
CB	0.80*	0.93***	-0.93***	-0.67	0.78*	1.00					
VF	-0.90**	-0.75*	0.81*	0.03	-0.72*	-0.72*	1.00				
E	0.78*	0.74*	-0.75*	-0.50	0.50	0.81*	-0.66	1.00			
σ_f	0.77*	0.81*	-0.82*	-0.58	0.49	0.89**	-0.68	0.94***	1.00		
ε_f	-0.70	-0.61	0.61	0.45	-0.58	-0.73*	0.54	-0.91**	-0.77*	1.00	
U_f	0.44	0.51	-0.53	-0.30	0.04	0.51	-0.47	0.45	0.67	-0.06	1.00

ρ, density of bread crumb; C/cm^2, cells/cm^2; MCA, mean cell area; CWT, cell wall thickness; SLCC, small-to-large cell count; CB, crumb brightness; VF, void fraction; E, Young's modulus; σ_f, fracture stress; ε_f, fracture strain; U_f, fracture energy. *, **, and *** indicate that the parameters are significantly, highly significantly, and very highly significantly correlated at 5, 1, and 0.1% probability, respectively.

Table 23. The Correlation Coefficients Between Structural and Mechanical Properties of CPS Bread Prepared at 60% Water Absorption.

	ρ	C/cm^2	MCA	CWT	SLCC	CB	VF	E	σ_f	ε_f	U_f
ρ	1.00										
C/cm^2	0.84**	1.00									
MCA	-0.84**	1.00***	1.00								
CWT	-0.86**	-0.99***	0.99***	1.00							
SLCC	0.86**	0.95***	-0.95***	-0.92**	1.00						
CB	0.96***	0.90**	-0.89**	-0.91**	0.89**	1.00					
VF	-0.96***	-0.72*	0.71*	0.72*	-0.77*	-0.93**	1.00				
E	0.98***	0.77*	-0.77*	-0.78*	0.80*	0.91**	-0.96***	1.00			
σ_f	0.96***	0.74*	-0.74*	-0.74*	0.81*	0.86**	-0.93***	0.95***	1.00		
ε_f	-0.74*	-0.67	0.64	0.68	-0.58	-0.80*	0.75*	-0.78*	-0.57	1.00	
U_f	0.54	0.37	-0.40	-0.37	0.54	0.40	-0.49	0.49	0.72*	0.15	1.00

ρ, density of bread crumb; C/cm^2, cells/cm^2; MCA, mean cell area; CWT, cell wall thickness; SLCC, small-to-large cell count; CB, crumb brightness; VF, void fraction; E, Young's modulus; σ_f, fracture stress; ε_f, fracture strain; U_f, fracture energy. *, **, and *** indicate that the parameters are significantly, highly significantly, and very highly significantly correlated at 5, 1, and 0.1% probability, respectively.

Table 24. The Correlation Coefficients Between Structural and Mechanical Properties of Blend (50% CWES and CPS Flour) Bread Prepared at 60% Water Absorption.

	ρ	C/cm^2	MCA	CWT	SLCC	CB	VF	E	σ_f	ε_f	U_f
ρ	1.00										
C/cm^2	0.81*	1.00									
MCA	-0.85**	-0.99***	1.00								
CWT	-0.82*	-0.94***	0.93***	1.00							
SLCC	0.74*	0.86**	-0.84**	-0.82*	1.00						
CB	0.95***	0.86**	-0.88**	-0.88**	0.68	1.00					
VF	-0.97***	-0.81*	0.84**	0.76*	-0.69	-0.94***	1.00				
E	0.91**	0.65	-0.67	-0.77*	0.51	0.92**	-0.86**	1.00			
σ_f	0.94***	0.73*	-0.75*	-0.78*	0.63	0.89**	-0.91**	0.92**	1.00		
ε_f	-0.66	-0.39	0.40	0.57	-0.21	-0.75*	0.61	-0.91**	-0.70	1.00	
U_f	0.25	0.32	-0.33	-0.15	0.51	0.03	-0.26	-0.12	0.25	0.51	1.00

ρ, density of bread crumb; C/cm^2, cells/cm^2; MCA, mean cell area; CWT, cell wall thickness; SLCC, small-to-large cell count; CB, crumb brightness; VF, void fraction; E, Young's modulus; σ_f, fracture stress; ε_f, fracture strain; U_f, fracture energy. *, **, and *** indicate that the parameters are significantly, highly significantly, and very highly significantly correlated at 5, 1, and 0.1% probability, respectively.

0.98 and 0.81 to 0.92, respectively. The correlation coefficients between Young's modulus and the other crumb grain features were relatively low and inconsistent for various types of flours and WA. The Young's modulus of bread crumb was positively correlated with density, cells/cm^2 and SLCC, and negatively correlated with void fraction, CWT, and MCA. From these results it appears that higher density, finer cellular structure, thinner cell walls, and lower void fraction lead to higher Young's modulus. The influence of various structural parameters on Young's modulus of bread crumb is generally similar to that of synthetic cellular materials discussed by Gibson and Ashby (1997), who indicated that Young's modulus increases with increasing density, uniformity and fineness, and with decreasing cell size.

The fracture stress of bread crumb, which was very highly correlated with the Young's modulus (R = 0.92 to 0.96), also showed a strong correlation with density and crumb brightness, with R values being comparable to those observed for Young's modulus (see Tables 19-24). The other crumb grain parameters correlated with fracture stress to a lesser extent. As was the case for the Young's modulus, the fracture stress of bread crumb was positively correlated with density, cells/cm^2 and SLCC, and negatively correlated with void fraction, CWT, and MCA. On the basis of these results, it appears that bread crumb with a lower void fraction, finer cellular structure, thinner cell walls and higher density would also result in stronger crumb. The influence of the structural parameters on fracture stress of bread crumb was generally similar to that observed for extruded corn meal (Barrett et al 1994), baked starch foam (Shogren et al 1998), and synthetic materials (Gibson and Ashby 1997).

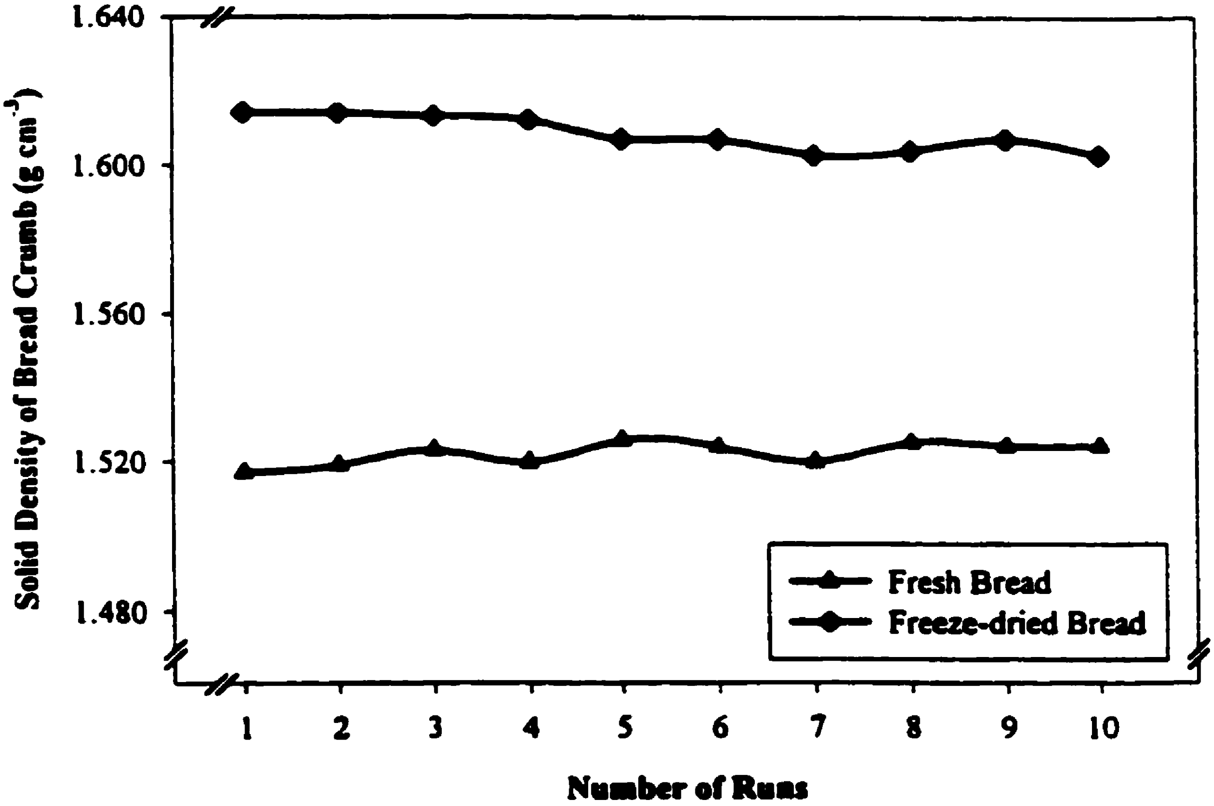
Fracture strain and energy had poor correlations (statistically insignificant) with density and crumb grain features. In some cases, depending on flour type and water absorption, these two mechanical properties were found to have either positive or negative correlation coefficients with the same structural parameter. These results suggested that the fracture strain and energy were not significantly influenced by the structural properties of bread crumb. Since in general, crumb structure had minor or insignificant effects on the fracture strain and energy, it is evident that these two mechanical properties are mostly affected by the properties of the cell walls. Therefore, it can be concluded that the influence of dough strength and WA on the physical properties of cell wall materials appear to be an important underlying factor that affects the fracture strain and energy of bread crumb.

4.3.2. Relationship Between Relative Density and Mechanical Properties

4.3.2.1. Relative Density

Relative density of bread crumb is equal to crumb density divided by solid (or cell walls) density. Figure 14 shows the solid density of fresh and freeze-dried CWRS bread as a function of number of measurements. For the fresh bread, the values of solid density were precise, since on average, the variation among the 10 consecutive measurements was very small ($CV = 0.2\%$) and was comparable to that of the freeze dried bread sample ($CV = 0.2\%$). Based on this excellent repeatability in solid density of fresh bread (no decline in solid density), one can conclude that the five purges which were performed before each run did not remove any moisture from the sample. In addition, the lower solid density of fresh bread crumb (1.522 g cm^{-3}) compared to the freeze-dried bread

Figure 14. Solid density measurements of fresh and freeze-dried CWRS bread crumb over 10 consecutive runs using a helium pycnometer.


1.640
1.600
1.560
1.520
1.480
Solid Density of Bread Crumb (g cm^{-3})
1
2
3
4
5
6
7
8
9
10
Number of Runs
Fresh Bread
Freeze-dried Bread

(1.601 g cm^{-3}) (Fig. 14) confirmed that the obtained results were accurate since fresh bread (containing ~ 40% moisture) is expected to have lower density.

The results of crumb wall solid density of CWRS bread crumb as a function of the three proof times are shown in Table 25. The solid density of bread crumb increased with increasing PT. This result is reasonable because the number of intramural cells in bread crumb (Burhans and Clapp 1942; Campbell et al 1991) is expected to decrease with increasing PT as cell walls stretch causing these tiny cells to open up and become part of larger gas cells. This would decrease the volume associated with the solids and therefore increase the solid density. Since the change in solid density as a function of PT was relatively small (14% compared to a 53% change in loaf density), an average solid density of 1.532 g cm^{-3} was used to calculate the relative density of bread crumb. The purpose of using the relative density instead of crumb density was to obtain an estimate of the mechanical properties of cell wall materials such as Young's modulus and fracture stress (see below). Using this value, the relative density of bread crumb samples ranged from 0.067 to 0.115. The relationships between Young's modulus and fracture stress to the relative density of bread crumb are presented and discussed below.

4.3.2.2. Young's Modulus Versus Relative Density

Figure 15 shows Young's modulus plotted against relative density (E, kN m^{-2}) on a double-log scale to fit the data to a power law equation of the following form (Gibson and Ashby 1997):

$$E=E_s\,(\rho/\rho_s)^n \qquad (11)$$

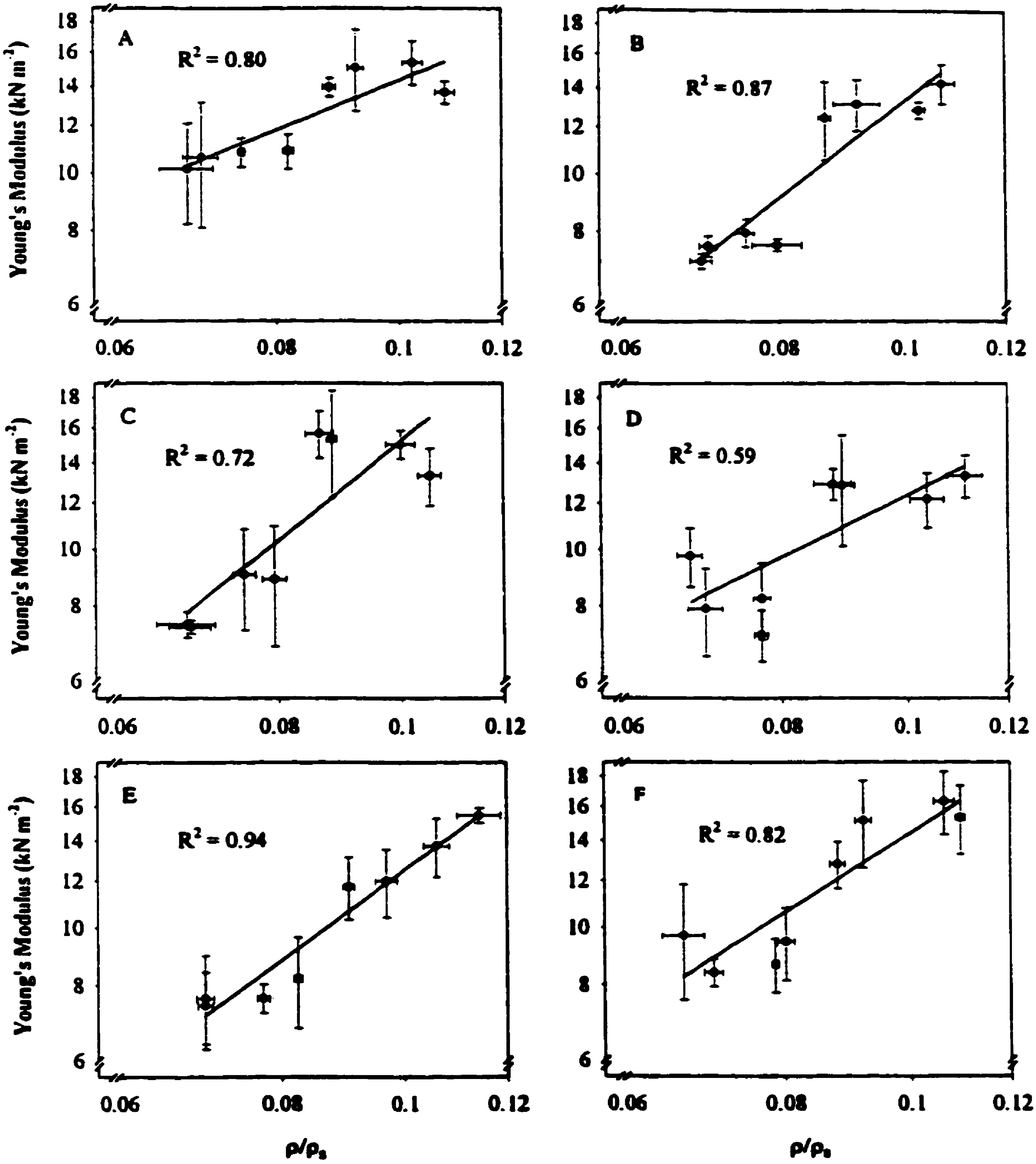
Where E_s (in kN m^{-2}) is the modulus of the cell walls, ρ (in g cm^{-3}) is the density of the bread crumb sample, and ρ_s (in g cm^{-3}) is the density of cell walls (or solid density). The

Table 25. Means and Standard Deviations of Loaf Characteristics and Solid Density of CWRS Bread Crumb as a Function of Proof Time.

Proof Time (min):	30	55	80
Loaf Volume (cm^3)	740 ±0	970 ±0	1090 ±14
Loaf Weight (g)	140.2 ±0.4	136.3 ±0.2	133.9±0.8
Loaf Density ($g\ cm^{-3}$)	0.189±.001	0.141±.029	0.123±.024
Solid Density ($g\ cm^{-3}$)	1.430±.014	1.542±.029	1.624±.024

Loaf density = loaf weight/loaf volume.

Figure 15. Changes in Young's modulus as a function of relative density for CWRS (A), CWES (C), CPS (E), and Blend (F) breads prepared with 60% water absorption, and for CWRS (B) and CWES (D) breads prepared with optimum water absorption.


A
R² = 0.80
B
R² = 0.87
C
R² = 0.72
D
R² = 0.59
E
R² = 0.94
F
R² = 0.82
Young's Modulus (kN m⁻²)
18
16
14
12
10
8
6
0.06
0.08
0.1
0.12
ρ/ρs

values of E_s are obtained by interpolation of the curves of *log* (E) versus *log* (ρ/ρ_s) shown in Fig. 15 to the intercept at $\rho/\rho_s = 1$, and n is the slope. Since bread crumb mainly has an open cellular structure (Gan et al 1990; van Vliet et al 1992; Keetels et al 1996b), the theoretical n value which should be obtained would be 2 (Gibson and Ashby 1997). The n, E_s, and R^2 values as a function of flour type and water absorption showed considerable variation (Table 26). The n values of bread crumb samples ranged from 0.98 to 1.75, while the E_s values ranged from 132 to 851 kN m^{-2}. The n values were less than the theoretical value, but were comparable to the results reported by Hutchinson et al (1987) and Shogren et al (1998) for extruded maize and baked starch foams, respectively. Since the variation in relative density was caused mainly by proof time, one would expect n values to be greater than 2. This is because as PT is extended, a crumb with a coarser grain and possibly missing cell walls (structural defects) is obtained as a result of gas cells coalescence (Kamman 1970; Pyler 1988). In addition to decreasing bulk density, the size of the defects (e.g. absence or broken cell walls as a result of cell rupture) is likely to increase with increasing PT. Therefore, one would anticipate that the Young's modulus would markedly decrease with increasing PT or decreasing relative density (Silva et al 1995) and therefore, the slope n of *log* (E) versus *log* (ρ/ρ_s) would be higher than 2, the theoretical value. However, the results of this study run counter to expectation since n values were lower than the theoretical value. This in turn suggested that the overall mechanical properties of the cell walls of bread crumb became stiffer with increasing PT and decreasing relative density. This finding is in line with the conclusion of van Vliet (1992) and co-workers who indicated that strain hardening occurred in dough cell walls or films as they were stretched as a result of increasing proof time.

Table 26. Relationships Between Relative Density and Mechanical Properties of Bread Crumb as a Function of Flour Type and Water Absorption.

		Log(E) vs. Log(ρ/ρ_s)			Log(σ_f) vs. Log(ρ/ρ_s)		
Flour	WA (%)	n	E_s	R^2	M	σ_s	R^2
CWRS	60	0.98	132	0.80	0.54	8.9	0.76
CWES	60	1.75	851	0.72	1.16	40.7	0.61
CPS	60	1.58	468	0.94	0.96	14.5	0.90
Blend	60	1.40	355	0.82	0.66	9.8	0.92
CWRS	65	1.71	676	0.87	1.16	33.9	0.89
CWES	63	1.11	158	0.59	0.47	7.1	0.55

WA, water absorption; E, Young's modulus of bread crumb (kN m^{-2}); ρ, bulk density of bread crumb (g cm^{-3}); ρ_s, solid density (g cm^{-3}); n, power index obtained for the equation $E/E_s \propto (\rho/\rho_s)^n$, E_s, modulus of the cell walls materials (kN m^{-2}); σ_f, fracture stress of bread crumb (kN m^{-2}); σ_s, fracture stress of cell walls (kN m^{-2}); m, power index obtained for the equation $\sigma_f/\sigma_s \propto (\rho/\rho_s)^m$.

This increase in the mechanical strength of the cell walls with PT further supports the earlier discussion (3.3.2.1) for explaining the mechanical behavior of bread crumb as a function of flour type and PT. For the Young's modulus of cell walls (E_s), the values obtained are of a reasonable magnitude, but they showed large variation between different flour types and WA. The wide variation in n and E_s values as a function of flour type and water absorption could be attributed to two factors which were not quantified in this study: 1) differences in the solid density of bread crumb and its impact on Young's modulus of the cell walls (Warburton et al 1990; Donald 1994); 2) variation in the defect size (Silva et al 1995) in crumb structure resulting from different flours responding to PT differently (Dobraszczyk and Roberts 1994). However, this would require further study.

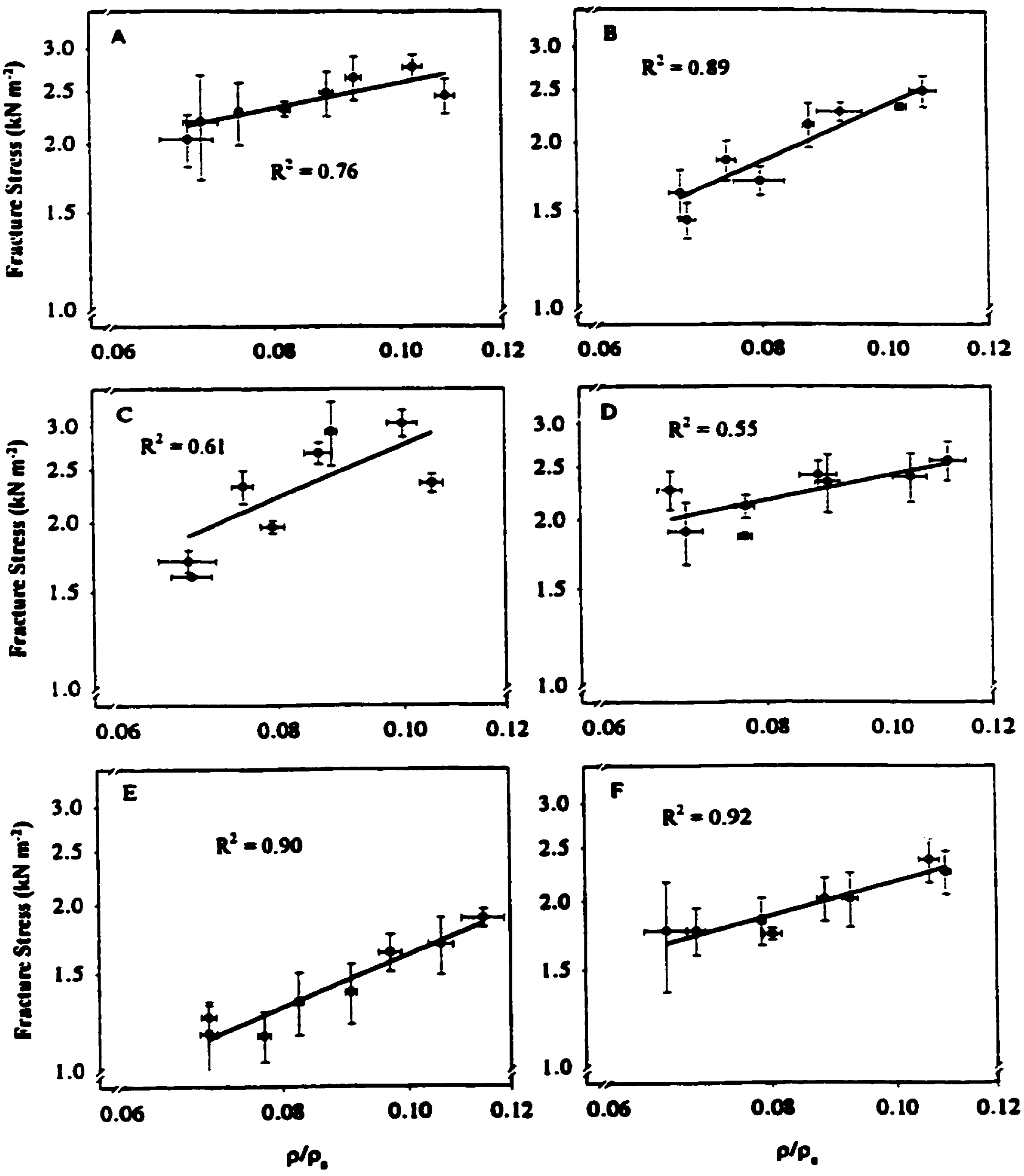
4.3.2.3. Fracture Stress Versus Relative Density

Figure 16 shows the fracture stress plotted against relative density of bread crumb (σ_f, kN m^{-2}) on a double-log scale to fit the data to a power law equation of the following form (Gibson and Ashby 1997):

$$\sigma_f = \sigma_s \ (\rho/\rho_s)^m \tag{12}$$

Where σ_s (in kN m^{-2}) is the fracture stress of the cell wall materials, ρ (in g cm^{-3}) is the density of the bread crumb sample, and ρ_s (in g cm^{-3}) is the density of cell wall materials. The values of σ_s are obtained by interpolation to the intercept at $\rho/\rho_s = 1$ from the curves of $log\ (\sigma_f)$ versus $log\ (\rho/\rho_s)$ shown in Fig. 16, and m is the slope. Table 26 shows the power index m, σ_s and R^2 values as a function of flour type and water absorption. The m values of bread crumb samples ranged from 0.47 to 1.16, while the σ_s values ranged from 7.1 to 40.7 kN m^{-2}. As was the case for Young's modulus, the m values were much lower than the theoretical value for open-cell structures which should equal 1.5 (Gibson and

Figure 16. Changes in fracture stress as a function of relative density for CWRS (A), CWES (C), CPS (E), and Blend (F) breads prepared with 60% water absorption, and for CWRS (B) and CWES (D) breads baked at optimum water absorption.


A
R² = 0.76
B
R² = 0.89
C
R² = 0.61
D
R² = 0.55
E
R² = 0.90
F
R² = 0.92
Fracture Stress (kN m⁻²)
1.0
1.5
2.0
2.5
3.0
0.06
0.08
0.10
0.12
ρ/ρₛ

Ashby 1997). These m and σ_s values were very consistent with the n and E_s values observed for the Young's modulus, respectively (R^2 were 0.90 and 0.81 between m and n, and between E_s and σ_s, respectively). These high correlation coefficients indicated that Young's modulus and fracture stress of bread crumb are strongly related properties which are affected by the changes in relative density in a similar manner. This also confirmed the relationship between Young's modulus and fracture stress which was determined earlier by correlation analysis (4.3.1). By following the same reasoning that was used for the Young's modulus, the low m values compared to the theoretical suggested that the fracture stress of cell wall materials of bread crumb increased with increasing PT as a result of strain hardening. The observed level of variation in the power indices m and fracture stress of cell walls σ_s were similar to that of n and E_s observed for the Young modulus (discussed above).

4.3.3. Prediction Models of Mechanical Properties of Bread Crumb

The correlation coefficients that were presented in Tables 19-24 suggested that structural parameters can be used to explain the variation observed in the mechanical properties of bread crumb. Despite the high correlation coefficients between mechanical and structural parameters (e.g., density and crumb brightness), the lack of consistency in the correlation coefficients among different flour samples and WA limited the usefulness of these individual structural parameters for predicting the changes in the mechanical properties of bread crumb. Therefore, the relationship between structural and mechanical properties was further examined using stepwise multiple linear regression analysis to generate models consisting of more than one structural parameter that would consistently estimate the mechanical properties of bread crumb. In the regression modeling, the mechanical properties, including Young's modulus, fracture stress, fracture strain and fracture energy were used as dependent variables, while density, void fraction, crumb brightness, CWT, cells/cm^2, MCA and SLCC were used as independent variables. Regression models containing up to three independent variables were examined.

None of the regression models permitted an accurate and consistent prediction of fracture strain and energy. These results were not surprising since it was previously pointed out (4.3.1) that fracture strain and fracture energy are mainly dependent on the mechanical properties of the cell walls which are in turn influenced by the formulation such as flour strength (protein quality) and WA and not on crumb structure.

Since Young's modulus and fracture stress are strongly related and were affected by the structural parameters in a similar manner, their relationships to structural properties will be discussed simultaneously. Crumb brightness and crumb density (separately) explained 61 to 95% of the variation in Young's modulus (from Tables 19-24). These two parameters (separately) also explained 53 to 93% of the variation in fracture strength. However, as mentioned above, neither density nor crumb brightness alone can be used to predict the modulus and the fracture stress of bread crumb because of the lack of consistency in R^2 values.

The best two-variable model, which contained both density and crumb brightness, resulted in a 0 to 8% increase in the prediction of the Young's modulus and fracture strength (see Tables 27 and 28). The coefficients of correlation ranged between 0.70 and 0.96 for the Young's modulus, and 0.74 to 0.97 for fracture stress. Despite the significant improvement in the predictive capacity of this two-variable model, it still suffered lack of

Table 27. Coefficients of Correlation Between Young's Modulus (kN m^{-3}) of Bread Crumb and a Two-Variable Model (Density and Crumb Brightness) as a Function of Flour Type and Water Absorption.

Flour	WA (%)	Crumb Density	Crumb Brightness	Two-Variable Model
CWRS	60	0.72	0.73	0.81
CWES	60	0.86	0.85	0.88
CPS	60	0.64	0.79	0.81
Blend	60	0.61	0.65	0.70
CWRS	65	0.95	0.82	0.96
CWES	63	0.82	0.85	0.86

Table 28. Coefficients of Correlation Between Fracture Stress (kN m^{-3}) of Bread Crumb and a Two-Variable Model (Density and Crumb Brightness) as a Function of Flour Type and Water Absorption.

Flour	WA (%)	Crumb Density	Crumb Brightness	Two-Variable Model
CWRS	60	0.66	0.83	0.86
CWES	60	0.89	0.90	0.93
CPS	60	0.54	0.73	0.74
Blend	60	0.59	0.80	0.81
CWRS	65	0.93	0.75	0.97
CWES	63	0.89	0.79	0.89

consistency (wide range of R^2, depending on flour type and WA). Therefore, three-variable models were also examined to obtain a better prediction of the Young's modulus and fracture stress. The selected three-variable models (as a function of flour type and WA) containing crumb density, crumb brightness, and SLCC resulted in up to 15% improvement in the predictive capacity of the Young's modulus (R^2 ranged from 0.76 to 0.97) and the fracture stress (R^2 ranged from 0.86 to 0.97). Figures 17 and 18 show predicted versus measured Young's modulus and fracture stress, respectively, for various flour types and WA. These models provided a good representation of the structural properties of bread crumb and indicated that Young's modulus and fracture stress can be predicted by a combination of structural features. For the different flour samples and WA, the density and crumb brightness generally had positive coefficients, while SLCC generally had a negative coefficient (Tables 29 and 30).

The rationale for density, crumb brightness, and SLCC being predictors of the Young's modulus and fracture stress is based on the following theory: higher density, smaller cell size, thinner cell wall, and narrower cell size distribution (uniformity) lead to greater mechanical strength (Kamman 1970; Pyler 1988; Gibson and Ashby 1997; Shogren 1998). Density is one of the most important structural parameters that contributes to the mechanical strength of cellular food materials such as bread crumb (Ponte et al 1962; Wassermann 1979), sponge cake (Attenburrow et al 1989), extruded corn meal (Barrett et al 1994) and baked starch foams (Shogren et al 1998). However, for crumb samples having the same density but different structure, the variation in strength and the modulus would depend on structural differences. Therefore, crumb brightness and SLCC were incorporated in the models to account for the variations in mechanical

Figure 17. Predicted versus measured Young's modulus for CWRS (A), CWES (C), CPS (E), and Blend (F) breads prepared with 60% water absorption, and for CWRS (B) and CWES (D) breads prepared with optimum water absorption.

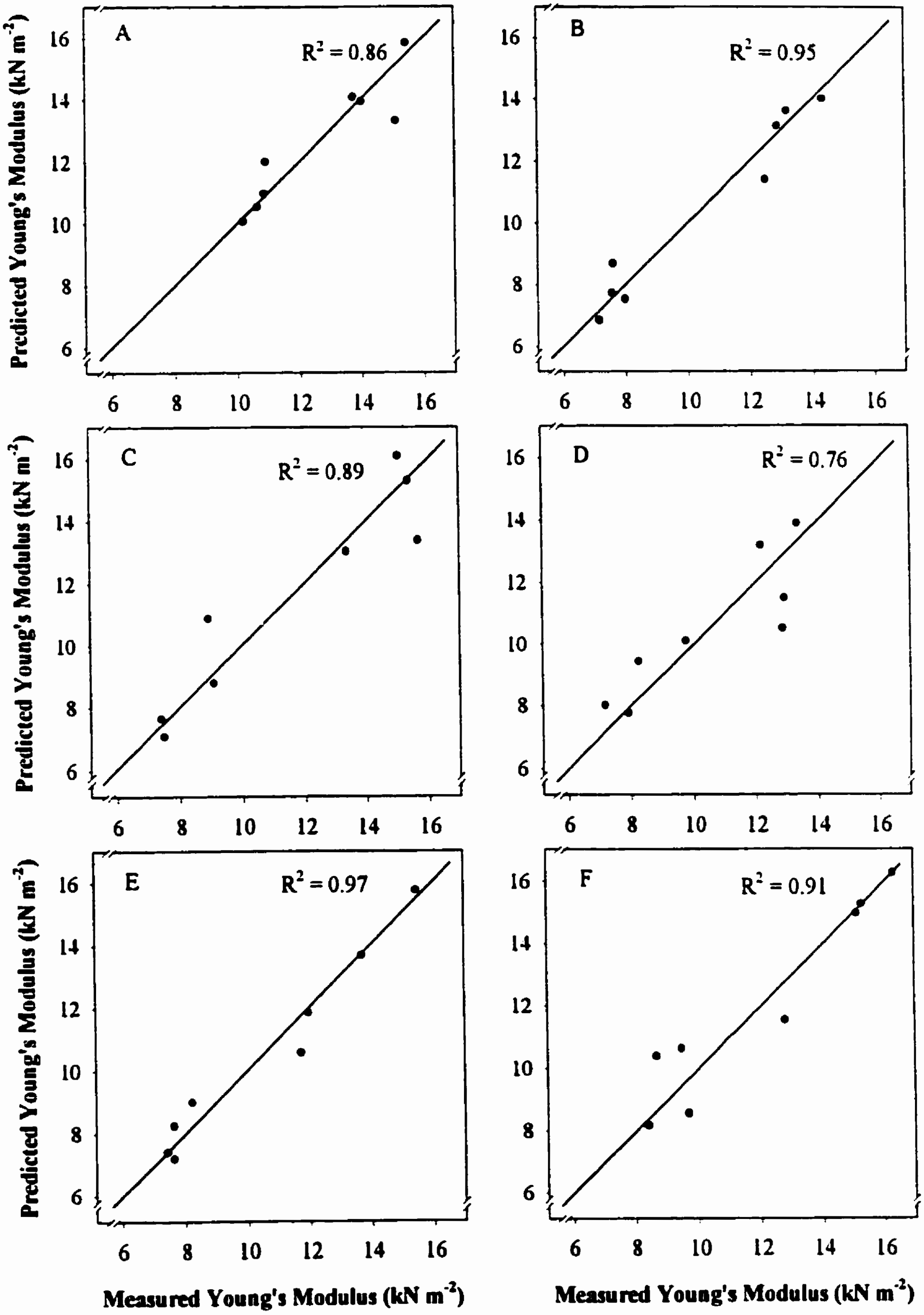

A
$R^2 = 0.86$
B
$R^2 = 0.95$
C
$R^2 = 0.89$
D
$R^2 = 0.76$
E
$R^2 = 0.97$
F
$R^2 = 0.91$
Predicted Young's Modulus (kN m^{-2})
Measured Young's Modulus (kN m^{-2})
6
8
10
12
14
16

Figure 18. Predicted versus measured fracture stress for CWRS (A), CWES (C), CPS (E), and Blend (F) breads prepared with 60% water absorption, and for CWRS (B) and CWES (D) breads prepared with optimum water absorption.

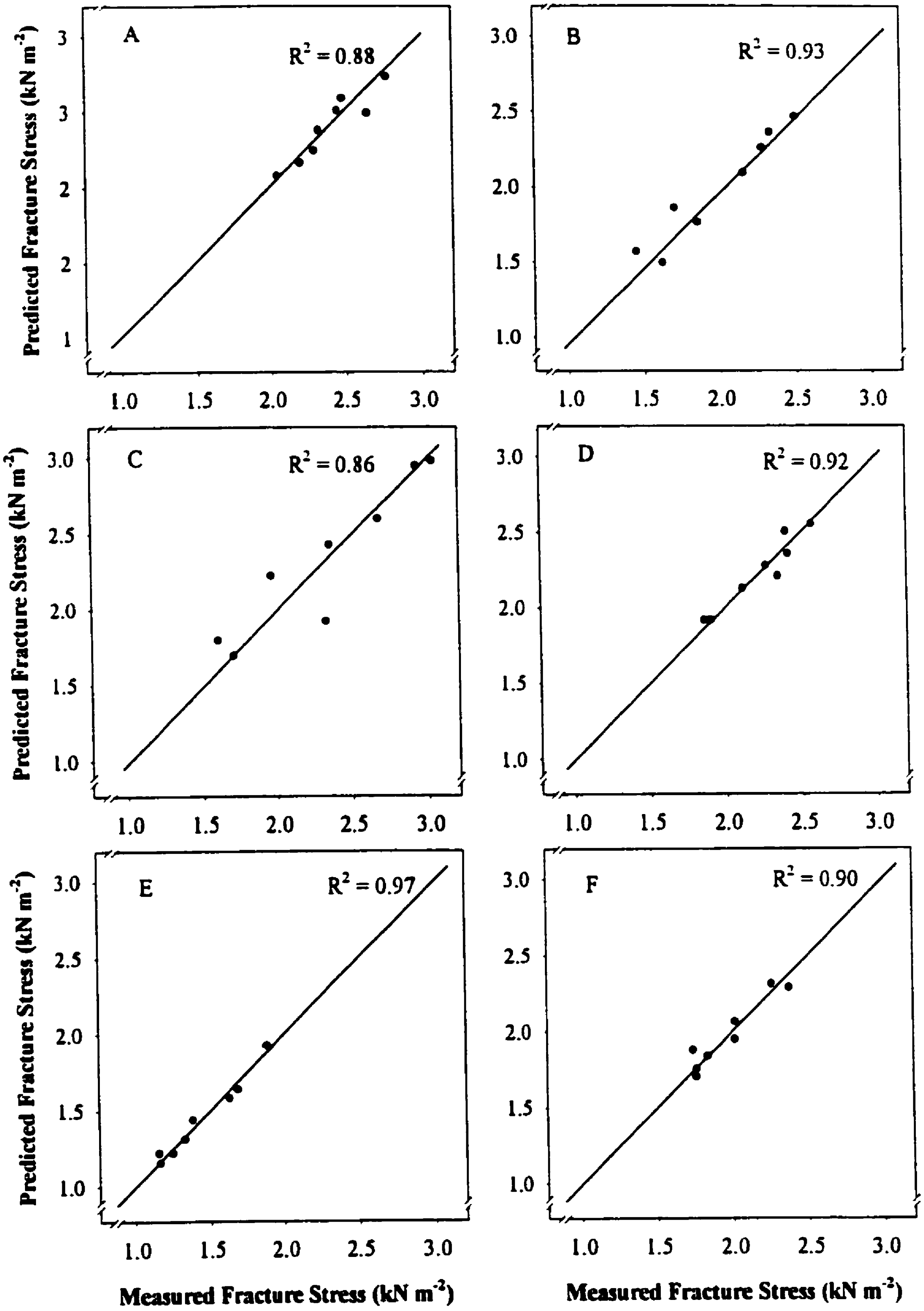

A
R² = 0.88
B
R² = 0.93
C
R² = 0.86
D
R² = 0.92
E
R² = 0.97
F
R² = 0.90
Predicted Fracture Stress (kN m⁻²)
Predicted Fracture Stress (kN m⁻²)
Predicted Fracture Stress (kN m⁻²)
3
3
2
2
1
3.0
2.5
2.0
1.5
1.0
1.0
1.5
2.0
2.5
3.0
Measured Fracture Stress (kN m⁻²)
Measured Fracture Stress (kN m⁻²)

Table 29. Coefficients for the Three-Variable Models Used to Predict Young's Modulus (kN m^{-2}) of Bread Crumb.

Flour	WA (%)	Intercept	Density (g cm^{-3})	Crumb Brightness	SLCC	R^2	P > F
CWRS	60	-34.16	95.39	0.217	-0.154	0.86	0.036
CWRS	65	-49.15	56.05	0.349	-0.317	0.95	0.004
CWES	60	-0.13	282.98	-0.044	-0.415	0.89	0.022
CWES	63	-85.04	43.38	0.542	-0.181	0.76	0.102
CPS	60	12.77	160.60	-0.121	-0.058	0.97	0.003
Blend	60	-49.60	80.26	0.345	-0.365	0.91	0.016

WA, water absorption; SLCC, small-to-large cell count.

Table 30. Coefficients for the Three-Variable Models Used to Predict Fracture Stress (kN m^{-2}) of Bread Crumb.

Flour	WA (%)	Intercept	Density (g cm^{-3})	Crumb Brightness	SLCC	R^2	P > F
CWRS	60	-5.34	6.37	0.040	-0.011	0.88	0.026
CWRS	65	-5.47	7.25	0.037	-0.008	0.93	0.009
CWES	60	2.57	46.78	-0.017	-0.075	0.86	0.035
CWES	63	-11.32	2.09	0.080	-0.026	0.92	0.012
CPS	60	4.71	17.08	-0.032	0.010	0.97	0.003
Blend	60	2.04	11.98	-0.007	-0.011	0.90	0.018

WA, water absorption; SLCC, small-to-large cell count.

strength that are associated with the changes in structural features. Crumb brightness was shown to be strongly related to the cellular structure of bread crumb (Tables 19-24). Burhans and Clapp (1942) indicated that the brightness of bread crumb is increased by the presence of a large number of small gas cells. In a recent publication, van Vliet et al (1992) pointed out that the whiteness of bread crumb is enhanced by the tiny gas cells which might not be visible to the naked eye. In this study, crumb brightness was found to be negatively correlated with CWT (R = –0.65 to –0.92) and MCA (R = -0.84 to –0.95) and positively correlated with the number of cells/cm^2 (R = 0.75 to 0.93). Therefore, it is evident that crumb brightness provides a good measure of the fineness of crumb cellular structure with higher crumb brightness values meaning finer crumb structure. On the other hand, SLCC, which was considered by Sapirstein et al (1994) as a measure of uniformity of the cellular structure may also reflect cell size distribution. Generally, the higher the SLCC the more uniform the crumb structure. The incorporation of SLCC in the model would appear to be a statistical correction factor. This is because lower SLCC values usually indicate the presence of structural defects such as broken or missing cell walls as a result of cell coalescence. Since these structural defects are known to degrade the mechanical strength of cellular materials (Silva et al 1995; Gibson and Ashby 1997), the negative coefficients for SLCC in the predicting models would run counter to expectation.

4.4. CONCLUSIONS

In this study, the relationship between structural and mechanical properties of bread crumb was assessed to determine the influence of crumb structure on the mechanical properties of bread crumb. Four types of flour with a wide range of inherent strength, two levels of water absorption, two sheeting treatments, and four proof times were used to create differences in the structural and mechanical properties of bread crumb. Both Young's modulus and fracture strength were found to be dependent on the cellular structure of bread crumb and the mechanical properties of the cell walls, with density and crumb brightness (separately) being the most highly correlated parameters. Young's modulus and fracture stress were successfully fitted to the power law theory of Gibson and Ashby (1997). However, the power indices were found to be lower than the theoretical values suggesting that with increasing proof time, the mechanical properties of the cell walls have improved as a result of strain hardening. A three-variable model containing density, crumb brightness, and SLCC permitted an accurate prediction of Young's modulus and fracture strength, with R^2 being higher than 0.76 and 0.86, respectively. Fracture strain and energy to fracture were not dependent on the structural parameters of bread crumb and appeared to be influenced by the properties of the cell wall materials. It was concluded therefore, that the mechanical properties are dependent on the structural properties and the mechanical properties of bread crumb as they are affected by bread ingredients and processing conditions.

5. General Discussion

One of the most important objectives of processing of cereal foods is to produce products with desirable physical and visual texture. Many of the resulting foods, e.g., bread, cakes, and extruded products, have a porous or cellular structure which consists of an interconnected network of solid struts or plates that form the edges and faces of the air cells (Gibson and Ashby 1997). Since the physical texture of such products is a key factor for their acceptance, identifying and understanding the elements that affect texture, have been a research focus for many food scientists (Wassermann 1979; Attenburrow et al 1989; Warburton et al 1992; Barrett et al 1994; Keetels et al 1996b; Shogren et al 1998). For synthetic cellular materials, Gibson and Ashby (1997) clearly showed that mechanical properties are dependent on cellular structure. They pointed out that relative density, cell shape, cell size, cell wall thickness (CWT), and distributions of cell size and CWT have a strong effect on the mechanical strength of cellular solids. For bread crumb, the mechanical properties were also found to be strongly related to its density (Ponte et al 1964; Wassermann 1979). Some researchers have speculated that other structural properties of bread crumb (i.e. cell size, grain uniformity, cell wall thickness) influence its mechanical properties (Kamman 1970; Pyler 1988), but this has not been studied yet.

5.1 Relationship Between Crumb Density and Crumb Grain Features

Crumb density is considered a quality factor in breadmaking since it is strongly related to loaf volume (Wassermann 1979), which is the primary criterion in scoring bread loaves (Pyler 1988). Besides its strong relationship with mechanical properties, crumb density is expected to be related to the structure of bread crumb on the basis that surface density of a bread slice (the proportion of cell wall material at the surface to total surface area) should be a good representation of its volume density (proportion of material's volume to total volume) (Underwood 1970). Assuming that cell wall density is invariant and the density of air equals zero, the volume density of cellular material in general is equivalent to its actual density (mass/unit volume). Therefore, it was conceivable that digital image analysis (DIA) could be used to predict crumb density because DIA measures crumb grain features based on identifying gas cells and cell walls in a given image of bread crumb (Sapirstein et al 1994). Since crumb density can be accurately and easily measured, its prediction from the computed crumb grain features was used as a means of assessing the accuracy of DIA for quantifying the structural parameters of bread crumb. The crumb density showed a high correlation with both crumb brightness and void fraction, but there was a variation in R^2 values depending on bread type. Other crumb grain features correlated with density to a lesser extent. Stepwise linear regression analysis was used to find a model containing structural parameters that consistently predicted the changes in the density of bread crumb. A two-variable model (shown below) comprising the void fraction and CWT permitted a good prediction of the density of the CWRS and CPS bread samples ($R^2 = 0.80$).

$$Density\ (g\ cm^{-3}) = 1.08 - (1.62 * VF) - (1.59 * CWT) \qquad \text{(Equation 10, 2.3.5)}$$

In the density-prediction model, the void fraction and CWT had negative coefficients. Surface density, which theoretically corresponds to $1 - VF$, is the basis of the prediction model. The coefficient 1.62 represents a correction factor for the underestimation of the void fraction (see Appendix II). CWT appeared to be a predictor of density on the grounds that it may account for the undetected intramural cells located in the cell walls (Burhans and Clapp 1942). In addition, CWT represents the materials surrounding the gas cells whose density seemed to change with processing conditions (Donald 1994).

The results of the dried bread samples indicated that both structural parameters and density changed with moisture loss. Upon drying, the density, crumb brightness, and number of cells/cm^2 increased, whereas, void fraction, CWT, and average cell area decreased. The relationships between crumb density and various crumb grain features were similar to those observed for fresh bread samples. In addition, the same two-variable model (Equation 10, 2.3.5) containing the void fraction and CWT allowed good prediction of the density of dried bread ($0.79 \leq R^2 \leq 0.82$, depending on drying time and flour type). These results further confirmed the robustness of the model in predicting crumb density, and clearly indicated that DIA accurately measured crumb grain features.

The model for predicting density was also tested on the bread of the second study, where samples (110 x 40 mm) were prepared using different formulations and processing conditions (3.2). The coefficient of determination (R^2) between measured and predicted density was 0.72. The reason for the relatively poorer relationship with these breads was attributed to the differences in dimensions of the bread samples in relation to that of the imaging field of view (FOV). In the first study, the samples' length-to-width ratio (80:60 or 1.33:1) was almost equal to that of the FOV (45:35 or 1.29:1), while in the second study, the samples' length-to-width ratio (110:40 or 2.75:1) was more than double that of FOV. Because of the significant variation in crumb density across a bread slice (Ponte et al 1962), the bread images gave a better representation of the grain features of the bread sample in the first study, and therefore, allowed a better prediction of the crumb density.

5.2 Relationship Between Structural and Mechanical Properties of Bread Crumb

The mechanical properties of cellular materials, including bread crumb, are affected by the mechanical properties of its cell walls (Gibson and Ashby 1997). If bread samples have cell walls with the same properties, then differences in their mechanical properties would be solely dependent on the differences in the structure (i.e. density and grain features). In this study, by varying flour type and water absorption (WA), the properties of the cell walls in bread were affected (3.3.2.1.1 and 3.3.2.3). Therefore, the relationship between structural and mechanical properties of bread crumb was examined for each flour type and WA separately, in order to eliminate their effects on the properties of cell walls. The variation in the structural properties of bread crumb was mainly achieved by varying proof time (PT).

Results showed that the structural properties only affected fracture stress and Young's modulus, but not fracture strain or energy to fracture. Crumb density, crumb brightness and void fraction were the most highly correlated parameter to Young's modulus and fracture stress, while the other grain features correlated with these two mechanical properties to a lesser extent. It was generally found that fracture stress and Young's modulus increased with increasing density, crumb brightness, cells/cm^2, and SLCC, and decreasing MCA, VF and CWT. These results were in good agreement with the theoretical and experimental results for synthetic materials having porous structure (Gibson and Ashby 1997) and for baked starch foams (Shogren et al 1998).

The power law theory relating both Young's modulus and fracture stress to relative density was applied to bread crumb. The cell wall density value of 1.532 g cm^{-3}

was used to calculate the relative density in order to obtain estimates of the Young's modulus (E_s) and fracture stress (σ_s) of the cell walls (the intercept at $\rho/\rho_s=1$, obtained from plots of log (E) versus log (ρ/ρ_s) and log (σ_f) versus log (ρ/ρ_s), respectively). Young's modulus and fracture stress of bread crumb were generally well fitted to the power law models (Equations 11 and 12). However, the power indices showed a large variation and were considerably lower than the theoretical values for industrial cellular solids based on regular foam structure. The low values of the power indices mean that the overall mechanical strength and stiffness of bread crumb decreased with decreasing relative density (as a result of increasing PT) at a lower rate than expected. Provided that the mechanical properties of cellular materials are a function of relative density and the mechanical properties of the cell walls (Gibson and Ashby 1997), it is reasonable to speculate that in the bread the mechanical strength and stiffness of the cell walls themselves were enhanced by increasing proof time. This speculation is supported by the fact that cell wall density of bread crumb increased with increasing PT. The increase in cell wall density can be explained by two mechanisms. Firstly, the number of intramural cells in dough may have ruptured and become part of larger cells (no longer part of the cell walls) as the dough's cell walls were stretched, thus reducing the volume of cell walls in the resulting bread. Secondly, molecular orientation and alignment of protein polymer chains may have led to stretching of the cell walls of the dough (van Vliet et al 1992), explaining the higher strength and lower volume of the cell walls of the bread crumb. The second explanation, which is known to cause the strain hardening phenomenon that occurs in dough cell walls upon extension (van Vliet et al 1992; Dobraszczyk and Roberts 1994), appears to be predominant. The calculated values of the

Young's modulus and fracture stress of bread crumb cell walls were 132-851 and 7.1-40.7 kN m^{-2}, respectively. Although these values showed an unexplained large variation (depending on flour type and WA), they were of a reasonable magnitude when compared to experiments on compressed bread crumb (Scanlon et al, unpublished results). It should be noted however, that the density of the whole bread sample (110 x 40 mm) was used in the analysis, while the mechanical properties were only measured from the central portion of the bread specimen (30 x 10 mm). This may have introduced some discrepancy in the results since the crumb density varies across the bread slice (Ponte et al 1962).

Stepwise linear regression analysis was used to obtain a model that accurately and consistently predicted various mechanical properties on the basis of structural parameters, which included density and crumb grain features. A three-variable model comprising crumb density, crumb brightness and SLCC permitted the prediction of Young's modulus and fracture strength. Depending on types of flour and WA, R^2 values ranged from 0.76 to 0.97 and from 0.86 to 0.94, respectively. The relationship between predicted versus measured Young's modulus and fracture stress for all data combined is shown in Figures 19 and 20, and can be seen to be very strong (R^2 values were 0.90 and 0.95, respectively). These results indicated that both Young's modulus and fracture stress of bread crumb can be accurately predicted from three elements of its structure. The reasons the model contains density, crumb brightness and SLCC as predictors of Young's modulus and fracture stress are as follows: density is known to contribute to the mechanical strength of

Figure 19. Relationship between measured and predicted Young's modulus of bread crumb samples prepared using different types of flour and water absorptions.

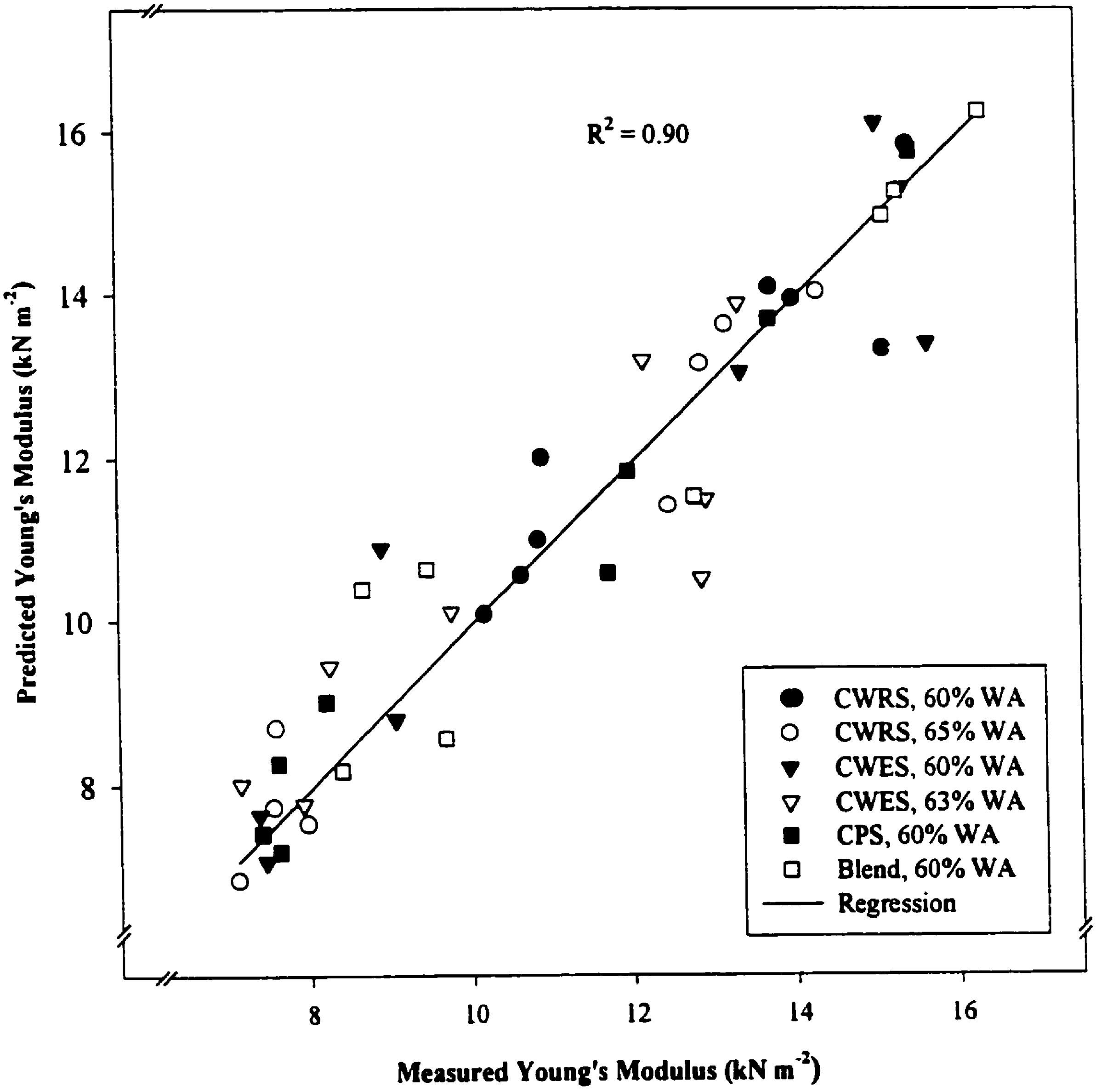
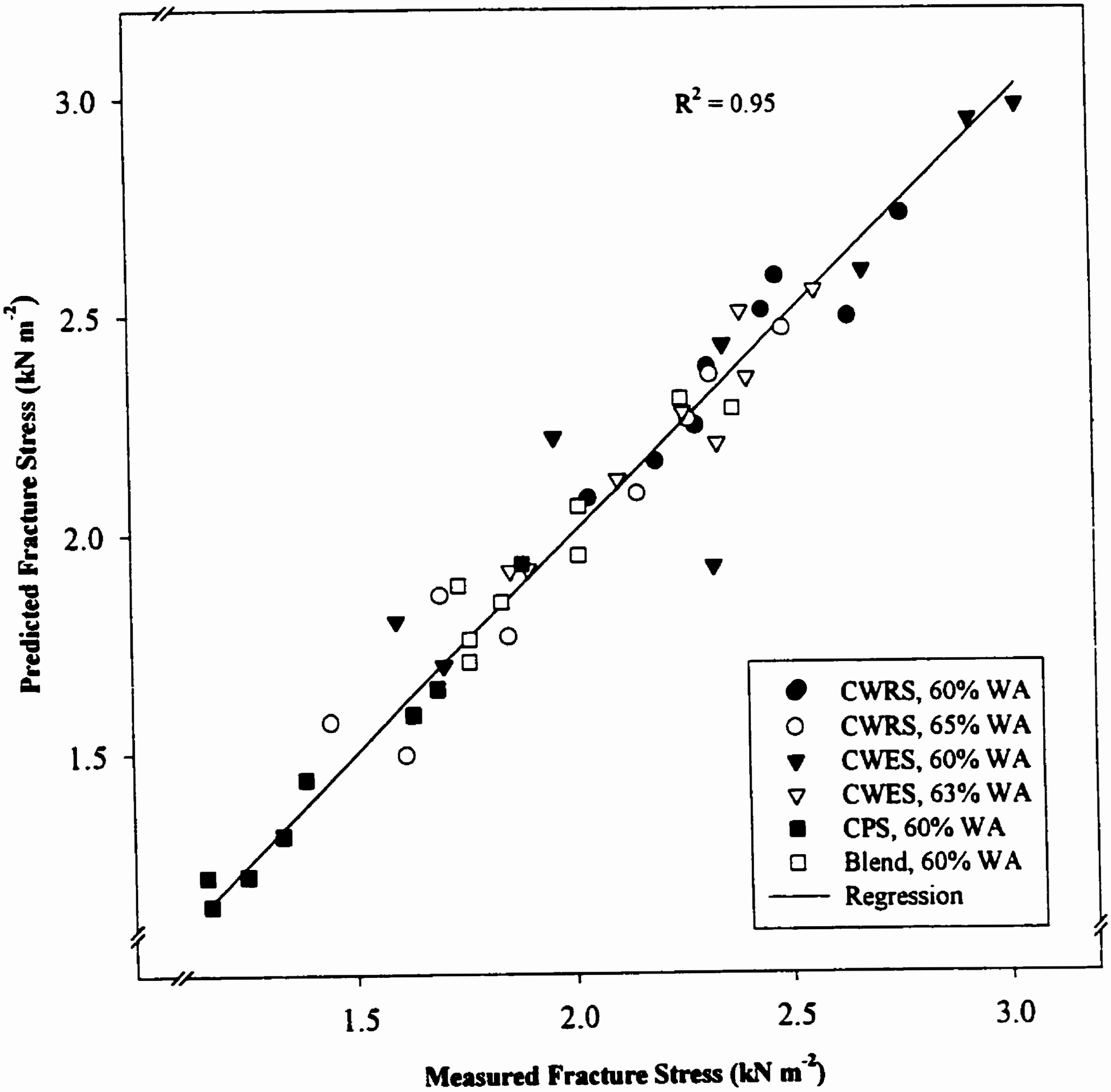

R² = 0.90
16
14
12
10
8
8
10
12
14
16
Predicted Young's Modulus (kN m⁻²)
Measured Young's Modulus (kN m⁻²)
● CWRS, 60% WA
○ CWRS, 65% WA
▼ CWES, 60% WA
▽ CWES, 63% WA
■ CPS, 60% WA
□ Blend, 60% WA
Regression

Figure 20. Relationship between measured and predicted fracture stress of bread crumb samples prepared using different types of flour and water absorptions.


R^2 = 0.95
3.0
2.5
2.0
1.5
Predicted Fracture Stress (kN m^{-2})
1.5
2.0
2.5
3.0
Measured Fracture Stress (kN m^{-2})
● CWRS, 60% WA
○ CWRS, 65% WA
▼ CWES, 60% WA
▽ CWES, 63% WA
■ CPS, 60% WA
□ Blend, 60% WA
— Regression

bread crumb (Ponte et al 1962; Wassermann 1979); crumb brightness and SLCC were incorporated in the model to account for the way that bread materials are distributed within the crumb structure, since cellular material having the same density but different grain features is expected to have different mechanical strength and stiffness. Crumb brightness is a measure of crumb fineness, since it increases with increasing number of small cells (Burhans and Clapp 1942; Kamman 1970). In addition, the results of this study showed that bread crumb with lower MCA, CWT, and higher number of cells/cm^2 has brighter appearance. The lower MCA, thinner cell walls, and higher number of cells/cm^2 in turn contribute to greater mechanical strength (Shogren et al 1998). SLCC, on the other hand, was considered a measure of crumb uniformity (Sapirstein et al 1994), and the higher the values the more uniform the crumb. SLCC is therefore expected to reflect structural defects in the bread crumb, since low values are normally associated with a high degree of coalescence (gas cell rupture). The latter is known to have a detrimental effect on the overall mechanical properties of cellular materials (Silva et al 1995; Silva and Gibson 1997) including those of bread crumb.

It was concluded from this study that the overall mechanical properties of bread crumb are dependent on the crumb structure and the mechanical properties of the cell walls as they are influenced by bread ingredients and processing conditions. DIA can therefore be used to predict the mechanical properties of the bread crumb from quantitative measurements of its structure as affected by the processing conditions only.

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APPENDICES

LIST OF FIGURES

LIST OF TABLES

APPENDIX I

Mean Cell Area: Observed Versus Actual

The cell area obtained by DIA on the basis of the examined surface of bread crumb is underestimated. Regardless of whether a given gas cell (spherical shape) is sectioned below or above its center, the resulting cross sectional area is smaller than the cross sectional area passing through the center (center of sphere). Therefore, in order to determine the degree of underestimation, the average of all possible cross sectional areas passing through the gas cell should be computed and compared to the cross sectional area which passes through the center.

Assumptions:

- gas cells have a uniform size distribution and are spherical in shape with a radius R giving a circular cell of radius r at the surface of the bread slice, where $r = (R^2 - x^2)^{1/2}$; x = distance from the center of the spherical cell to the surface of the slice, with $-R \leq x \leq R$ (see figure 1).
- during bread slicing, the spherical cells are randomly sectioned at a distance x from their centers.
- the sectioned cells are representative of the population of cells in a given slice, since the number of cells observed at the surface of a bread slice ranged from 1017 to 3850.

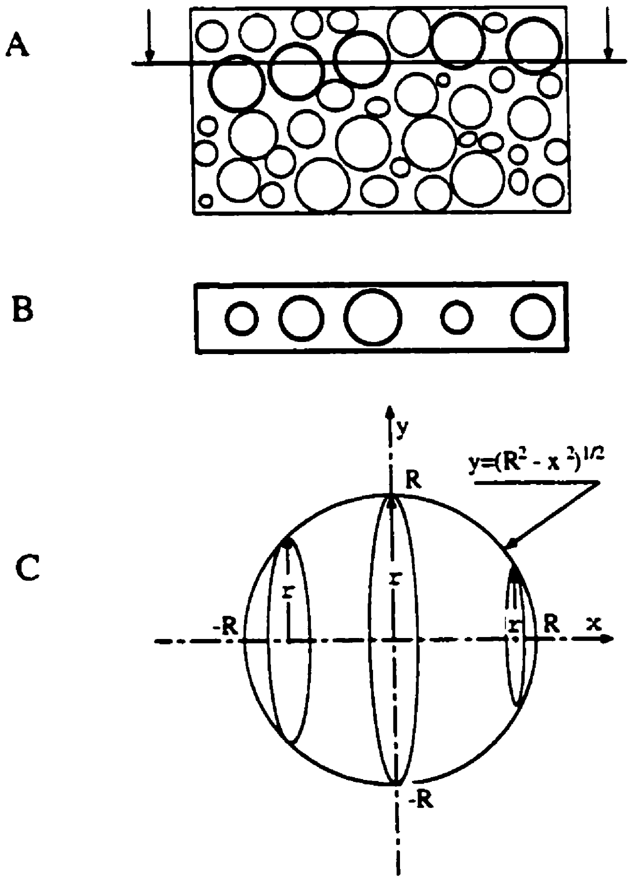
The average gas cell area of radius r, sectioned at a distance x from the center plane is described by the function $A_{ave}(x)$:

$$A_{ave}(x) = \frac{1}{2R} \int_{-R}^{R} \pi(R^2 - x^2)\,dx$$

$$A_{ave}(x) = \frac{2}{3}\pi R^2$$

Therefore, on average, the cell area observed at the surface of the bread slice represents 66% of the cross sectional area at the center of the sphere.

Figure 1. Schematic representation of bread structure (A) sectioned as indicated with arrows, cross-sectional area of sectioned cells (B), and model of individual cell sectioned at 3 different locations, producing different radii r (C). The equation shown calculates the radius r as a function of x, distance from the center of the sphere, and the radius (R) of the sphere itself.


A
B
C
y
y=(R² - x²)^1/2
R
r
r
r
-R
R
x
-R

APPENDIX II

Void Fraction: Observed Versus Actual

Depending on whether the spherical (assumed) gas cells of radius R are sectioned above or below their centers, the exposed cell volume based on cell size observed at the surface of the bread slice could be under- or over-estimated (Fig 2). This problem arises from the two dimensional nature of the DIA system, which compute the cell radius as $(Area/\pi)^{1/2}$ based on cell area observed at the cut surface. Consequently, the exposed cell volume $V_E(x)$ derived from DIA system is equivalent to $2/3\pi r^3$, where $r = (R^2 - x^2)^{½}$ and $-R \leq x \leq R$ (see Fig. 1C). In contrast, the true cell volume $V_T(x)$ corresponds to the portion of the gas cell below the sectioning plane. Therefore, in order to determine whether, on average, the gas cell volume is properly estimated, one needs to compare the mean exposed cell volume $V_{Eave}(x)$ and the mean true cell volume $V_{Tave}(x)$, for all possibilities of sectioning a gas cell. The equation $V_T(x)$ of true cell volume, the portion of the cell below the sectioning plane, as a function of distance x from the center can be determined by the volumes of revolution theorem. This equation is derived as follows:

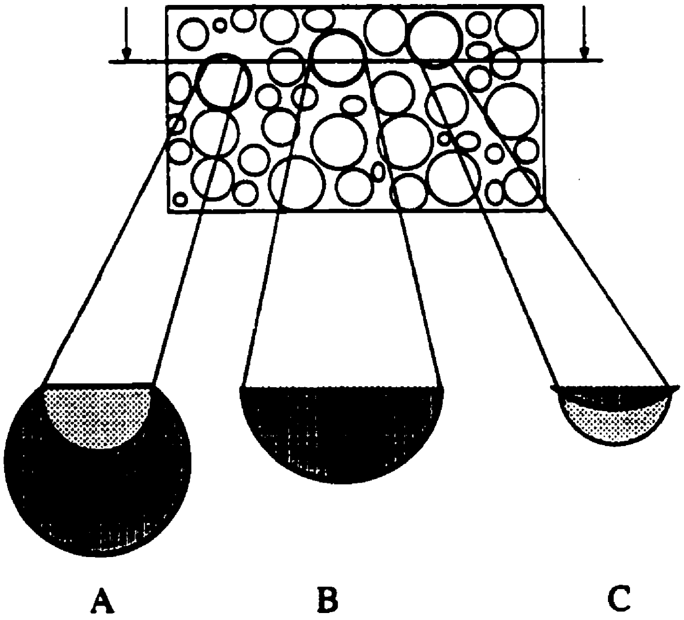
$$V_T(x) = \int \pi (R^2 - x^2) dx$$

For simplification, $R=1$, so $-1 \leq x \leq 1$. Therefore,

$$V_T(x) = \int \pi (1 - x^2) dx$$

$$V_T(x) = \pi (x - \frac{x^3}{3} + \frac{2}{3})$$

Figure 2. Schematic diagram of a section of bread crumb and the actual and predicted volumes of three gas cells cut at different distances from their respective centers: cell A sectioned above its center, cell B is sectioned, and cell C is cut below its center. For cells A and C, the digital imaging system would under- and over-estimate the void fraction, respectively, as indicated by the ratio of darker to lighter regions.


A
B
C

Considering all sectioning possibilities, where $-1 \leq x \leq 1$, the mean true cell volume,

$$V_{Tave}(x) = \frac{1}{2}\int_{-1}^{1} \pi \left(x - \frac{x^3}{3} + \frac{2}{3}\right) dx$$

$$V_{Tave}(x) = \frac{2}{3}\pi$$

$V_{Tave}(x)$, is:

In contrast, by DIA, the mean exposed cell volume, $V_{Eave}(x)$, based on cell size at the sample surface, where $-1 \leq x \leq 1$ is:

$$V_{Eave}(x) = \frac{1}{2}\int_{-1}^{1} V_O(x)\, dx$$

$$V_{Eave}(x) = \frac{1}{2}\int_{-1}^{1} \frac{2}{3}\pi(1 - x^2)^{3/2}\, dx$$

Let $x = sin\theta$, so $d\theta = cos\theta\, d\theta$, so that $-\frac{\pi}{2} \leq \theta \leq \frac{\pi}{2}$

$$V_{Eave}(x) = \frac{1}{3}\pi \int_{-\pi/2}^{\pi/2} (cos\theta)^4\, d\theta$$

$$V_{Eave}(x) = \frac{1}{3}\pi \int_{-\pi/2}^{\pi/2} \frac{3}{8} + \frac{1}{2}cos2\theta + \frac{1}{8}cos4\theta \quad d\theta$$

$$V_{Eave}(x) = \frac{1}{8}\pi^2$$

By comparing the two results, $V_{Tave}(x)$ and $V_{Eave}(x)$ one can conclude that by estimating the cell volume from surface measurements, the volume of the cells is underestimated by a factor of 1.70.

APPENDIX III

Baking Results, Density, Grain Features, and Mechanical Properties of Bread Crumb

Table 1. Baking Results for 35 min Proof Time[1].

Flour	WA (%)	No. SP	Dough Lt. (cm)	Proof Ht. (mm)	Loaf Wt. (g)	Loaf Vol. (cm^3)
CWRS	60	3	56.1 ±2.9	91.0 ±0.0	318.5 ±2.8	1775 ±25
	60	5	66.0 ±4.4	89.3 ±1.2	318.5 ±3.1	1692 ±14
	65	3	58.8 ±0.7	92.3 ±2.1	325.0 ±1.9	1800 ±25
	65	5	75.4 ±1.5	90.7 ±2.5	326.9 ±0.3	1750 ±25
CWES	60	3	46.6 ±0.7	91.3 ±2.1	316.5 ±1.9	1800 ±25
	60	5	58.4 ±2.5	86.3 ±0.6	316.2 ±1.7	1692 ±14
	63	3	52.1 ±2.2	92.0 ±3.6	322.4 ±3.0	1817 ±29
	63	5	66.5 ±4.8	87.0 ±0.6	324.8 ±3.3	1700 ±43
CPS	60	3	66.9 ±2.9	86.7 ±3.5	315.7 ±1.6	1608 ±29
	60	5	84.7 ±1.5	82.3 ±2.1	319.2 ±1.4	1533 ±14
Blend	60	3	59.3 ±1.9	88.0 ±2.0	317.1 ±0.8	1700 ±50
	60	5	71.1 ±2.5	85.3 ±2.5	319.1 ±2.4	1625 ±25

[1] Means ± standard error; WA, water absorption; No. SP, number of sheeting passes; Lt., length; Ht., height; Wt., weight; Vol., volume.

Table 2. Baking Results for 45 min Proof Time[1].

Flour	WA (%)	No. SP	Dough Lt. (cm)	Proof Ht. (mm)	Loaf Wt. (g)	Loaf Vol. (cm^3)
	60	3	55.9 ±3.4	107.0 ±2.0	313.6 ±1.1	2058 ±14
CWRS	60	5	71.8 ±2.7	103.3 ±2.5	315.0 ±1.3	1983 ±52
	65	3	63.9 ±1.9	106.3 ±3.1	320.9 ±0.7	2108 ±14
	65	5	78.1 ±4.5	103.3 ±0.6	322.3 ±1.3	2050 ±75
CWES	60	3	48.3 ±2.5	106.3 ±3.1	314.7 ±0.8	2100 ±43
	60	5	60.1 ±2.6	102.3 ±3.1	314.3 ±0.6	2042 ±63
	63	3	49.1 ±2.6	106.0 ±2.6	315.1 ±2.5	2092 ±29
	63	5	63.5 ±1.8	101.7 ±0.6	318.0 ±1.9	2067 ±14
CPS	60	3	70.3 ±2.9	102.3 ±2.5	312.5 ±1.2	1825 ±25
	60	5	84.7 ±1.5	98.3 ±2.5	314.2 ±1.2	1750 ±25
Blend	60	3	59.7 ±2.2	105.0 ±1.7	313.4 ±1.2	2000 ±43
	60	5	71.1 ±1.8	103.7 ±3.1	315.2 ±1.6	1992 ±87

[1] Means ± standard error; WA, water absorption; No. SP, number of sheeting passes; Lt., length; Ht., height; Wt., weight; Vol., volume.

Table 3. Baking Results for 60 min Proof Time[1].

Flour	WA (%)	No. SP	Dough Lt. (cm)	Proof Ht. (mm)	Loaf Wt. (g)	Loaf Vol. (cm^3)
CWRS	60	3	56.7 ±0.7	126.0 ±1.0	309.1 ±1.7	2375 ±25
	60	5	69.9 ±3.4	122.7 ±0.6	311.1 ±0.5	2300 ±66
	65	3	63.1 ±1.9	126.3 ±0.6	316.5 ±0.5	2482 ±16
	65	5	73.2 ±1.9	123.7 ±1.2	316.6 ±3.2	2392 ±63
CWES	60	3	46.2 ±2.9	124.7 ±2.3	308.1 ±0.5	2450 ±25
	60	5	61.0 ±2.5	122.3 ±1.5	309.3 ±1.6	2325 ±25
	63	3	48.3 ±1.3	125.0 ±1.7	312.9 ±3.8	2492 ±63
	63	5	64.8 ±1.3	123.3 ±1.2	312.6 ±1.4	2425 ±0
CPS	60	3	71.1 ±2.5	123.3 ±0.6	308.2 ±1.6	2117 ±29
	60	5	83.4 ±2.6	119.7 ±1.5	310.7 ±0.9	2025 ±66
Blend	60	3	61.0 ±4.4	124.7 ±0.6	308.8 ±0.5	2325 ±25
	60	5	74.5 ±1.5	123.3 ±0.6	308.1 ±1.2	2242 ±52

[1] Means ± standard error; WA, water absorption; No. SP, number of sheeting passes; Lt., length; Ht., height; Wt., weight; Vol., volume.

Table 4. Baking Results for 85 min Proof Time[1].

Flour	WA (%)	No. SP	Dough Lt. (cm)	Proof Ht. (mm)	Loaf Wt. (g)	Loaf Vol. (cm^3)
CWRS	60	3	54.6 ±1.0	143.3 ±2.2	307.3 ±2.4	2700 ±50
	60	5	69.5 ±3.3	140.8 ±1.5	305.6 ±2.5	2708 ±80
	65	3	60.5 ±0.7	143.7 ±3.1	312.7 ±1.7	2750 ±50
	65	5	75.9 ±1.6	142.5 ±2.4	312.2 ±2.5	2742 ±95
CWES	60	3	47.3 ±2.2	143.7 ±3.2	305.7 ±1.6	2775 ±75
	60	5	61.0 ±3.6	139.0 ±1.0	304.3 ±2.2	2742 ±118
	63	3	52.4 ±3.0	143.0 ±2.7	307.9 ±1.3	2892 ±14
	63	5	64.8 ±1.3	139.0 ±2.6	306.4 ±3.1	2742 ±72
CPS	60	3	70.5 ±3.8	140.8 ±0.8	304.1 ±2.9	2483 ±115
	60	5	90.2 ±1.5	140.0 ±0.8	304.9 ±2.3	2392 ±80
Blend	60	3	61.0 ±5.1	142.3 ±3.4	304.2 ±1.7	2617 ±104
	60	5	69.5 ±4.1	139.5 ±2.4	304.7 ±2.5	2608 ±29

[1] Means ± standard error; WA, water absorption; No. SP, number of sheeting passes; Ht., Lt., length; height; Wt., weight; Vol., volume.

Table 5. Means and Standard Errors of Bread Crumb Density (g/cm^3) as a Function of Flour Type, Proof Time, Number of Sheeting Passes (SP), and Water Absorption (WA)[1].

Flour	WA	SP	Proof Time (min)			
Type	(%)		35	45	60	85
CWRS	60	3	0.156 ±0.003	0.134 ±0.002	0.115 ±0.001	0.107 ±0.003
	60	5	0.166 ±0.003	0.141 ±0.002	0.125 ±0.001	0.104 ±0.005
	65	3	0.157 ±0.002	0.132 ±0.001	0.115 ±0.002	0.106 ±0.002
	65	5	0.163 ±0.004	0.140 ±0.006	0.122 ±0.005	0.107 ±0.002
CWES	60	3	0.153 ±0.004	0.131 ±0.003	0.115 ±0.002	0.105 ±0.004
	60	5	0.161 ±0.003	0.134 ±0.001	0.122 ±0.003	0.104 ±0.005
	63	3	0.158 ±0.005	0.134 ±0.004	0.118 ±0.001	0.106 ±0.003
	63	5	0.170 ±0.006	0.136 ±0.003	0.118 ±0.002	0.104 ±0.002
CPS	60	3	0.162 ±0.004	0.138 ±0.001	0.118 ±0.001	0.107 ±0.001
	60	5	0.175 ±0.007	0.148 ±0.003	0.126 ±0.001	0.107 ±0.002
Blend	60	3	0.162 ±0.003	0.134 ±0.002	0.120 ±0.001	0.102 ±0.004
	60	5	0.167 ±0.001	0.141 ±0.002	0.122 ±0.002	0.108 ±0.002

[1] Means ± standard error.

Table 6. Means and Standard Errors of Number of Cells/cm^2 as a Function of Flour Type, Proof Time, Number of Sheeting Passes (SP), and Water Absorption (WA)[1].

Flour	WA	SP	Proof Time (min)			
Type	(%)		35	45	60	85
CWRS	60	3	92.2 ±4.8	92.6 ±4.0	87.2 ±3.1	79.2 ±0.8
	60	5	96.3 ±2.9	90.7 ±1.6	92.7 ±4.0	77.7 ±1.7
	65	3	93.0 ±6.1	91.5 ±4.1	93.7 ±2.8	78.6 ±2.5
	65	5	93.8 ±9.9	89.5 ±1.8	95.5 ±6.7	81.4 ±2.4
CWES	60	3	95.2 ± .6	91.2 ±4.1	83.2 ±2.0	78.5 ±4.0
	60	5	98.7 ±2.4	89.4 ±1.2	88.8 ±1.2	76.7 ±5.0
	63	3	94.5 ±1.2	91.4 ±3.4	80.7 ±3.5	76.6 ±0.6
	63	5	92.6 ±3.1	90.9 ±0.9	92.3 ±2.5	84.2 ±0.8
CPS	60	3	88.9 ±5.0	90.7 ±2.4	82.3 ±2.5	74.6 ±2.1
	60	5	91.8 ±3.4	89.7 ±3.0	87.4 ±2.5	70.7 ±3.7
Blend	60	3	93.7 ±2.7	94.5 ±1.4	90.2 ±5.3	77.9 ±2.7
	60	5	92.4 ±1.5	88.1 ±3.8	86.7 ±1.6	80.4 ±1.6

[1] Means ± standard error.

Table 7. Means and Standard Errors of Mean Cell Area (mm^2) as a Function of Flour Type, Proof Time, Number of Sheeting Passes (SP), and Water Absorption (WA)[1].

Flour	WA	SP	Proof Time (min)			
Type	(%)		35	45	60	85
CWRS	60	3	0.521 ±0.028	0.526 ±0.021	0.578 ±0.029	0.636 ±0.013
	60	5	0.485 ±0.014	0.530 ±0.010	0.526 ±0.020	0.637 ±0.009
	65	3	0.516 ±0.037	0.533 ±0.029	0.525 ±0.015	0.642 ±0.020
	65	5	0.505 ±0.048	0.537 ±0.010	0.510 ±0.039	0.612 ±0.016
CWES	60	3	0.504 ±0.022	0.543 ±0.024	0.606 ±0.015	0.641 ±0.033
	60	5	0.477 ±0.012	0.543 ±0.005	0.551 ±0.005	0.664 ±0.046
	63	3	0.514 ±0.006	0.540 ±0.023	0.618 ±0.035	0.662 ±0.009
	63	5	0.514 ±0.020	0.533 ±0.006	0.529 ±0.020	0.597 ±0.013
CPS	60	3	0.545 ±0.038	0.532 ±0.015	0.598 ±0.028	0.663 ±0.022
	60	5	0.514 ± .020	0.537 ±0.019	0.556 ±0.017	0.707 ±0.046
Blend	60	3	0.505 ±0.016	0.516 ±0.009	0.544 ±0.031	0.666 ±0.035
	60	5	0.513 ±0.015	0.551 ±0.025	0.565 ±0.009	0.623 ±0.015

[1] Means ± standard error

Table 8. Means and Standard Errors of Cell Wall Thickness (μm) as a Function of Flour Type, Proof Time, Number of Sheeting Passes (SP), and Water Absorption (WA)[1].

Flour	WA	SP	Proof Time (min)			
Type			35	45	60	85
CWRS	60	3	752 ±31	734 ±30	764 ±33	813 ±22
	60	5	802 ±28	798 ±18	770 ±35	847 ±19
	65	3	771 ±23	771 ±21	773 ±22	857 ±24
	65	5	818 ±59	787 ±16	790 ±33	843 ±34
CWES	60	3	743 ±10	727 ±33	775 ±18	846 ±63
	60	5	771 ±26	770 ±22	779 ±25	844 ±23
	63	3	744 ±8	751 ±12	825 ±15	808 ±17
	63	5	798 ±28	804 ±26	785 ±7	775 ±37
CPS	60	3	771 ±2	773 ±25	807 ±19	874 ±24
	60	5	751 ±23	776 ±15	797 ±21	912 ±2
Blend	60	3	745 ±15	734 ±19	793 ±45	832 ±12
	60	5	758 ±27	769 ±34	789 ±7	813 ±8

[1] Means ± standard error

Table 9. Means and Standard Errors of Small-to-Large Cell Count Ratio (SLCC) as a Function of Flour Type, Proof Time, Number of Sheeting Passes (SP), and Water Absorption (WA)[1].

Flour Type	WA	SP	Proof Time (min)			
			35	45	60	85
CWRS	60	3	39.1 ±2.6	36.6 ±2.7	35.7 ±3.1	30.5 ±1.9
	60	5	50.9 ±3.9	42.1 ±2.2	39.0 ±1.5	30.0 ±0.8
	65	3	38.4 ±5.1	36.3 ±2.8	40.4 ±0.9	33.3 ±2.1
	65	5	38.4 ±5.3	33.3 ±1.7	39.0 ±3.8	32.5 ±1.3
CWES	60	3	45.4 ±7.0	37.6 ±1.3	38.3 ±3.4	34.3 ±3.7
	60	5	58.7 ±9.6	35.3 ±2.2	36.9 ±1.2	35.2 ±4.9
	63	3	45.7 ±5.7	38.9 ±4.4	38.8 ±3.6	29.1 ±0.6
	63	5	39.5 ±3.4	43.1 ±0.7	41.4 ±1.7	33.7 ±4.1
CPS	60	3	34.4 ±4.4	35.1 ±1.8	30.7 ±1.7	28.1 ±0.9
	60	5	37.0 ±2.5	37.6 ±3.3	34.3 ±1.5	27.7 ±0.6
Blend	60	3	34.9 ±1.9	37.6 ±0.5	34.2 ±0.8	30.0 ±1.5
	60	5	38.5 ±3.3	32.2 ±3.3	33.4 ±1.0	31.9 ±0.3

[1] Means ± standard error.

Table 10. Means and Standard Errors of Crumb Brightness as a Function of Flour Type, Proof Time, Number of Sheeting Passes (SP), and Water Absorption (WA)[1].

Flour Type	WA	SP	Proof Time (min)			
			35	45	60	85
CWRS	60	3	189.14 ±1.10	188.35 ±0.67	182.69 ±1.67	180.4 ±2.4
	60	5	185.40 ±1.47	186.50 ±0.17	185.36 ±1.62	178.3 ±3.8
	65	3	188.04 ±1.03	185.03 ±0.78	180.44 ±0.98	173.5 ±2.2
	65	5	189.53 ±1.57	187.41 ±1.26	181.44 ±2.80	175.1 ±2.5
CWES	60	3	186.74 ±2.24	185.53 ±0.82	177.44 ±0.08	173.8 ±3.0
	60	5	182.64 ±2.19	183.92 ±0.46	182.68 ±1.93	174.2 ±3.9
	63	3	183.69 ±0.57	180.24 ±1.26	175.10 ±3.11	172.3 ±1.7
	63	5	182.00 ±0.92	179.67 ±1.76	178.58 ±1.73	178.4 ±2.7
CPS	60	3	189.61 ±0.60	183.54 ±0.98	178.75 ±1.01	171.9 ±2.0
	60	5	188.33 ±1.42	185.03 ±0.94	180.86 ±0.61	173.9 ±2.5
Blend	60	3	190.07 ±1.81	185.83 ±1.13	182.13 ±3.66	176.7 ±5.3
	60	5	189.88 ±2.95	188.58 ±1.02	181.50 ±1.73	176.3 ±3.2

[1] Means ± standard error.

Table 11. Means and Standard Errors of Void Fraction as a Function of Flour Type, Proof Time, Number of Sheeting Passes (SP), and Water Absorption (WA)[1].

Flour Type	WA	SP	Proof Time (min)			
			35	45	60	85
CWRS	60	3	0.4728 ±.0035	0.4835 ±.0019	0.4908 ±.0022	0.4929 ±.0027
	60	5	0.4618 ±.0047	0.4735 ±.0036	0.4843 ±.0035	0.4877 ±.0028
	65	3	0.4706 ±.0004	0.4806 ±.0031	0.4836 ±.0014	0.4926 ±.0029
	65	5	0.4600 ±.0037	0.4739 ±.0015	0.4798 ±.0055	0.4918 ±.0022
CWES	60	3	0.4757 ±.0024	0.4892 ±.0011	0.4959 ±.0043	0.4950 ±.0065
	60	5	0.4664 ±.0013	0.4810 ±.0022	0.4866 ±.0033	0.4966 ±.0013
	63	3	0.4798 ±.0029	0.4905 ±.0023	0.4907 ±.0029	0.5025 ±.0032
	63	5	0.4648 ±.0033	0.4770 ±.0013	0.4851 ±.0053	0.5002 ±.0059
CPS	60	3	0.4673 ±.0028	0.4786 ±.0045	0.4870 ±.0006	0.4898 ±.0027
	60	5	0.4666 ±.0034	0.4749 ±.0034	0.4829 ±.0039	0.4839 ±.0006
Blend	60	3	0.4701 ±.0016	0.4841 ±.0020	0.4842 ±.0012	0.4937 ±.0034
	60	5	0.4684 ±.0061	0.4800 ±.0032	0.4865 ±.0014	0.4969 ±.0017

[1] Means ± standard error.

Table 12. Means and Standard Errors of Young's Modulus (kN m^{-2}, 0-2% strain) as a Function of Flour Type, Proof Time, Number of Sheeting Passes (SP), and Water Absorption (WA)[1].

Flour Type	WA	SP	Proof Time (min)			
			35	45	60	85
CWRS	60	3	15.43 ±1.32	14.01 ±0.51	10.84 ±0.59	10.63 ±2.53
	60	5	13.72 ±0.62	15.11 ±2.38	10.89 ±0.72	10.17 ±1.95
	65	3	12.85 ±0.42	12.46 ±1.92	7.97 ±0.43	7.12 ±0.21
	65	5	14.31 ±1.14	13.16 ±1.34	7.59 ±0.17	7.55 ±0.31
CWES	60	3	15.05 ±0.80	15.66 ±1.39	9.05 ±1.76	7.38 ±0.19
	60	5	13.35 ±1.48	15.36 ±3.12	8.89 ±2.04	7.46 ±1.38
	63	3	12.17 ±1.29	12.91 ±0.78	7.16 ±0.71	7.92 ±1.34
	63	5	13.33 ±1.10	12.85 ±2.73	8.25 ±1.22	9.75 ±1.13
CPS	60	3	13.71 ±1.56	11.71 ±1.42	7.62 ±0.41	7.41 ±1.01
	60	5	15.46 ±0.45	11.97 ±1.57	8.21 ±1.41	7.62 ±1.35
Blend	60	3	16.31 ±2.00	12.78 ±1.14	8.66 ±0.89	9.68 ±2.12
	60	5	15.30 ±2.05	15.13 ±2.55	9.45 ±1.32	8.39 ±0.45

[1] Means ± standard error.

Table 13. Means and Standard Errors of Fracture Stress (kN m^{-2}) of Bread Crumb as a Function of Flour Type, Proof Time, Number of Sheeting Passes (SP), and Water Absorption (WA)[1].

Flour	WA	SP	Proof Time (min)			
Type			35	45	60	85
CWRS	60	3	2.768 ±0.147	2.478 ±0.234	2.289 ±0.299	2.197 ±0.475
	60	5	2.445 ±0.182	2.643 ±0.246	2.318 ±0.072	2.040 ±0.222
	65	3	2.324 ±0.029	2.153 ±0.199	1.854 ±0.155	1.619 ±0.161
	65	5	2.492 ±0.167	2.273 ±0.089	1.699 ±0.102	1.443 ±0.108
CWES	60	3	3.035 ±0.170	2.678 ±0.122	2.327 ±0.164	1.599 ±0.006
	60	5	2.354 ±0.093	2.928 ±0.390	1.963 ±0.051	1.705 ±0.078
	63	3	2.394 ±0.246	2.408 ±0.146	1.859 ±0.016	1.902 ±0.244
	63	5	2.567 ±0.212	2.339 ±0.287	2.109 ±0.102	2.262 ±0.182
CPS	60	3	1.691 ±0.202	1.384 ±0.173	1.155 ±0.121	1.248 ±0.065
	60	5	1.888 ±0.072	1.636 ±0.128	1.330 ±0.174	1.164 ±0.167
Blend	60	3	2.375 ±0.219	2.016 ±0.182	1.839 ±0.181	1.764 ±0.400
	60	5	2.257 ±0.202	2.018 ±0.228	1.740 ±0.042	1.766 ±0.174

[1] Means ± standard error.

Table 14. Means and Standard Errors of Fracture Strain of Bread Crumb as a Function of Flour Type, Proof Time, Number of Sheeting Passes (SP), and Water Absorption (WA)[1].

Flour	WA	SP	Proof Time (min)			
Type			35	45	60	85
CWRS	60	3	0.39 ±0.03	0.38 ±0.04	0.43 ±0.02	0.42 ±0.00
	60	5	0.37 ±0.02	0.38 ±0.03	0.44 ±0.03	0.42 ±0.04
	65	3	0.37 ±0.01	0.36 ±0.02	0.44 ±0.02	0.42 ±0.04
	65	5	0.35 ±0.03	0.36 ±0.03	0.43 ±0.03	0.34 ±0.03
CWES	60	3	0.45 ±0.03	0.38 ±0.02	0.57 ±0.02	0.42 ±0.01
	60	5	0.39 ±0.05	0.44 ±0.03	0.48 ±0.09	0.47 ±0.03
	63	3	0.41 ±0.03	0.42 ±0.02	0.50 ±0.02	0.51 ±0.03
	63	5	0.44 ±0.04	0.40 ±0.03	0.53 ±0.02	0.48 ±0.04
CPS	60	3	0.26 ±0.01	0.25 ±0.01	0.30 ±0.05	0.37 ±0.04
	60	5	0.27 ±0.01	0.31 ±0.03	0.34 ±0.00	0.33 ±0.04
Blend	60	3	0.32 ±0.01	0.35 ±0.01	0.43 ±0.01	0.37 ±0.01
	60	5	0.33 ±0.05	0.28 ±0.02	0.41 ±0.05	0.42 ±0.05

[1] Means ± standard error.

Table 15. Means and Standard Errors of Fracture Energy (J m^{-3}) of Bread Crumb as a Function of Flour Type, Proof Time, Number of Sheeting Passes (SP), and Water Absorption (WA)[1].

Flour Type	WA	SP	Proof Time (min)			
			35	45	60	85
CWRS	60	3	707 ±64	627 ±128	635 ±105	581 ±140
	60	5	597 ±67	653 ±11	648 ±68	551 ±73
	65	3	566 ±11	490 ±19	512 ±59	429 ±84
	65	5	555 ±51	528 ±37	458 ±45	300 ±47
CWES	60	3	902 ±86	672 ±26	842 ±64	435 ±22
	60	5	606 ±101	815 ±37	601 ±112	507 ±41
	63	3	631 ±89	662 ±47	569 ±15	613 ±84
	63	5	755 ±98	606 ±86	686 ±13	673 ±12
CPS	60	3	290 ±34	230 ±29	235 ±66	299 ±18
	60	5	333 ±21	342 ±17	294 ±43	244 ±53
Blend	60	3	498 ±35	456 ±35	500 ±29	422 ±115
	60	5	506 ±98	366 ±32	463 ±58	585 ±96

[1] Means ± standard error.

APPENDIX IV

Treatments and Interaction Effects on the Characteristics of Bread Baked at Fixed (60%) Water Absorption.

Table 16. General Linear Models Procedure

Source	Levels	Values
Proof Time (PT, min)	4	35, 45, 60 and 85
Flour (Fl)	4	Blend, CPS, CWES and CWRS
No. Sheeting Passes (SP)	2	3 and 5
Replication (Rep)	3	1, 2 and 3

Number of observations in data set = 96 (4 x 4 x 2 x 3)

Table 17. Treatments and Interaction Effects for Bread Loaf Volume (cm^3) Prepared at Fixed Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	11945019.5	3981673.177	1273.02	0.0001
Fl	3	1046165.36	348721.788	111.49	0.0001
SP	1	105006.510	105006.510	33.57	0.0001
Rep	2	6497.396	3248.698	1.04	0.3600
PT*SP	3	14967.448	4989.149	1.60	0.1996
PT*Fl	9	55631.510	6181.279	1.98	0.0573
Fl*SP	3	6738.281	2246.094	0.72	0.5449
PT*Fl*SP	9	9641.927	1071.325	0.34	0.9569

Table 18. Treatments and Interaction Effects for Bread Crumb Density ($g\ cm^{-3}$) Prepared at Fixed Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	0.04360439	0.01453480	789.21	0.0001
Fl	3	0.00059428	0.00019809	10.76	0.0001
SP	1	0.00074088	0.00074088	40.23	0.0001
Rep	2	0.00049216	0.00024608	13.36	0.0001
PT*SP	3	0.00021807	0.00007269	3.95	0.0122
PT*Fl	9	0.00021657	0.00002406	1.31	0.2519
Fl*SP	3	0.00004020	0.00001340	0.73	0.5394
PT*Fl*SP	9	0.00014829	0.00001648	0.89	0.5354

Table 19. Treatments and Interaction Effects for Number of Cells/cm^2 of Bread Crumb Prepared at Fixed Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	3836.2988501	1278.7662834	42.60	0.0001
Fl	3	239.7912793	79.9304264	2.66	0.0557
SP	1	3.5458594	3.5458594	0.12	0.7322
Rep	2	1.7933732	0.8966866	0.03	0.9706
PT*SP	3	144.3084869	48.1028290	1.60	0.1979
PT*Fl	9	155.4366113	17.2707346	0.58	0.8122
Fl*SP	3	54.0408159	18.0136053	0.60	0.6174
PT*Fl*SP	9	122.8485638	13.6498404	0.45	0.8990

Table 20. Treatments and Interaction Effects for Mean Cell Area (MCA, mm^2) of Bread Crumb Prepared at Fixed Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	0.29160875	0.09720292	59.68	0.0001
Fl	3	0.00940400	0.00313467	1.92	0.1348
SP	1	0.00203355	0.00203355	1.25	0.2681
Rep	2	0.00269647	0.00134823	0.83	0.4418
PT*SP	3	0.00786361	0.00262120	1.61	0.1962
PT*Fl	9	0.00797183	0.00088576	0.54	0.8368
Fl*SP	3	0.00230046	0.00076682	0.47	0.7037
PT*Fl*SP	9	0.01270626	0.00141181	0.87	0.5592

Table 21. Treatments and Interaction Effects for Cell Wall Thickness (CWT, μm) of Bread Crumb Prepared at Fixed Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	122143.05467	40714.35156	20.60	0.0001
Fl	3	12369.55494	4123.18498	2.09	0.1111
SP	1	6552.49582	6552.49582	3.32	0.0734
Rep	2	5328.62844	2664.31422	1.35	0.2672
PT*SP	3	4199.64684	1399.88228	0.71	0.5507
PT*Fl	9	14956.44589	1661.82732	0.84	0.5817
Fl*SP	3	4654.91789	1551.63930	0.79	0.5067
PT*Fl*SP	9	5847.30357	649.70040	0.33	0.9623

Table 22. Treatments and Interaction Effects for Small-to-Large Cell Count (SLCC) of Bread Crumb Prepared at Fixed Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	1626.8721540	542.2907180	18.98	0.0001
Fl	3	784.5570935	261.5190312	9.15	0.0001
SP	1	129.5626198	129.5626198	4.53	0.0372
Rep	2	128.5620098	64.2810049	2.25	0.1140
PT*SP	3	245.3928738	81.7976246	2.86	0.0439
PT*Fl	9	609.5444159	67.7271573	2.37	0.0226
Fl*SP	3	74.5218327	24.8406109	0.87	0.4619
PT*Fl*SP	9	210.8650659	23.4294518	0.82	0.6001

Table 23. Treatments and Interaction Effects for Crumb Brightness of Bread Crumb Prepared at Fixed Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	2075.1778841	691.7259614	55.92	0.0001
Fl	3	227.9649674	75.9883225	6.14	0.0010
SP	1	0.0523445	0.0523445	0.00	0.9483
Rep	2	152.1457133	76.0728566	6.15	0.0037
PT*SP	3	65.8626237	21.9542079	1.77	0.1612
PT*Fl	9	132.2099486	14.6899943	1.19	0.3189
Fl*SP	3	17.1755982	5.7251994	0.46	0.7092
PT*Fl*SP	9	61.6778942	6.8530994	0.55	0.8289

Table 24. Treatments and Interaction Effects for Void Fraction of Bread Crumb Prepared at Fixed Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	0.00741381	0.00247127	80.83	0.0001
Fl	3	0.00063130	0.00021043	6.88	0.0004
SP	1	0.00049507	0.00049507	16.19	0.0002
Rep	2	0.00000955	0.00000478	0.16	0.8557
PT*SP	3	0.00008360	0.00002787	0.91	0.4407
PT*Fl	9	0.00016447	0.00001827	0.60	0.7940
Fl*SP	3	0.00022310	0.00007437	2.43	0.0734
PT*Fl*SP	9	0.00015116	0.00001680	0.55	0.8326

Table 25. Treatments and Interaction Effects for Young's Modulus (kN m^{-2}) of Bread Crumb Prepared at Fixed Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	719.516163	239.838721	53.45	0.0001
Fl	3	58.1573866	19.3857955	4.32	0.0080
SP	1	0.04375927	0.04375927	0.01	0.9217
MC	1	1.33892004	1.33892004	0.30	0.5869
Temp	1	0.81001057	0.81001057	0.18	0.6724
Rep	2	183.550749	91.7753746	20.45	0.0001
PT*SP	3	9.22920094	3.07640031	0.69	0.5643
PT*Fl	9	55.5589959	6.17322177	1.38	0.2194
Fl*SP	3	5.16890594	1.72296865	0.38	0.7649
PT*Fl*SP	9	16.3506398	1.81673776	0.40	0.9277

Table 26. Treatments and Interaction Effects for Fracture Stress (kN m^{-2}) of Bread Crumb Prepared at Fixed Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	7.11498557	2.37166186	20.90	0.0001
Fl	3	13.9867046	4.66223489	41.09	0.0001
SP	1	0.03445789	0.03445789	0.30	0.5836
MC	1	0.08418736	0.08418736	0.74	0.3924
Temp	1	0.37472939	0.37472939	3.30	0.0742
Rep	2	1.05331429	0.52665714	4.64	0.0134
PT*SP	3	0.50957960	0.16985987	1.50	0.2245
PT*Fl	9	1.62777650	0.18086406	1.59	0.1377
Fl*SP	3	0.27473548	0.09157849	0.81	0.4949
PT*Fl*SP	9	0.67351027	0.07483447	0.66	0.7416

Table 27. Treatments and Interaction Effects for Fracture Strain of Bread Crumb Prepared at Fixed Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	0.10177292	0.03392431	12.48	0.0001
Fl	3	0.27751413	0.09250471	34.03	0.0001
SP	1	0.00003168	0.00003168	0.01	0.9144
MC	1	0.00021391	0.00021391	0.08	0.7800
Temp	1	0.00074503	0.00074503	0.27	0.6025
Rep	2	0.04520423	0.02260212	8.31	0.0006
PT*SP	3	0.00477842	0.00159281	0.59	0.6266
PT*Fl	9	0.02388522	0.00265391	0.98	0.4687
Fl*SP	3	0.00257702	0.00085901	0.32	0.8137
PT*Fl*SP	9	0.04215441	0.00468382	1.72	0.1034

Table 28. Treatments and Interaction Effects for Fracture Energy (J m^{-3}) of Bread Crumb Prepared at Fixed Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	150813.1220	50271.0407	3.46	0.0218
Fl	3	2261457.577	753819.192	51.84	0.0001
SP	1	8804.3003	8804.3003	0.61	0.4396
MC	1	7394.2875	7394.2875	0.51	0.4786
Temp	1	34623.1682	34623.1682	2.38	0.1281
Rep	2	7535.0050	3767.5025	0.26	0.7726
PT*SP	3	70290.0749	23430.0250	1.61	0.1962
PT*Fl	9	202420.141	22491.1268	1.55	0.1527
Fl*SP	3	42353.3401	14117.7800	0.97	0.4125
PT*Fl*SP	9	205921.803	22880.2004	1.57	0.1440

APPENDIX V.

Treatments and Interaction Effects on the Characteristics of Bread Prepared at Optimum Water Absorption

Table 29. General Linear Models Procedure

Class	Levels	Values
Proof Time (PT, min)	4	35, 45, 60 and 85
Flour (Fl)	4	Blend, CPS, CWES and CWRS
No. Sheeting Passes (SP)	2	3 and 5
Replication (Rep)	3	1, 2 and 3

Number of observations in data set = 96 (4 x 4 x 2 x 3)

Table 30. Treatments and Interaction Effects for Loaf Volume (cm^3) of Bread Prepared at Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	12388293.75	4129431.25	1470.30	0.0001
Fl	3	1478981.25	492993.75	175.53	0.0001
SP	1	108004.16	108004.16	38.46	0.0001
Rep	2	7635.94	3817.96	1.36	0.2644
PT*SP	3	6293.75	2097.91	0.75	0.5282
PT*Fl	9	99745.83	11082.87	3.95	0.0005
Fl*SP	3	9314.58	3104.86	1.11	0.3537
PT*Fl*SP	9	20412.50	2268.06	0.81	0.6109

Table 31. Treatments and Interaction Effects for Density ($g\ cm^{-3}$) of Bread Crumb Prepared at Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	0.04575216	0.01525072	582.76	0.0001
Fl	3	0.00032537	0.00010846	4.14	0.0097
SP	1	0.00064132	0.00064132	24.51	0.0001
Rep	2	0.00027419	0.00013710	5.24	0.0079
PT*SP	3	0.00020765	0.00006922	2.64	0.0569
PT*Fl	9	0.00018322	0.00002036	0.78	0.6372
Fl*SP	3	0.00007326	0.00002442	0.93	0.4301
PT*Fl*SP	9	0.00015205	0.00001689	0.65	0.7538

Table 32. Treatments and Interaction Effects for Number of Cells/cm^2 of Bread Crumb Prepared at Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	3049.5537	1016.5179	26.91	0.0001
Fl	3	330.8740	110.2913	2.92	0.0409
SP	1	20.2095	20.2094	0.54	0.4672
Rep	2	152.1415	76.0707	2.01	0.1421
PT*SP	3	131.2446	43.7482	1.16	0.3329
PT*Fl	9	278.5154	30.9462	0.82	0.6005
Fl*SP	3	121.4436	40.4812	1.07	0.3676
PT*Fl*SP	9	211.4413	23.4935	0.62	0.7738

Table 33. Treatments and Interaction Effects for Mean Cell Area (MCA, mm^2) of Bread Crumb Prepared at Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	0.2400125	0.08000419	48.28	0.0001
Fl	3	0.0140333	0.00467779	2.82	0.0460
SP	1	0.0044432	0.00444322	2.68	0.1066
Rep	2	0.0140499	0.00702500	4.24	0.0188
PT*SP	3	0.0058669	0.00195566	1.18	0.3246
PT*Fl	9	0.0139948	0.00155498	0.94	0.4989
Fl*SP	3	0.0067334	0.00224447	1.35	0.2650
PT*Fl*SP	9	0.0156660	0.00174067	1.05	0.4116

Table 34. Treatments and Interaction Effects for Cell Wall Thickness (CWT, μm) of Bread Crumb Prepared at Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	76503.863	25501.2877	13.93	0.0001
Fl	3	12555.690	4185.2301	2.29	0.0874
SP	1	1779.8262	1779.8263	0.97	0.3279
Rep	2	249.1675	124.5837	0.07	0.9343
PT*SP	3	6624.8952	2208.2984	1.21	0.3149
PT*Fl	9	32500.3452	3611.1495	1.97	0.0578
Fl*SP	3	612.5174	204.1725	0.11	0.9530
PT*Fl*SP	9	13524.1429	1502.6825	0.82	0.5992

Table 35. Treatments and Interaction Effects for Small-to-Large Cell Count Ratio (SLCC) of Bread Crumb Prepared at Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	791.416	263.80551	10.87	0.0001
Fl	3	460.464	153.48815	6.32	0.0008
SP	1	5.57489	5.574892	0.23	0.6334
Rep	2	44.9795	22.489786	0.93	0.4013
PT*SP	3	12.3330	4.111018	0.17	0.9167
PT*Fl	9	215.851	23.983522	0.99	0.4590
Fl*SP	3	41.0850	13.695013	0.56	0.6406
PT*Fl*SP	9	193.641	21.515723	0.89	0.5424

Table 36. Treatments and Interaction Effects for Crumb Brightness of Bread Prepared at Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	2261.4954	753.831814	57.90	0.0001
Fl	3	342.1135	114.037821	8.76	0.0001
SP	1	35.6688	35.6687529	2.74	0.1029
Rep	2	30.3197	15.1598315	1.16	0.3188
PT*SP	3	23.9962	7.9987394	0.61	0.6082
PT*Fl	9	160.3689	17.818768	1.37	0.2218
Fl*SP	3	7.4548	2.4849392	0.19	0.9022
PT*Fl*SP	9	58.4223	6.4913686	0.50	0.8699

Table 37. Treatments and Interaction Effects for Void Fraction of Bread Crumb Prepared at Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	0.0081308	0.00271029	87.73	0.0001
Fl	3	0.0009035	0.00030116	9.75	0.0001
SP	1	0.0005024	0.00050235	16.26	0.0002
Rep	2	0.0000360	0.00001801	0.58	0.5613
PT*SP	3	0.0001479	0.00004931	1.60	0.1994
PT*Fl	9	0.0002625	0.00002916	0.94	0.4944
Fl*SP	3	0.0002563	0.00008544	2.77	0.0493
PT*Fl*SP	9	0.0001747	0.00001941	0.63	0.7685

Table 38. Treatments and Interaction Effects for Young's Modulus (kN m^{-2}) of Bread Crumb Prepared at Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	689.089467	229.6964892	58.20	0.0001
Fl	3	34.8325182	11.61083943	2.94	0.0402
SP	1	10.7922093	10.79220932	2.73	0.1034
Temp	1	4.96666818	4.96666818	1.26	0.2664
MC	1	0.02467761	0.02467761	0.01	0.9372
REP	2	110.8580445	55.4290222	14.04	0.0001
PT*SP	3	1.98702711	0.66234237	0.17	0.9177
PT*Fl	9	26.51136171	2.94570686	0.75	0.6652
Fl*SP	3	2.12569712	0.70856571	0.18	0.9099
PT*Fl*SP	9	21.08050449	2.34227828	0.59	0.7973

Table 39. Treatments and Interaction Effects for Fracture Stress (kN m^{-2}) of Bread Crumb Prepared at Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	5.50733648	1.83577883	19.64	0.0001
Fl	3	6.93345532	2.31115177	24.72	0.0001
SP	1	0.11057077	0.11057077	1.18	0.2811
Temp	1	0.04565020	0.04565020	0.49	0.4874
MC	1	0.00609398	0.00609398	0.07	0.7994
Rep	2	0.54568228	0.27284114	2.92	0.0617
PT*SP	3	0.02962943	0.00987648	0.11	0.9565
PT*Fl	9	0.50741058	0.05637895	0.60	0.7894
Fl*SP	3	0.17771318	0.05923773	0.63	0.5962
PT*Fl*SP	9	0.42737025	0.04748558	0.51	0.8631

Table 40. Treatments and Interaction Effects for Fracture Strain of Bread Crumb Prepared at Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	0.12586364	0.04195455	18.36	0.0001
FL	3	0.24937079	0.08312360	36.37	0.0001
SP	1	0.00040122	0.00040122	0.18	0.6767
Temp	1	0.00021670	0.00021670	0.09	0.7592
MC	1	0.00039058	0.00039058	0.17	0.6808
Rep	2	0.03579182	0.01789591	7.83	0.0010
PT*SP	3	0.00430023	0.00143341	0.63	0.6002
PT*Fl	9	0.02053504	0.00228167	1.00	0.4513
Fl*SP	3	0.00653181	0.00217727	0.95	0.4210
PT*Fl*SP	9	0.02966901	0.00329656	1.44	0.1908

Table 41. Treatments and Interaction Effects for Fracture Energy (J m^{-3}) of Bread Crumb Prepared at Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	76243.0152	25414.3384	2.61	0.0595
Fl	3	1372517.61	457505.870	47.02	0.0001
SP	1	3984.7234	3984.7234	0.41	0.5247
Temp	1	553.5333	553.5333	0.06	0.8123
MC	1	187.3690	187.3690	0.02	0.8901
Rep	2	51715.667	25857.833	2.66	0.0784
PT*SP	3	10639.182	3546.3941	0.36	0.7789
PT*Fl	9	85025.131	9447.2369	0.97	0.4730
Fl*SP	3	33594.173	11198.057	1.15	0.3361
PT*Fl*SP	9	84463.470	9384.8300	0.96	0.4781

APPENDIX VI

Treatments and Interaction Effects on the Characteristics of CWRS and CWES Bread Baked at Fixed (60%) and Optimum Water Absorption

Table 42. General Linear Models Procedure

Class	Level	Values
Proof Time (PT, min)	4	35, 45, 60 and 85
Flour (Fl)	2	CWES and CWRS
Water Absorption (WA, %)	2	fixed and optimum
No. Sheeting Passes (SP)	2	3 and 5
Replication (Rep)	3	1, 2 and 3

Number of observations in data set = 96 (4 x 2 x 2 x 2 x 3)

Table 43. Treatments and Interaction Effects for Loaf Volume (cm^3) of CWRS and CWES Bread Prepared at Fixed and Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	13493313.2	4497771.09	1732.39	0.0001
WA	1	57281.510	57281.510	22.06	0.0001
Fl	1	22052.344	22052.344	8.49	0.0050
SP	1	116552.34	116552.34	44.89	0.0001
Rep	2	1214.062	607.031	0.23	0.7922
PT*SP	3	9511.198	3170.399	1.22	0.3096
PT*Fl	3	12865.365	4288.455	1.65	0.1866
Fl*SP	1	5937.760	5937.760	2.29	0.1355
PT*WA	3	12136.198	4045.399	1.56	0.2085
Fl*WA	1	3094.010	3094.010	1.19	0.2792
WA*SP	1	21.094	21.094	0.01	0.9285
PT*Fl*SP	3	11021.615	3673.872	1.42	0.2469
PT*Fl*WA	3	3552.865	1184.288	0.46	0.7139
PT*WA*SP	3	8521.615	2840.538	1.09	0.3584
Fl*WA*SP	1	250.260	250.260	0.10	0.7572
PT*Fl*WA*SP	3	6271.615	2090.538	0.81	0.4957

Table 44. Treatments and Interaction Effects for Crumb Density (g cm^{-3}) of CWRS and CWES Bread Prepared at Fixed and Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	0.04056663	0.01352221	503.17	0.0001
WA	1	0.00002083	0.00002083	0.78	0.3820
Fl	1	0.00005293	0.00005293	1.97	0.1655
SP	1	0.00049746	0.00049746	18.51	0.0001
Rep	2	0.00045685	0.00022842	8.50	0.0005
PT*SP	3	0.00031648	0.00010549	3.93	0.0125
PT*Fl	3	0.00002448	0.00000816	0.30	0.8226
Fl*SP	1	0.00003093	0.00003093	1.15	0.2875
PT*WA	3	0.00005100	0.00001700	0.63	0.5968
Fl*WA	1	0.00005931	0.00005931	2.21	0.1425
WA*SP	1	0.00000359	0.00000359	0.13	0.7160
PT*Fl*SP	3	0.00004701	0.00001567	0.58	0.6283
PT*Fl*WA	3	0.00006429	0.00002143	0.80	0.5000
PT*WA*SP	3	0.00002988	0.00000996	0.37	0.7745
Fl*WA*SP	1	0.00000263	0.00000263	0.10	0.7555
PT*Fl*WA*SP	3	0.00002872	0.00000957	0.36	0.7848

Table 45. Treatments and Interaction Effects for Number of Cells/cm^2 of CWRS and CWES Bread Crumb Prepared at Fixed and Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	3138.9253	1046.3084	27.17	0.0001
WA	1	8.9121094	8.9121094	0.23	0.6321
Fl	1	40.456066	40.456066	1.05	0.3093
SP	1	95.547201	95.547202	2.48	0.1203
Rep	2	124.95666	62.478333	1.62	0.2056
PT*SP	3	180.20313	60.067712	1.56	0.2081
PT*Fl	3	189.81317	63.271057	1.64	0.1885
Fl*SP	1	14.747563	14.747563	0.38	0.5383
PT*WA	3	86.757524	28.919175	0.75	0.5259
Fl*WA	1	4.3890005	4.3890005	0.11	0.7368
WA*SP	1	6.8248890	6.8248890	0.18	0.6752
PT*Fl*SP	3	34.263031	11.421010	0.30	0.8277
PT*Fl*WA	3	38.609128	12.869709	0.33	0.8006
PT*WA*SP	3	93.921642	31.307214	0.81	0.4915
Fl*WA*SP	1	18.453834	18.453834	0.48	0.4913
PT*Fl*WA*SP	3	28.671342	9.5571140	0.25	0.8623

Table 46. Treatments and Interaction Effects for Mean Cell Area (MCA, mm^2) of CWRS and CWES Bread Crumb Prepared at Fixed and Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	0.22698613	0.07566204	46.31	0.0001
WA	1	0.00058979	0.00058979	0.36	0.5501
Fl	1	0.00431294	0.00431294	2.64	0.1093
SP	1	0.01195506	0.01195506	7.32	0.0088
Rep	2	0.00327291	0.00163645	1.00	0.3731
PT*SP	3	0.00883380	0.00294460	1.80	0.1560
PT*Fl	3	0.00701730	0.00233910	1.43	0.2421
Fl*SP	1	0.00066125	0.00066125	0.40	0.5270
PT*WA	3	0.00478966	0.00159655	0.98	0.4093
Fl*WA	1	0.00013753	0.00013753	0.08	0.7727
WA*SP	1	0.00046494	0.00046494	0.28	0.5956
PT*Fl*SP	3	0.00181514	0.00060505	0.37	0.7747
PT*Fl*WA	3	0.00209949	0.00069983	0.43	0.7334
PT*WA*SP	3	0.00575296	0.00191765	1.17	0.3270
Fl*WA*SP	1	0.00171099	0.00171099	1.05	0.3101
PT*Fl*WA*SP	3	0.00146352	0.00048784	0.30	0.8263

Table 47. Treatments and Interaction Effects for Cell Wall Thickness (CWT, µm) of CWRS and CWES Bread Crumb Prepared at Fixed and Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	55660.850236	18553.616745	7.93	0.0001
WA	1	2553.211793	2553.211793	1.09	0.3002
Fl	1	2014.123719	2014.123719	0.86	0.3571
SP	1	10125.833168	10125.833168	4.33	0.0416
Rep	2	7560.653164	3780.326582	1.62	0.2070
PT*SP	3	13570.198741	4523.399580	1.93	0.1334
PT*Fl	3	6053.862808	2017.954269	0.86	0.4653
Fl*SP	1	1186.453126	1186.453126	0.51	0.4790
PT*WA	3	6252.075864	2084.025288	0.89	0.4510
Fl*WA	1	827.008647	827.008647	0.35	0.5543
WA*SP	1	1502.298913	1502.298913	0.64	0.4260
PT*Fl*SP	3	1451.714232	483.904744	0.21	0.8913
PT*Fl*WA	3	7946.959162	2648.986387	1.13	0.3430
PT*WA*SP	3	1912.148547	637.382849	0.27	0.8450
Fl*WA*SP	1	216.888412	216.888412	0.09	0.7618
PT*Fl*WA*SP	3	2533.075366	844.358455	0.36	0.7814

Table 48. Treatments and Interaction Effects for Small-to-Large Cell Count Ratio (SLCC) of CWRS and CWES Bread Crumb Prepared at Fixed and Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	1836.1889028	612.0629676	17.32	0.0001
WA	1	48.6210667	48.6210667	1.38	0.2453
Fl	1	131.5314260	131.5314260	3.72	0.0583
SP	1	81.9427852	81.9427852	2.32	0.1329
Rep	2	356.7140621	178.3570310	5.05	0.0093
PT*SP	3	66.0437112	22.0145704	0.62	0.6028
PT*Fl	3	95.1032490	31.7010830	0.90	0.4478
Fl*SP	1	0.2550625	0.2550625	0.01	0.9326
PT*WA	3	368.819588	122.9398627	3.48	0.0211
Fl*WA	1	0.0077341	0.0077341	0.00	0.9882
WA*SP	1	81.3863202	81.3863202	2.30	0.1342
PT*Fl*SP	3	31.1737216	10.3912405	0.29	0.8295
PT*Fl*WA	3	200.2373086	66.7457695	1.89	0.1407
PT*WA*SP	3	295.2972394	98.4324131	2.79	0.0481
Fl*WA*SP	1	34.1611574	34.1611574	0.97	0.3293
PT*Fl*WA*SP	3	105.4163716	35.1387905	0.99	0.4015

Table 49. Treatments and Interaction Effects for Crumb Brightness of CWRS and CWES Bread Prepared at Fixed and Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	1511.9012753	503.9670918	45.03	0.0001
WA	1	99.1758398	99.1758398	8.86	0.0042
Fl	1	333.8536523	333.8536523	29.83	0.0001
SP	1	7.0461813	7.0461813	0.63	0.4306
Rep	2	37.5877358	18.7938679	1.68	0.1949
PT*SP	3	89.3487232	29.7829077	2.66	0.0558
PT*Fl	3	20.6994929	6.8998310	0.62	0.6070
Fl*SP	1	3.2236118	3.2236118	0.29	0.5934
PT*WA	3	34.0941688	11.3647229	1.02	0.3920
Fl*WA	1	0.1743931	0.1743931	0.02	0.9011
WA*SP	1	32.9882878	32.9882878	2.95	0.0910
PT*Fl*SP	3	32.5743945	10.8581315	0.97	0.4126
PT*Fl*WA	3	97.1956619	32.3985540	2.89	0.0422
PT*WA*SP	3	36.0313274	12.0104425	1.07	0.3671
Fl*WA*SP	1	1.6384729	1.6384729	0.15	0.7033
PT*Fl*WA*SP	3	6.4849154	2.1616385	0.19	0.9007

Table 50. Treatments and Interaction Effects for Void Fraction of CWRS and CWES Bread Crumb Prepared at Fixed and Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	0.00860607	0.00286869	89.10	0.0001
WA	1	0.00001000	0.00001000	0.31	0.5794
Fl	1	0.00087632	0.00087632	27.22	0.0001
SP	1	0.00127294	0.00127294	39.54	0.0001
Rep	2	0.00009400	0.00004700	1.46	0.2402
PT*SP	3	0.00033208	0.00011069	3.44	0.0221
PT*Fl	3	0.00002165	0.00000722	0.22	0.8793
Fl*SP	1	0.00000461	0.00000461	0.14	0.7066
PT*WA	3	0.00021443	0.00007148	2.22	0.0947
Fl•WA	1	0.00003253	0.00003253	1.01	0.3187
WA*SP	1	0.00000003	0.00000003	0.00	0.9772
PT*Fl*SP	3	0.00002639	0.00000880	0.27	0.8445
PT*Fl*WA	3	0.00001298	0.00000433	0.13	0.9392
PT*WA*SP	3	0.00002760	0.00000920	0.29	0.8355
Fl*WA*SP	1	0.00004522	0.00004522	1.40	0.2405
PT*Fl*WA*SP	3	0.00002271	0.00000757	0.24	0.8716

Table 51. Treatments and Interaction Effects for Young's Modulus (kN m^{-2}) of CWRS and CWES Bread Crumb Prepared at Fixed and Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	636.025001	212.008333	47.17	0.0001
WA	1	29.6272873	29.6272873	6.59	0.0128
Fl	1	4.16033653	4.16033653	0.93	0.3399
SP	1	1.34419912	1.34419912	0.30	0.5865
Temp	1	2.82352424	2.82352424	0.63	0.4311
MC	1	0.27627178	0.27627178	0.06	0.8050
Rep	2	115.631667	57.8158337	12.86	0.0001
PT*SP	3	0.95679714	0.31893238	0.07	0.9753
PT*Fl	3	7.32989438	2.44329813	0.54	0.6543
Fl*SP	1	0.00750189	0.00750189	0.00	0.9675
PT*WA	3	7.40438124	2.46812708	0.55	0.6507
Fl*WA	1	8.87923771	8.87923771	1.98	0.1650
WA*SP	1	9.31602420	9.31602420	2.07	0.1552
PT*Fl*SP	3	4.08291651	1.36097217	0.30	0.8233
PT*Fl*WA	3	24.8056175	8.26853919	1.84	0.1496
PT*WA*SP	3	10.1787932	3.39293109	0.75	0.5239
Fl*WA*SP	1	0.44442795	0.44442795	0.10	0.7543
PT*Fl*WA*SP	3	1.50597333	0.50199111	0.11	0.9529

Table 52. Treatments and Interaction Effects for Fracture Stress (kN m^{-2}) of CWRS and CWES Bread Crumb Prepared at Fixed and Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	8.12477263	2.70825754	23.18	0.0001
WA	1	0.63049850	0.63049850	5.40	0.0236
Fl	1	0.15809861	0.15809861	1.35	0.2493
SP	1	0.00539756	0.00539756	0.05	0.8305
Temp	1	0.04270201	0.04270201	0.37	0.5477
MC	1	0.03075258	0.03075258	0.26	0.6098
Rep	2	0.41683583	0.20841792	1.78	0.1767
PT*SP	3	0.23526846	0.07842282	0.67	0.5730
PT*Fl	3	0.10136390	0.03378797	0.29	0.8330
Fl*SP	1	0.00203466	0.00203466	0.02	0.8954
PT*WA	3	0.31816175	0.10605392	0.91	0.4427
Fl*WA	1	0.53673854	0.53673854	4.59	0.0361
WA*SP	1	0.27792373	0.27792373	2.38	0.1282
PT*Fl*SP	3	0.31766242	0.10588747	0.91	0.4434
PT*Fl*WA	3	1.04507761	0.34835920	2.98	0.0383
PT*WA*SP	3	0.62741796	0.20913932	1.79	0.1587
Fl*WA*SP	1	0.10724154	0.10724154	0.92	0.3418
PT*Fl*WA*SP	3	0.23655763	0.07885254	0.67	0.5708

Table 53. Treatments and Interaction Effects for Fracture Strain of CWRS and CWES Bread Crumb Prepared at Fixed and Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	0.11319234	0.03773078	13.76	0.0001
WA	1	0.00070311	0.00070311	0.26	0.6144
FL	1	0.08087501	0.08087501	29.50	0.0001
SP	1	0.00206518	0.00206518	0.75	0.3889
Temp	1	0.00004764	0.00004764	0.02	0.8956
MC	1	0.00007158	0.00007158	0.03	0.8722
Rep	2	0.04776670	0.02388335	8.71	0.0005
PT*SP	3	0.00303519	0.00101173	0.37	0.7756
PT*Fl	3	0.00668937	0.00222979	0.81	0.4916
Fl*SP	1	0.00055093	0.00055093	0.20	0.6556
PT*WA	3	0.00078319	0.00026106	0.10	0.9624
Fl*WA	1	0.00596621	0.00596621	2.18	0.1454
WA*SP	1	0.00060956	0.00060956	0.22	0.6390
PT*Fl*SP	3	0.00361748	0.00120583	0.44	0.7254
PT*Fl*WA	3	0.00803383	0.00267794	0.98	0.4098
PT*WA*SP	3	0.01721201	0.00573734	2.09	0.1107
Fl*WA*SP	1	0.00303318	0.00303318	1.11	0.2971
PT*Fl*WA*SP	3	0.00963936	0.00321312	1.17	0.3280

Table 54. Treatments and Interaction Effects for Fracture Energy (J m^{-3}) of CWRS and CWES Bread Crumb Prepared at Fixed and Optimum Water Absorption.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	3	302953.334	100984.44	6.83	0.0005
WA	1	89857.1113	89857.111	6.08	0.0166
FL	1	269303.515	269303.51	18.21	0.0001
SP	1	9052.73346	9052.7334	0.61	0.4370
Temp	1	1487.24673	1487.2467	0.10	0.7522
MC	1	0.43908	0.43908	0.00	0.9957
Rep	2	60310.0326	30155.016	2.04	0.1390
PT*SP	3	37391.2044	12463.734	0.84	0.4758
PT*Fl	3	2839.84725	946.61575	0.06	0.9787
Fl*SP	1	2378.64718	2378.6471	0.16	0.6898
PT*WA	3	45926.2402	15308.746	1.04	0.3835
FL*WA	1	84019.3685	84019.368	5.68	0.0203
WA*SP	1	26071.0961	26071.096	1.76	0.1892
PT*FL*SP	3	32648.1388	10882.712	0.74	0.5346
PT*FL*WA	3	123253.812	41084.604	2.78	0.0488
PT*WA*SP	3	122549.275	40849.758	2.76	0.0497
Fl*WA*SP	1	33826.3070	6.30703	2.29	0.1356
PT*Fl*WA*SP	3	84988.9332	28329.644	1.92	0.1366