



**WHEAT BREAD FIRMNESS AND FRESHNESS PROPERTIES DEPENDENCE ON
DOUGH FLOW AND HARDENING BEHAVIOUR****JEAN DIDIER KOUASSI-KOFFI^{1,2,3*}, FANKROMA MARTIAL THIERRY KONE³,
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Received 30th Nov. 2016; Revised 25th Dec. 2016; Accepted 10th March 2017; Available online 1st May 2017

ABSTRACT

Wheat bread rheological properties help to improve baking performance. We strive to show how the main properties of bread such as firmness and freshness can be predicted from knowledge of the basic dough rheological properties. Glucose oxidase was added to the bread dough flour in order to improve its rheological properties. At any constant cross-head speed in lubricated squeeze flow rheology, a power law could be fitted to the stress versus strain data depending on the dough viscoelasticity level. The “consistency index” (K) increases continuously with the strain and the “flow behaviour index” (n) is constant only up to a low strain value (≈ 0.25) and then decreases. Reliability properties of bread such as rising volume, density, strength and extensibility to deformation were determined as indicator of firmness and freshness properties. It was obtained $45.4\text{--}87.8\pm 1\%$ of bread peak resistance to deformation and was highest for the bread enriched by glucose oxidase than the control bread in a ratio of $4.5\pm 0.1\%$. These rising volume and decreasing density of the bread lead to

increase its firmness and freshness properties which depend thus on the initial dough flow and hardening behaviour level.

Key words: Wheat bread; firmness; dough flow behavior; lubricated squeeze flow rheology

INTRODUCTION

Bread is a bakery product preferred by consumers for its firmness and freshness which are indicators of quality. These physical properties are essential for bread making technology. They give valuable information such as strength, consistency, resistance and extensibility during the bread making process [1].

Rheological properties of bread dough initially at the origin of the bread quality change greatly at breadmaking process. During the formation and processing of wheat bread dough and its transformation to bread, a large number of physical, chemical and biochemical changes on the microstructural level, take place. Those changes can have significant effects on the machinability of the bread dough and then the quality of the final bread [2, 3]. In these conditions, accurate assessment of bread structure has spawned a great deal of several researches the last few years. Firmness and freshness of the bread crumb depend essentially of flour, water, temperature and time of baking during breadmaking process [3].

Bread is a leavened food produced via fermentation of flour starch involving

chemical interactions of various food ingredients. These interactions can be adjusted to create desirable products, once the underlying chemical and physical processes are well understood [4]. Some studies have been devoted to various aspects of breadmaking process regarding the final bread physical appearance. Wheat flour, water, salt, sugar, yeast and sometime other ingredients are often mixed in varying proportions for fermentation and then baking [4, 5]. This baking process represents a highly complex interaction of physical, chemical and biological processes to obtain bread. Mixing transforms the combination of flour, water and other ingredients into cohesive viscoelastic dough. During baking, there is the combination of gas production and retention which cause changes in bread dough rheological properties due to the flour proteins reactions [4, 5].

The microstructure of flour changes continuously during breadmaking process until, in the final bread, the structure is fixed [6]. Rheological properties of wheat bread dough are largely governed by gluten. Gluten, the protein phase of wheat flour,

also has the ability to form a continuous macromolecular network. This structure of bread dough depend on gluten and its possible interaction to other proteins, lead to its rheological properties difficult for prediction [6]. The bread dough proteins oxidation induces the formation of proteins network and improves the bread structural properties. Enzymes are used in breadmaking to optimize bread dough properties and improve bread quality. The use of enzymes instead of chemical oxidants is a very interesting option to improve breadmaking performance, because they are perceived as natural and non-toxic food components. Enzymes are specific biological catalysts able to react under mild conditions of temperature ($T^{\circ}\text{C}$) and potential of hydrogen (pH). They contribute to the formation of covalent bonds between polypeptide chains within proteins (intramolecular crosslinks) or between proteins (intermolecular crosslinks) [7, 8].

Glucose Oxidase (GOX) (EC 1.1.3.4) from *Aspergillus niger* catalyzes the oxidation of β -D glucose to gluconic acid and hydrogen peroxide. GOX is an enzyme with oxidizing effect due to the hydrogen peroxide released from its catalytic reaction [7, 8]. This reaction is the mechanism by which GOX improves bread quality. Wikström and Eliasson [8] indicate that

hydrogen peroxide produced during GOX reaction causes the oxidation of the free sulfhydryl units. It gives disulfide linkages and the gelation of water soluble pentosanes. These proteins reactions change wheat bread dough rheological properties. They observed an increase in bread tenacity and extensibility upon GOX addition.

Much of researches in bakery processing have been devoted to the testing of physical properties of fresh dough and then bread freshness. The study of wheat bread rheology can provide numerous information about bread dough formulation, structure, processing and then final bread quality [9]. The objective of this study was to ensure wheat bread firmness and freshness in order to prevent too compact structure of the final bread crumb. It supposed to provide concrete information of consistency, hardness, strength and extensibility on the bread dough in lubricated squeeze flow rheology and then predict its final bread quality. To reach this objective, a previously experienced quantity of glucose oxidase was added to the dough to improve its viscoelasticity level [8]. Then we had related bread compressibility to its firmness and to dough squeeze flow rheological properties. These rheological properties are so important basis knowledge for baking process and then the final bread quality.

MATERIALS AND METHODS

Ingredients for bread dough

All-purpose wheat flour (type 55) variety “Apache” obtained from Groupe Soufflet was used without any chemical or proteins supplementation. It contained 12.3 wt % water, 11.6 wt % protein and 0.58 wt % ash (moist basis). It was particularly intended for baking products. It was stored in a freezer at -20°C for 7 days and then at 4°C for 1 to 3 days before using. Basic dough formula (flour basis) consisted of 2.0 wt % salt, 1.62 wt % glucose, 51.96 wt % added water, 5 nkatal/g of GOX (only for dough with GOX. It could be used 48 hours after preparation) and 3 wt % yeast (it was used up to 96 hours after preparation and only for dough fermentation). The ingredients were weighed and placed in sealed boxes in a refrigerator at 4°C during the night before the test.

Mixing ingredients, kneading dough and manufacture

The Brabender Farinograph (Brabender-USA) was used to mix ingredients and to knead the dough. It has a capacity of 300 g flour (450-500 g dough).

For the kneading process, we have used a quantity of 200g flour, the maximum water absorption capacity indicated by the Brabender device and 85% of humidity (ambient conditions). The water temperature was $4\pm 0.2^{\circ}\text{C}$ in order to have

correlation with the water recirculated temperature in the Farinograph system.

The kneading time was 5.8 minutes necessary to obtain bread dough with a high quality [10].

A dough at 41.3 wt % water (total water moist basis) was obtained at the end of the kneading process. It was then left to rest for 5 min at 25°C tightly closed in the storage system of Chopin Alveograph to allow the relaxation of induced stresses during kneading process. The manual laminating system of the Chopin Alveograph was used under lubricated conditions to prepare samples of thicknesses $L_0 = 08 \pm 0.15$ mm by manual rolling (8 round trips). A disk was then cut with a circular punch (diameter 32 mm) to obtain samples for rheological tests with an initial aspect ratio $2R_0/L_0$ of 4. Paraffin oil ($\eta = 0.15$ Pa.s) was used as a lubricant before mixing ingredients and during dough manufacture. It was satisfied the conditions of Secor *et al.* [11] and Macosko [12] considering wheat flour dough viscous properties.

Lubricated squeezing flow (LSF) experiments

Two rheometers, MCR301 (Physica-Anton Paar, Austria) and CT3 Texture Analyzer (Brookfield Engineering Laboratories, Inc. USA) have been used to the lubricated squeezing flow experiments In order to ensure reliable results [13].

Test performed by rheometer MCR301 (Physica-Anton Paar, Austria)

LSF experiments have been performed with a rheometer MCR301 (Physica-Anton Paar, Austria) using paraffin oil ($\eta = 0.15$ Pa.s). A stainless steel upper plate (50 mm diameter) and a Teflon Peltier down plate (100 mm diameter) were used. After resting time (30 min) at 18-20°C in the Chopin Alveograph chamber, the bread dough sample disk was placed on the lubricated Peltier plate of the MCR 301. The lubricated upper plate was then placed in contact with the surface of the disk at a contact force no greater than 0.1 Newton (N) but allowing contact between the upper plate and the entire surface of the lubricated dough disk. This sample was then left to rest for 5 min to allow the relaxation of induced stresses until the normal force was less than 0.01 N.

When starting the LSF experiment, even at very small compression speeds, the normal force increases from the beginning of the experiment without any change of curvature that may indicate a change of contact surface. Thus, it was considered that the sample was totally in contact with both plates. Constant plate speed (CPS) tests were carried out up to 2.4 mm dough final thickness at different speeds, v , from 0.005→1.5 mm.s⁻¹, allowing to provide concrete rheological properties such as

consistency, hardness, behavior, apparent viscosity, stress, strain and strain rate of the bread dough sample. Constant biaxial extension rates ($\dot{\epsilon}_b$) from 0.005→1.5 s⁻¹ were obtained by varying $L(t)$ (the lubricated upper plate displacement) following this equation :

$$L(t) = L_0 \exp(-2\dot{\epsilon}_b t)$$

(1)

where L_0 is the initial sample thickness.

Under both driving modes, the resulting normal force, F , was measured every 0.015 s. The $L(t)$ - $F(t)$ files were generated by a data-processing interface ($F(t)$ is the normal force). All tests were performed at a temperature of 25°C. After completion of the test, when the upper plate was raised, no dough remained on it, and the thin dough film did not present any holes or discontinuities.

Under various experimental conditions, it was observed that the dough disks retained a circular shape and displayed rapid strain recovery indicating that extension was, at least in part, reversible.

Test Performed by Rheometer CT3 Texture Analyzer (Brookfield Engineering Laboratories, Inc. USA)

Dough freshness and hardness properties were determined by CT3 Texture Analyzer (10 kg load cell). TexturePro CT V1.5 Software were using for equipment control

and initial data handling. The maximum force of the first compression cycle was also used. A cylinder probe TA4/1000 of 38.1mm diameter was attached to a moving cross-head. The bread dough samples were subjected to compression under the following conditions: 1 mm.s⁻¹ constant cross-head speed, 5g trigger load and 70% maximum deformation in lubricated conditions. Paraffin oil ($\eta = 0.15$ Pa.s) was used satisfy the conditions described by Secor *et al.* [11] and Macosko [12].

Molding dough

After kneading, 250g of dough were removed. The hands were first cleaned with sample flour in order to minimize stickiness dough on the skin.

The bottom of the mold was covered with greaseproof paper. The edges were lubricated with a thin layer of rapeseed oil ($\eta = 0.16$ Pa.s) at temperature of 25°C. This oil was used as a lubricant satisfying the conditions of Secor *et al.* [11] and Macosko [12], considering wheat flour dough viscous properties. This lubricant was used in order to restore the entire kneading dough.

Fermentation dough

The mold of the bread dough was placed in a fermentation oven. It was regulated at 25°C of temperature and 85% of humidity for fermentation process.

The molded dough was fermented during 90 min. This time (90 min) was essential to

obtain better fermented dough than those made with a standard 180 min of fermentation [14]. The dough was then punched and molded for baking process.

Baking dough

The fermented dough was baked in domestic oven (Henry Simon Limited, Cheshire, UK) during 60 min at 180°C of temperature. The beginning and the end of the process were indicated by a beep sound emitted by the oven temperature regulator system.

Wheat bread and its volume measurement

White loaf bread was obtained at end of the baking process. It was remained 2 hours at 25°C in the storage room 85% of humidity. It was then placed in an airtight plastic bag during 24 hours for its relaxation. Method of colza seeds was used to measure the volume of the bread [15].

The bread rheological properties were performed after this storage period.

Compression bread crumb

Bread freshness and hardness properties were first determined by CT3 Texture Analyzer (10 kg load cell) using TexturePro CT V1.5 Software (Brookfield Engineering Laboratories, Inc. USA) for equipment control and initial data handling. A cylinder probe TA4/1000 of 38.1mm diameter was attached to a moving cross-head.

A stainless steel knife was used to prepare cylindrical slices bread 25 mm of diameter and 52 mm of thickness. Sample bread was then centered under probe. It was compressed under the following conditions: 1 mm.s^{-1} of constant cross-head speed, 5g of trigger load and 70% of maximum deformation.

A second test was performed by TAXT2i (Stable Microsystems Ltd, Godalming, UK) with a flat stainless steel probe 10 cm of diameter and 25 kg of cell to confirm the CT3 Texture Analyzer results. The Texture Expert Exceed software (version 2.03) was used for the data acquisition and processing.

Cylindrical slices crumb 25 mm of diameter and 52 mm of thicknesses were compressed at 0.33 mm/s of constant cross-head speed to obtain 70% of maximum deformation. The test was taken place immediately after making slices breads in order to avoid samples crumbs drying.

Bread crumb and crust physical properties

The bread crust and crumb were directly observed visually taking into account the color, touch feeling, crust thickness and crumb alveoli width and number.

Samples slices bread were cut in the parallel direction of its lifting into the oven during the baking process in order to preserve and protect their alveolar structure.

Samples breads 3 mm of thickness were scanned. Picture was taken with a flatbed scanner (Epson® Perfection V370 Photo Flatbed Scanner) covered with a black box to avoid the influence of the surrounding light. This device provided good contrast between the black background and the clear brackets. The slices breads were positioned in the center of the scanner in order to minimize the variations of resolution during imaging.

The images were taken with 4800 x 9600 dpi optical resolution and enlargement up to 13" x 19". These samples were eventually observed visually from (x100) of image scale magnitude. They showed slices crumbs alveolar width and crusts thickness. Slices crumbs and crusts were visualized 24 hours after the baking process in order to have total firmness and freshness concentrations.

Statistical Analysis

All determinations reported in this study were carried out in triplicates. Mean value and standard deviation were calculated. Analysis of variance (ANOVA) and correlations were also performed.

Tukey's Honest Significant Difference (HSD) test at $P < 0.05$ was used for mean values separation. It was made in order to evaluate differences among samples while the relationship between measured

parameters was assessed by Pearson's test (significant level at $p \leq 0.05$).

RESULTS AND DISCUSSION

Dough Resistance, Strength and Extensibility to Deformation

Lubricated squeezing flow experiments on wheat flour dough have been performed in constant plate speed mode, i.e. at a permanently increasing extension rate [16]. It was shown that at any constant biaxial strain, a power law could be fitted to the stress versus extension rate data. The "consistency index" (K) increased

continuously with the strain and the "flow behaviour index" (n) was constant only up to a low strain value (≈ 0.25) and then decreased. For wheat flour doughs, an increase in K with extension may be associated to a strain-hardening and viscoelasticity phenomenon in lubricated squeezing flow experiments [16]. In this case, wheat dough strain-hardening, viscoelasticity behaviour and then the bread compressibility experiments were performed in lubricated squeezing flow conditions in order to show how to prevent the final bread quality.

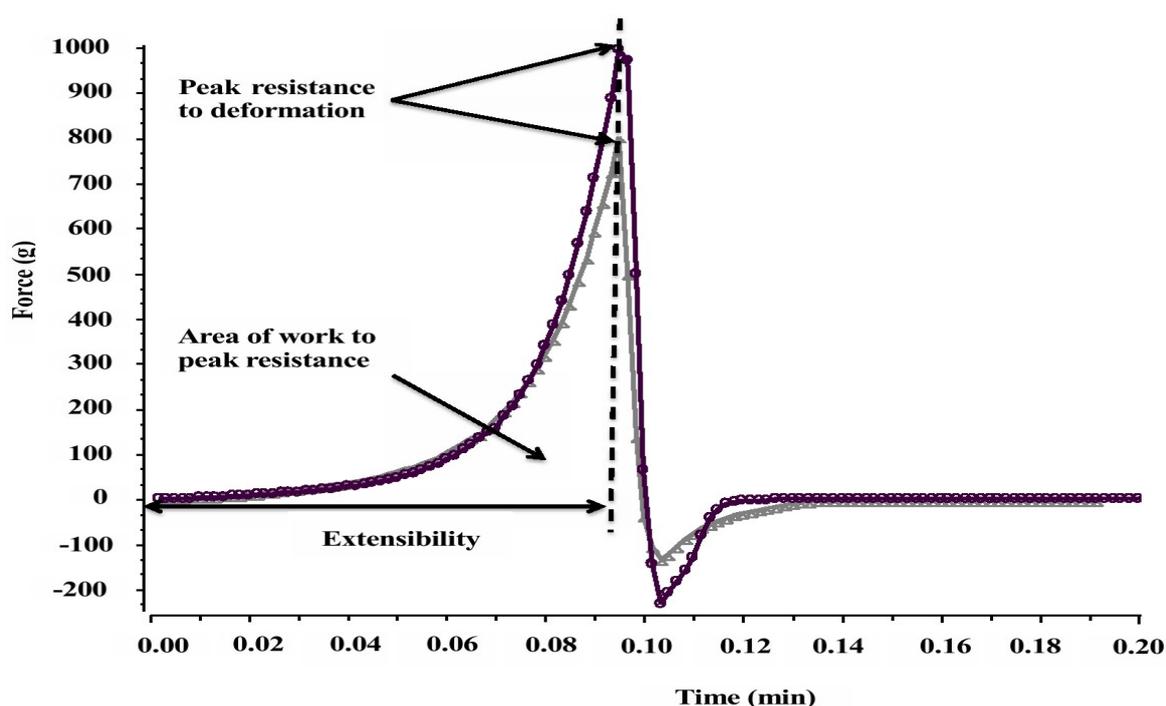


Figure 1 Variations of wheat flour dough compression force versus time. (o) dough enriched by GOX, (Δ) dough without GOX, temperature = 25°C. Data obtained from tests performed by rheometers CT3 Texture Analyzer (Brookfield Engineering Laboratories, Inc. USA) and MCR301 (Physica-Anton Paar, Austria) [17]

Figure 1 shows the variations of wheat dough compression force measured versus time [17]. Wheat dough compression test performed by rheometers is based on the

theory that dough peak resistance and compressibility depends on the dough consistency level. These rheological theories were explored and exploited to

study wheat dough behavior versus stress amplitudes. Dough peak resistance to deformation as shown by maximum height within curves is so higher for the dough enriched by GOX than the control dough in a ratio of $0.8\pm 0.1\%$ (Fig. 1). However, the both doughs were consistent for baking products because their values were higher than 500 UB [18].

The distance between the trigger value and the peak resistance measured in millimeters (mm) is obtained after 0.09 min of compression (Fig. 1) showing the dough extensibility level. However during the first 0.07 min of compression, the extensibility of the bread dough without GOX is slightly higher than the dough enriched by GOX in a ratio of $0.15\pm 0.01\%$ (Fig. 1). The area between trigger point and peak resistance is larger for the dough enriched by GOX than the control dough. This area indicates the both doughs work level. Results over a period have shown greatest and most significant difference between the both samples within dough extensibility and area of work to peak deformation.

The strength values of both doughs are shown to illustrate some inconsistency, which may affect the impact of the test data. These results were agreed with Rasiah *et al.* [19] conclusion when they observed an increase in dough elasticity and a

decrease in dough viscosity with GOX addition. However they results are lower than our dough work values with GOX addition in a ratio of $1.5\pm 0.3\%$. The dough resistance, strength and extensibility to deformation depend on its viscoelasticity level. Wheat dough rheological properties variations affect the gas bubbles development and their rising volume during fermentation process and then the final bread quality.

Peak resistance, area of work and extensibility of wheat bread crumb to deformation

Peak resistance, area of work and extensibility of the wheat bread crumb to deformation are defined as an indication of bread firmness and freshness. The bread firmness and freshness could be influenced by the dough viscoelasticity level [17]. There could have significant differences ($P < 0.05$) physical properties between breads of different viscoelasticity level [17]. In order to know how bread dough viscoelasticity level increasing by the GOX supplement could influence bread quality, the resistance and extensibility tests of bread to deformation were performed (Fig.2).

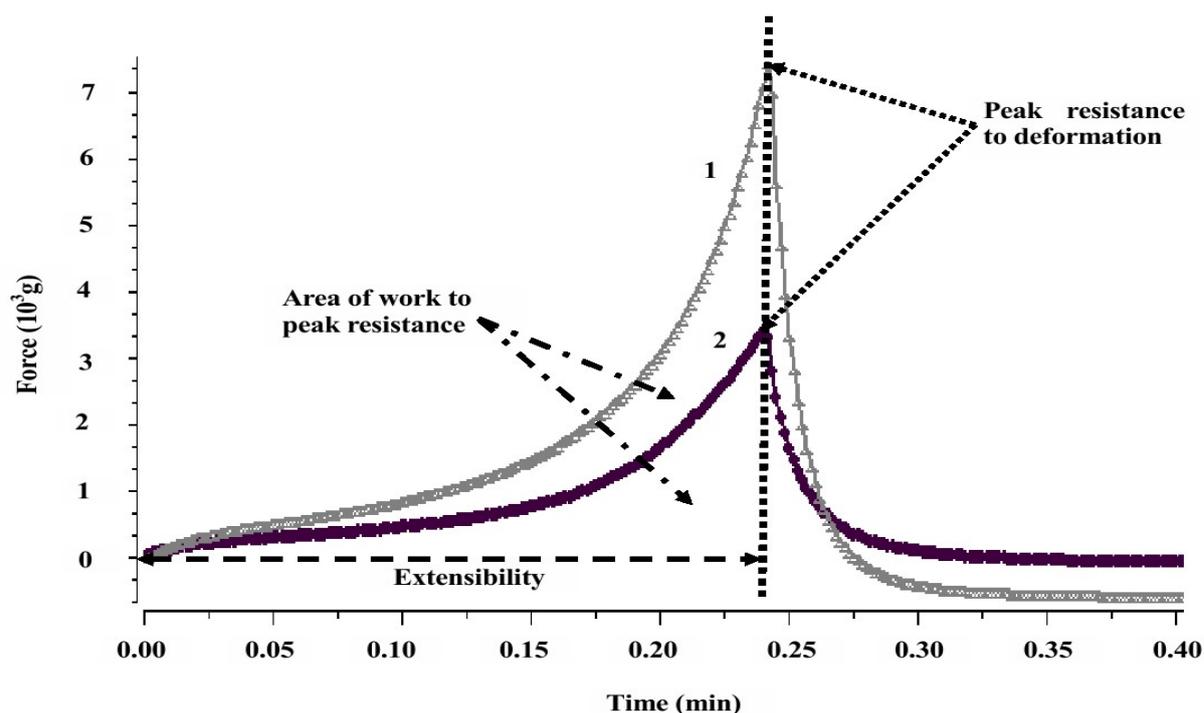


Figure 2 Variations of wheat bread crumb compression force versus time. (Δ , 1) bread crumb enriched by GOX, (\blacklozenge , 2) control bread crumb without GOX, test performed by rheometer CT3 texture analyzer (Brookfield, USA), temperature = 25°C.

Figure 2 shows the variations of wheat bread crumb compression force measured versus time. Bread crumb peak resistance to deformation, as shown by maximum height within curves, may be termed "crumb strength" and indicator of better quality of bread (Fig. 2). It specifies that the bread crumb enriched by GOX is stronger than the control bread crumb. Ratio of $4.5 \pm 0.1\%$ was distinguished between the both peak resistances of bread crumb. In the both cases, the crumb is consistent because their dough consistence values are respectively high than 500 Brabender Unit (BU), the arbitrary unit value for dough consistency quality.

The distance between the trigger value and the peak resistance is measured in millimeter (mm) and termed "crumb extensibility" necessary for freshness and firmness quality of the bread. At the end of compression test, the extensibility time is 0.24 min for the both breads crumb (Fig. 2). This extensibility time (0.24 min) indicates the force period of crumbs resistance to deformation. It confirms the degree of the both crumb elasticity. The area between trigger point and peak resistance which may be termed "bread crumb work" is larger for the dough enriched by GOX than the control dough. This work area of bread crumb confirms the strength effects of bread enriched by GOX than the control

bread. This behavior of the bread crumb approves its dough height tenacity level related by Hibberd and Parker [20]. Similar results of these authors over a staling period have shown greatest and most significant difference between samples within bread crumb extensibility and area of work to peak deformation. However the peak values of crumb strength were shown to illustrate some inconsistency. They may thus affect significantly the tests data which were confirmed by Bloksma [21].

These observations obtained from slices crumbs show that the bread enriched by GOX has good resistance, strength and extensibility than the control bread without GOX. Some research groups [22] are obtained similar results observing increasing effects of bread tenacity, elasticity and extensibility with their bread samples supplemented by GOX. Their results are slightly lower than our values with GOX addition in a ratio of $1.5 \pm 0.1\%$. These higher values of bread physical properties are probably due to reactions on dough because of GOX addition [8]. Indeed, wheat flour supplemented with GOX is able to form cohesive bread dough having high level of viscoelastic and possessing ability to retain gas and form better bread. These gas bubbles development during fermentation are more essential for light texture of bakery

products. Hibberd and Parker [20] described similar results with several dynamic measurements of bread which were correlated to be its static firmness.

Bread rheological properties such as strength, consistence and extensibility are important for the milling and bakery industries in view of the prediction of dough processing parameters and the quality of final bread. Their quality variations are proportional to the bread firmness measurements (Fig.1, 2, 4) which are as indication of bread crumb freshness. The higher is the dough viscoelasticity level; the better is the crumb (Fig.1, 2, 4) to reconstitute the bread and to have a fine and consistent structure and texture as indicators of good product for consumers.

Wheat bread weight and volume measurement

The alveolar structure of bread crumb is an important factor that contributes to the textural properties of fresh bread. It is an important indicator of bread weight and volume quality. Numerous are crumb alveoli; better would be the bread digestibility. The texture and density of bread are controlled by the way their rheology during the baking process. They cause variations of bread weight and volume versus time after baking [23]. In order to know how modifications of the bread dough cellular structure by GOX can

influence the final bread physical appearance; the weight and volume test were performed.

The bread weight and volume are shown that the density of the dough enriched by GOX (0.27 ± 0.01 g/ml) is more stimulating than the witness dough (0.32 ± 0.03 g/ml) in a ratio of $84.4 \pm 0.02\%$. The density of breads may also depend on the loss of water due to the temperature rising ($25 \rightarrow 180^\circ\text{C}$) and proteins catalytic reactions (GOX supplement) during the baking process confirmed by Moore and Hosney [24]. Several complex proteins reactions are disrupted in the dough with the addition of GOX which cause the reorganization of the final bread structure and texture.

The weight and volume of the bread with GOX supplement are more significant (higher) than the control bread due to these initial catalytic reactions on dough which improve its alveolar structure. These reactions permitted the reorganization of proteins network from the mixing to baking via kneading and fermentation processes. These reactions permitted to obtain voluminous and airy bread. These results are agreed with the texture of baking

products described by Vemulapalli *et al.* [25]. They had demonstrated also that physical property of bread such as density (w/v) which may be related to gluten quantity and quality and thus to the rheological properties of bread dough, depend of the initial cellular structure of the dough. This reorganization of dough macrostructure depends of the proteins networks which were modified partially by GOX addition to wheat flour at the early steps of breadmaking.

Wheat bread crumb compression and relaxation force variations versus time

In order to ensure reliable and approved results, a second rheometer TAXT2i (Stable Microsystems Ltd, Godalming, UK) (Fig. 3) was used. This rheometer was also used for compression measurements just as the first rheometer. Bread crumb compression and relaxation under an applied force are an indication of bread resistance and consistency to deformation. Better are the compression and relaxation of the crumb, better are the firmness and freshness of the bread.

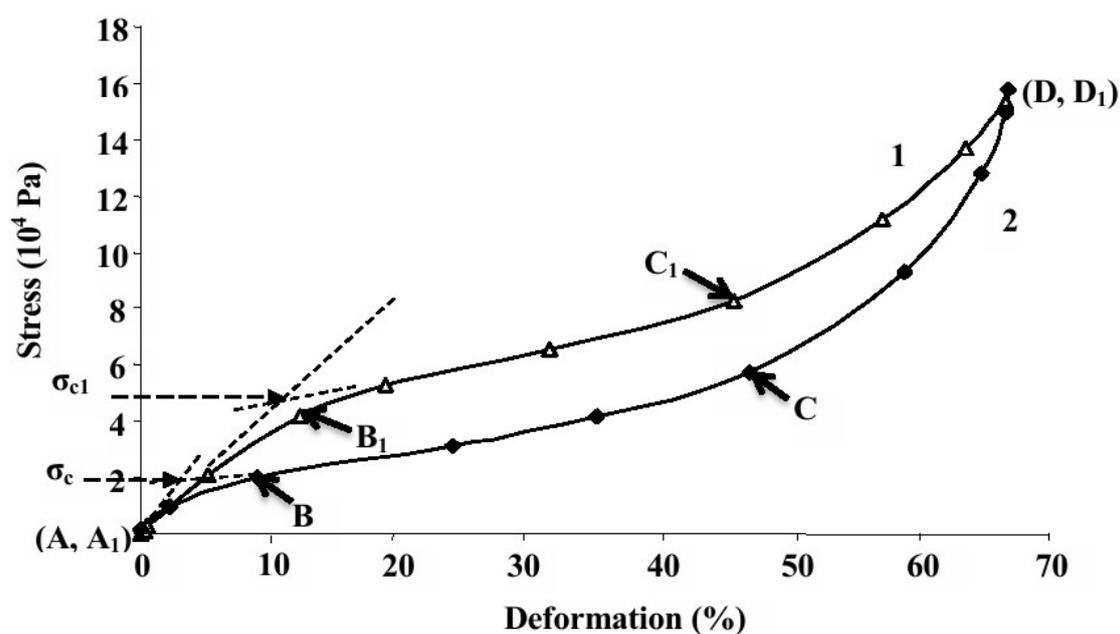


Figure 3 Variations of stress amplitudes versus the wheat bread crumb deformation. (A, 1) bread crumb enriched by GOX, ((♦, 2) control bread crumb without GOX, (σ_c , σ_{c1}) stress limits, (AB, A_1B_1) deformation elastic phase, (BC, B_1C_1) non-reversible compression phase, (CD, C_1D_1) densification phase, (Pa) Pascal.

Figure 3 indicates the variations of the stress amplitude as a function of the bread crumb deformation i.e., the crumb resistance to compression force. The normal force increases versus time for the both crumb (slices crumb obtained with dough enriched or no with GOX). However, there are high increasing effects of the normal force obtained with of the crumb supplemented by GOX. It was observed $4.5 \pm 0.1\%$ of maximum stress values ratio between the both crumbs (Fig. 3). Willhoft [26] has reported similar increasing results of compression force with bread crumb without GOX. He has concluded that the crumb firming was one of the most important elements of bread staling. It was also the simplest to define

objectively the crumb freshness. He has then demonstrated that the importance firming of the bread was as an indicator of bread quality. In this way the high firmness of the crumb enriched by GOX shows a best quality.

However the rising effects of bread crumb compression force obtained in this study are higher than those reported by this literature in a ratio of $1.7 \pm 0.2\%$ for the both tests. This important difference of the bread resistance to deformation is probably due to GOX catalytic reactions during mixing, kneading and fermentation processes.

The shape of the stress curves during the compression of the both crumbs is approximately similar. The stress magnitude variations have three main

phases shown by the shape of deformation-time diagram plotted by the rheometer [27] (Fig. 3). The compression tests performed on the samples crumbs give stress limits (σ_c (N/m^2)) and young apparent module E_{app} (kN/m^2) for the both crumbs during their deformation. In any case, elastic deformation, non-reversible compression and densification phases are higher for the crumb enriched by GOX (Fig. 3). It follows:

- Control bread crumb without GOX : $\sigma_c = 2$ (kN/m^2) and $E_{\text{app}} = 1.2$ (kN/m^2);
- Bread crumb enriched by GOX: $\sigma_c = 5$ (kN/m^2) and $E_{\text{app}} = 5.6$ (kN/m^2).

In the both case, a ratio of 40% is obtained for stress limits (σ_c) and 21% for apparent module (E_{app}) between the both crumbs. The slices crumbs variations curves versus the deformation include three (Fig. 3) similar domains of those related by Attenburrow *et al.* [27]. They depend of the stress amplitude and the bread quality properties.

The first area is the elastic deformation phase where the apparent Young modulus (E_{app}) value indicates the elasticity behavior of the bread. It corresponds to the bread reversible deformation domain and its best quality response to deformations.

The second area corresponds to the non-reversible compression phase of the bread. In this area the walls of the bread are flexed

by limit stress (σ_c) indicating the alveoli elasticity limits. This crumb is also more airy.

Finally the densification phase for which there is almost no air into the crumb alveoli. They are crushed and the walls are compacted. These effects will cause more deficiency reactions of the crumb, producing linearly increasing of the stress curves versus the bread deformation.

For each behavior phase of crumb to deformation, similar results are reported by Malkei *et al.* [28]. However they have used wheat flour without GOX adding. They indicated that the Young modulus and the critical stress level depended of the bread compression direction compared to the axis of the dough expansion into the oven. Hibbert and Parker [20] reported again that bread compression tests performed perpendicularly to the bread dough expansion axis into the oven give best values of critical constraints (σ_c) and apparent Young modulus (E_{app}). However improved values of critical constraints (σ_c) and apparent Young modulus (E_{app}) are obtained in this study by GOX supplemented to wheat flour than their results (Fig. 3). Indeed, improving effects of bread crumb compression force obtained in this study are higher than those reported by this literature in a ratio of $1.7 \pm 0.2\%$ for the both tests shown above.

Bread crumb physical properties

Physical properties of the bread are the first qualities criterions of consumers choices because they can be touched, observed and smelled directly. Bread crumb alveoli width and their quantity can predict its aeration, porosity and compatible

properties related by Bailey [29]. These characteristics of bread give indications of digestive quality.

In order to know how the physical properties of the bread crumb can improve basic knowledges, visual characterization of slices bread by images pickup was done.

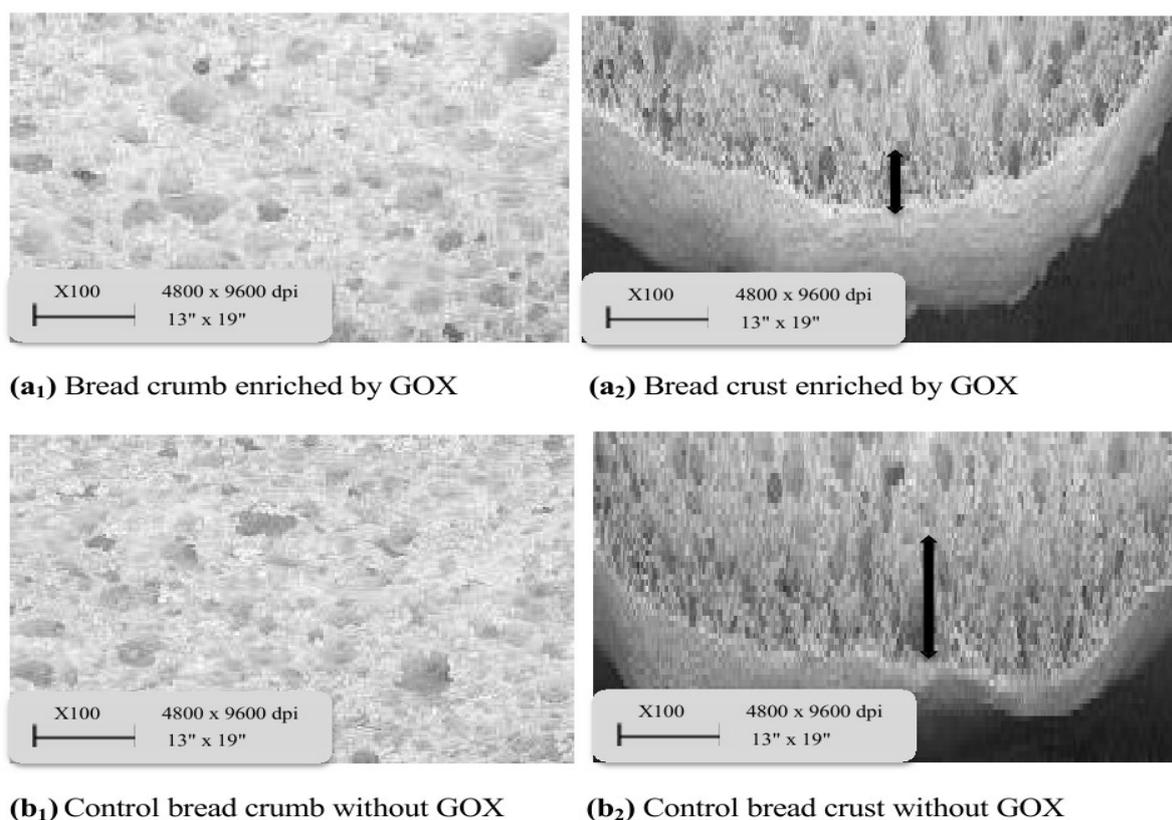


Figure 4: Representative images of wheat bread crumb and crust alveolar physical appearance obtained by Epson® Perfection V370 Photo Flatbed Scanner. (a₁; a₂) bread crumb and crust enriched by GOX, (b₁; b₂) control bread crumb and crust without GOX. (4800 x 9600 dpi) image optical resolution, (13" x 19") image enlargement. (x100) amplitudes of images scale, (↔) bread crust thickness level.

Figure 4 shows images of slices crumbs alveolar width and crusts thickness for both samples breads. The crumb of bread enriched by GOX shows more alveoli with larger and rounded diameters. The crust has less thick and homogeneous appearance (Fig. 4a). In contrast, the crumb of the

control bread obtained without GOX shows few alveoli with smaller width and heterogeneous appearance. This crumb is sparse and thick. The crust is thicker and slightly darkened. It presents more white dots which are not good quality marks (Fig. 4b).

Higher is alveoli quantity and less is the thickness of the crust, better is the quality of the bread confirmed by Hibberd and Parker [20]. These physical properties of bread are very important to staling evaluation and general crumb quality control [29]. They confirmed that measurement of bread crumb rheological properties is the evaluation of its staling, conservation and then its general quality control. Other article [26] of bread crumb rheology study devoted sections to measurements of the firmness, softness, compressibility and elasticity which are similar with our results. These rheological properties are necessary and as indicator of better quality of bread.

These rheological properties of bread crumb obtained with GOX added can now led to several methods developed in rheology and microscopy for bread crumb structure and texture studies.

Bread firmness and compressibility properties dependence on dough flow and hardening behaviors

Bread compressibility properties are studied in order to establish a relationship between its compressibility and the dough flow and hardening behaviors. During wheat dough compression, all data and results are derived from calculations of the "consistency index" K , "flow behavior index" n , and "strain hardening index" m .

They used strain and stress values for calculations which depend of the force applied, the sample dough sizes. These calculations permitted to reach to the dough flow and hardening behaviors and then evaluate the resulting bread freshness and firmness properties. So that at constant crosshead speed mode, and considering dough as an incompressible material, the biaxial strain could be shown that [16]:

$$\varepsilon_b = 1/2.Ln(L_0/L(t)) \dots \dots (2)$$

where L_0 and $L(t)$ are the initial sample thickness and its value at time t , respectively. The 1/2 factor is added to take into account the biaxial character of the deformation. The biaxial extension rate is:

$$\dot{\varepsilon}_b = -1/2.[dL(t)/L(t).dt] \dots \dots (3)$$

The corresponding biaxial stress is then:

$$\sigma_b = F(t)/S(t) = F(t)/\pi.R^2(t) \dots \dots (4)$$

where, $F(t)$, $S(t)$ and $R(t)$ are the measured normal force, the dough disk area and its radius, respectively. The initial dough disk radius used during the present study was much smaller than those of the upper and lower plates of the instrument. The values of the deformation (i.e., stress and strain rate) obtained were used versus dough strain to determine its apparent viscosity. Therefore, if the dough was considered as incompressible, Eq. (4) becomes:

$$\sigma = F(t).L(t)/\pi.R_0^2 \dots \dots (5)$$

where R_0 is the initial dough disk radius. The apparent biaxial viscosity is given by:

$$\eta_{\text{app}} = \sigma_b / \dot{\varepsilon}_b \dots\dots\dots (6)$$

An empirical analysis of the data obtained on wheat flour dough and gluten using a mechanical testing machine at a constant crosshead speed and with plate radius equal to the dough disk radius ($R(t) = R_0$) was developed by Van Vliet's group [30]. The force, $F(t)$ and displacement, $L(t)$ curves at various crosshead speeds (v) were converted into stress-strain curves using Eq. (2) and Eq. (4). At a given value of v , there was a simultaneous increase in σ_b and $\dot{\varepsilon}_b$. The group of Van Vliet [30] observed that, at any fixed value of ε_b , a power-law could be seen between σ_b (or η_b) and $\dot{\varepsilon}_b$. For a fixed value of $\dot{\varepsilon}_b$, σ_b increases exponentially with ε_b . The following relationship could then be written:

$$\ln \sigma_b = A + n \ln \dot{\varepsilon}_b + m \varepsilon_b \dots\dots\dots (7)$$

where A , n and m are constant to be adjusted to experimental data. It should be noted that, under experimental conditions, m only remains constant in a limited strain domain. Then for any given ε_b , Eq. (7) corresponds to a power law, where A is equal to $\log K$, K being the "consistency index". When $n < 1$ is obtained, i.e. η_b decreased and $\dot{\varepsilon}_b$ increased. This case corresponds to a strain rate thinning behavior for a purely viscous extensional flow ("flow behavior index"), and $m > 0$. Factor m in Eq. (7) was interpreted by van Vliet's group [30] as a "strain hardening"

parameter. Van Vliet *et al.* [30] proposed that, in the context of biaxial extension, no necking will occur if these conditions are applied to the results obtained in LSF. In this case, the parameter m became:

$$m = d \ln \sigma_b / d \varepsilon_b > 2 \dots\dots\dots (8)$$

When ensuring LSF at a constant crosshead plate speed, the biaxial strain rate, biaxial strain and resulting stress vary throughout the test. An increase in the biaxial deformation rate during squeezing should induce a continuous increase in stress. However, the "strain hardening" parameter m , continues to be a subject of research, interpretation and discussion. It is also of considerable interest when it is related with dough behavior during proofing and oven-rising. Consequently, the data processing to obtain the dough rheological properties remains long and difficult, being of capital interest for scientists. However, only values of these parameters, K , "consistency index", n , "flow behavior index" and m , "strain hardening index", can permit to predict the future bread freshness and firmness properties such as shown in figure 4.

CONCLUSIONS

Wheat bread rheological properties study has permitted to obtain description of its firmness and freshness. These properties of the bread depend largely on the dough flow and strain hardening behaviors. The strain-hardening and viscoelasticity behaviors of

the dough performed in lubricated squeezing flow conditions show an opportunity to prevent the final bread quality. The glucose oxidase has enhanced the dough flow, hardening indexes, and its structure that have permitted to obtain a good quality of final bread such as airy and tender crumb, less crunchy, more alveoli in the crumb, thinner and thicker crust than a control bread without enzyme adding.

ACKNOWLEDGMENTS

We thank to Romanian Government and Francophone University Agency (AUF) who are supported partially this research project through the Eugen Ionescu Postdoctoral scholarship program.

We thank again the support from European Social Fund, Human Resources Development Operational Program, Project No. POSDRU/159/1.5/S/132765.

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