Research Article

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Relation between ultrasonic properties, rheology and baking quality for bread doughs of widely differing formulation

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Abstract

BACKGROUND: The objective was to evaluate whether an ultrasonic reflectance technique has predictive capacity for breadmaking performance of doughs made under a wide range of formulation conditions. Two flours of contrasting dough strength augmented with different levels of ingredients (inulin, oil, emulsifier or salt) were used to produce different bread doughs with a wide range of properties. Breadmaking performance was evaluated by conventional large-strain rheological tests on the dough and by assessment of loaf quality. The ultrasound tests were performed with a broadband reflectance technique in the frequency range of 0.3–6 MHz.

RESULTS: Principal component analysis showed that ultrasonic attenuation and phase velocity at frequencies between 0.3 and 3 MHz are good predictors for rheological and bread scoring characteristics.

CONCLUSIONS: Ultrasonic parameters had predictive capacity for breadmaking performance for a wide range of dough formulations. Lower frequency attenuation coefficients correlated well with conventional quality indices of both the dough and the bread.

Keywords: bread dough; rheology; ultrasound; breadmaking; bakery ingredients

INTRODUCTION

Reliable prediction of the functionality of wheat flours, and how this functionality is affected by other ingredients, is a key objective in the baking industry.[1] Several techniques are available to accomplish this objective, including chemical or spectroscopic tests on flour to assess the quality and quantity of gluten proteins,[2,3] mechanical tests that measure the rheological properties of the dough made from wheat flour[4,5] or how the flour is affected by bakery ingredients[6,7] and direct assessments of the quality of the resulting end-product.[8,9]

In terms of mechanical tests conducted on dough, a distinction is often made between large strain tests, where mechanical properties are evaluated under conditions relevant to the process conditions that the dough undergoes in a bakery,[5,10] and small strain tests, where insights into relations between dough structure and mechanical properties are sought.[11–13] Many workers have found that extensional tests have shown the best discrimination of baking performance between different wheat cultivars.[5,14,15] Kokelaar *et al.*[16] argued that the bread dough should meet three bulk rheological requirements for good breadmaking performance: optimal resistance to deformation, high extensibility (large fracture strain) and high strain hardening. It is generally accepted that strain hardening of dough is important for preventing premature rupture of the dough film between two gas cells during their expansion, which translates to a bread loaf with a large specific volume and a fine and regular crumb structure.[10,14]

One small strain technique that has been used for the non-destructive characterization of the physical properties and structure of dough is low-intensity ultrasound.[17] As a result, there has been interest in using ultrasound in recent years to investigate the properties of wheat flour doughs.[18–24] A number of useful technological parameters can be obtained from ultrasonic measurements. For example, Garcia-Alvarez *et al.*[21] showed that dough consistency, an important criterion in the handling of breadmaking doughs, could be determined from ultrasonic measurements conducted on doughs prepared from a wide range of flour qualities.

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Factors that influence the breadmaking performance of flour of a given quality have also been the focus of ultrasonic studies of dough properties. Bubbles, which are known to critically influence the properties of breadmaking doughs,[25] have been studied ultrasonically;[26] the technique is particularly sensitive to bubbles in dough because of large differences in the compressibility and density of the dough matrix compared to the gas in the bubbles.[17,20,26] The addition of shortening alters dough properties[27] and this has been studied ultrasonically,[28] as has the addition of water,[29] another important factor in breadmaking performance.[1]

The aim of this paper was to evaluate whether an ultrasonic reflectance technique that uses longitudinally polarized ultrasonic pulses has predictive capacity for the breadmaking performance of doughs made from a wide range of formulation conditions. For this purpose, two flours of contrasting dough strength and different levels of ingredients (such as inulin, oil, emulsifier and salt) were used. Breadmaking performance was evaluated by conventional large-strain rheological tests on the dough and by assessment of loaf quality so that a comprehensive evaluation of functionality was conducted.

MATERIALS AND METHODS

Materials

Two commercial common wheat flours – flour S (strong, alveograph $W = 325$, $P/L = 0.56$ and 360 g kg^{-1} wet gluten) and flour MS (moderately strong, $W = 210$, $P/L = 0.48$ and 320 g kg^{-1} wet gluten) were used (Grandi Molini Italiani, Porto Marghera, VE, Italy). Frutafit® TEX inulin (number average degree of polymerization = 22) and distilled monoglycerides (DMG) (Myvatex Mighty Soft LT) were kindly donated by Sensus (Roosendal, Netherlands) and Kerry Ingredients and Flavours (Mozzo, BG, Italy), respectively. Commercial extra-virgin olive oil was purchased from Monini (Spoleto, PG, Italy). Sodium chloride was analytical grade. Tap water was used for making doughs.

Dough preparation

Six dough treatments were analysed, prepared using wheat flour and four ingredients in different amounts (inulin, oil, salt and DMG) (Table 1). Mixtures of wheat flour (50 g on a 14% moisture basis) and inulin, salt or DMG were premixed in a 50 g farinograph bowl for 5 min. Water was added to the wheat flour and its associated formulation to give a consistency of 500 BU in the farinograph (Table 1). Dough was mixed at 30 °C until it was optimally developed (Table 1). The preparation of doughs containing oil required a two-step procedure:[7] first, the mixing of the dry ingredients and water was performed for the time (t_{water}, min) required to develop the gluten network by bringing the farinograph curve to a maximum, and then the oil was added and the dough mixed until it reached a consistency of 500 BU (t_{oil}, min). After mixing, the dough was kept in a sealed container for density, rheological and ultrasound measurements. At least three replicate doughs were prepared for each formulation on different days.

Dough density measurements

Dough density was measured to ascertain the amount of air incorporated into the dough during mixing using 25 mL gravimetric bottles (Kimble Glass Inc., Vineland, NJ, USA) and 5 g subsamples of dough.[28]

Determination of dough rheological properties

Large deformation rheological properties of doughs at 25 °C were evaluated. A texture analyser (TA.XT2, Stable Micro Systems, Godalming, UK) equipped with a 5 kgf load cell and a Kieffer dough and gluten extensibility rig was used to perform a uniaxial extension test on the processed dough according to Peressini *et al.*[12] The fracture stress (σ_{max}), Hencky strain (ε_H) at fracture stress and the integrated area under the stress–strain curve were taken as measures of resistance to extension, extensibility and energy required for extension, respectively. An apparent strain hardening index (dln σ_{max}/dε_H, USH) was computed in the strain interval of 20–95% of the dough sample's fracture strain.

Biaxial extensional properties were determined by performing a lubricated uniaxial compression test with a Zwick mechanical testing apparatus (Zwick/Roell, Zwick USA, Kennesaw, GA, USA) equipped with a 5 kN load cell and parallel circular platens. The dough from the farinograph was rested for 45 min at room temperature to allow relaxation of stresses from dough preparation.[30] The cylindrical test piece (37 mm diameter and 6 mm height) was placed on the lower platen and compressed to a final height of 0.5 mm at 0.03 mm s^{-1}. To achieve maximum slip the two parallel platens (136 mm diameter) were lubricated with paraffin oil. An apparent strain hardening index (BSH) was computed in the strain interval of 0.5–1.5 (true strain), approximately nominal strains of 40–80%.

Ultrasound measurements

A Panametrics broadband transducer was used, with a central frequency of 3.5 MHz (Olympus NDT Canada Ltd, Alberta, Canada), which was embedded in an acrylic block (similar to the shear wave reflectance method of Leroy *et al.*[31]). The transducer was used in a normal incidence wave reflection set-up. Doughs were placed on the acrylic delay block after a light film of ultrasound gel was applied. Good contact between the dough and the block was established by placing an approximately 2 kg metal weight on top of the dough.

The transducer emitted an ultrasonic pulse that travelled through the acrylic delay block and was reflected back and detected by the same transducer. The reflected signal was averaged 250 times to improve the signal-to-noise ratio before being displayed on a digitizing oscilloscope (Tektronix model TDS 544A, Tektronix Canada Inc., Toronto, Canada). Reference signals were acquired prior to measurement of each sample by measuring the reflectance from air.

The longitudinal velocity and attenuation coefficient at a range of frequencies, covering the bandwidth of the transducer, were determined by comparing the phases and magnitudes of the Fourier transforms of the signal transmitted through the sample relative to those of the reference signal, using Matlab 7.0 software for data elaboration.[32]

Breadmaking

The Canadian Short Process (CSP) method was used to evaluate baking potential.[33] Dough ingredients included wheat flour (100 g on 14% moisture basis) and four ingredients in different amounts (inulin, oil, salt and DMG) (Table 1), fresh compressed yeast (3 g), sugar (4 g), ascorbic acid (150 ppm solution), ammonium phosphate (0.1 g) and optimum water as assessed by farinograph analysis (variable, see Table 1). Ingredients were mixed in a GRL-200 mixer at 30 °C and 165 rpm to 10% past peak consistency. The dough was rested 15 min at 30 °C, punched and rounded by hand,

Table 1. Ingredients and mixing times used to prepare different doughs

Sample	Flour S (g)[a]	Flour MS (g)[a]	DMG[d](g)	NaCl (g)	Oil (g)	Inulin (g)	Water content (g kg^{-1})[b]	Mixing time (min)[c]
A	0	50	0	1.2	0	4	410	11.5
B	50	0	0.5	0	0	4	431	14
C	0	50	0.5	1.2	3	4	389	13 + 4
D	50	0	0	0	0	0	447	4
E	0	50	0.5	0	3	0	401	3 + 2.5
F	50	0	0.5	0	3	0	410	3 + 2

[a] On 14% moisture basis.
[b] g water in 1 kg dough.
[c] The double values indicate $t_{water} + t_{oil}$.
[d] Distilled monoglycerides.

and given a proof of 15 min (30 °C). Dough was then sheeted, moulded, panned, proven at 37.5 °C (85% relative humidity) for 70 min and baked for 30 min at 205 °C. After cooling, all loaves were stored at room temperature in plastic bags. Bread quality was evaluated 24 h after baking.

Determination of loaf volume

Loaf volume (mL) was determined by rapeseed displacement according to AACC Method 10-05.[34]

Measurement of crumb firmness

Crumb firmness was measured using AACC Method 74-09[34] with slight modifications. A bread crumb indentation test was performed using a texture analyser (TA.XT2, Stable Micro Systems, Godalming, UK) equipped with a 500 gf load cell and an aluminium plunger (18 mm diameter). A force–displacement curve was recorded and the indentation stress at 25% compression was calculated (firmness, Pa). Data are reported as the average of nine measurements from three loaves.

Crumb image analysis

Visual crumb structure was evaluated by image analysis with the Analyse Score Scan (ASE) software package (American Institute of Baking, Manhattan, KS, USA). Bread slices were individually scanned. The information provided by the software was cell density (number mm^{-2}), mean cell area (mm^2, MCA), cell elongation (–, CE) and cell wall thickness (mm).

Statistical analysis

Data are reported as the mean of three measurements, which were performed on three doughs and loaves from different experiments unless otherwise mentioned.

Statistical differences in dough rheological properties and bread characteristics were determined by one-way analysis of variance (ANOVA) and Tukey's comparison test ($P < 0.05$) using Statistica 7.1 for Windows software package (StatSoft, Inc., Tulsa, OK, USA, 2008).

The internal degree of correlation separately for the two sets of variables (rheological and bread scoring the first, ultrasonic velocities and attenuation coefficients at different frequencies the second) was investigated applying principal component analysis (PCA). Six different frequencies across the acoustic spectrum were chosen (0.3, 0.5, 1, 2 and 3 MHz) to represent the whole of the signal for a given sample. The correlation structure of the variables, as well as the scores of the observations on the new components, were reported using biplots.

Partial least squares (PLS) regression was used to analyse the relationships between the rheological and bread scoring parameters and the ultrasonic parameters at the different frequencies. We assumed rheological and bread scoring parameters to be the set of dependent variables (matrix **Y**) of a multivariate linear regression model where the ultrasonic parameters at the five frequencies acted as a set of covariates (matrix **X**), i.e.

$$\mathbf{Y} = \mathbf{X}\beta$$

where β is a matrix of coefficients linking the two sets. The two sets of variables were centred and scaled so that the results do not depend on the adopted measurement units.

PLS operates by constructing a reduced set of predictors from **X** and a reduced set of response variables from **Y**, so that the correlation between the two new sets of variables is maximized. The number of components was determined by minimizing the cross-validated root mean square error of prediction (RMSEP), i.e. the mean distance between the observed value of the response variables and the predicted ones, computed by leaving out in turn a single observation from the estimation set.

The overall goodness of fit of the PLS model was evaluated on the basis of the overall fraction of the explained variation (R^2) and its cross-validated counterpart, the fraction of predicted variation, Q^2. Values of the fraction of expected variation specific for each **Y** parameter were also inspected to detect potential quality problems limited to any one specific variable. The effect of the predictors was expressed in terms of coefficients and using the variable importance in projection (VIP) index. Care should be taken, however, in interpreting the contribution of the single **X** variables, because the regressors are correlated owing to their values not being experimentally controlled.

All statistical analyses were conducted using the packages *stats* and *pls* of R, version 3.0.1.[35,36]

RESULTS AND DISCUSSION

In order to relate ultrasonic properties to the rheological and baking quality of the doughs, experiments were conducted with two different wheat flours (strong and moderately strong) and various ingredients. The dough formulations were selected from a preliminary study regarding the influence of different ingredients on dough and breadmaking properties. The particular formulations were chosen with the intention of studying doughs that had a wide range of technological potential.

Dough rheological properties

In selecting mixing times that were technologically appropriate, we evaluated the variation in optimal mixing time of various formulations by farinograph analysis. Farinograph curves of the different formulations are shown in Fig. 1. Moisture content and time to produce dough with optimal consistency were 389–447 g kg^{-1} and 4–17 min, respectively (Table 1). The addition of inulin resulted in a decrease in optimum moisture content of the dough, probably due to a lubricating effect of sugars and oligosaccharides according to evidence from other studies.[6,37] Time required for dough development, or to reach a dough consistency equivalent to 500 BU, greatly increased as a consequence of fibre addition.[6] This effect can be mainly related to the intrinsic water absorption ability of inulin, leading to competition with the gluten proteins for available water to form a gel. Optimal mixing conditions were also influenced by oil addition (Table 1). Regarding the doughs containing oil, a two-step process was necessary in dough preparation: (i) the dry ingredients were mixed with water for the time required to develop the gluten; (ii) oil was added to the dough and mixing continued until optimal consistency was reached.[7,38] In fact, several previous trials demonstrated that it was not possible to develop the dough if the oil was added directly with the other ingredients, as it had a suppressive effect on gluten development. The addition of oil decreased the optimum moisture content of the dough; the lowest value was obtained when oil was used in combination with inulin (389 g kg^{-1} for formulation C).

It was expected that decreasing values of dough density would be found with respect to increased mixing time, as more air would be entrained.[28] Dough density at optimum mixing time ranged from 1182 to 1223 kg m^{-3} (Table 2). However, the highest value was observed for formulation A, which was characterized by a relatively high mixing time of 11.5 min, and no significant differences in dough density were observed between B and D ($P = 0.05$). Other factors such as varying the dough formulation are expected to influence the density values. Ingredients could either affect the amount of air entrained into the dough (by altering its viscosity), regardless of the mixing time employed, or the amount of air entrained remains constant, but the density of the other ingredients influences the final density value of the dough.[39,40]

A combination of different large deformation tests, such as uniaxial and biaxial elongation, were performed to evaluate dough rheological properties, which are widely recognized as important determinants of bread quality.[5,10] Large differences in the elongation parameters of doughs were observed (Table 2). Strain hardening ($d\ln \sigma_{max} / d\varepsilon_H$) varied in the range 1.05–1.57 and 1.97–2.69 for uniaxial and biaxial elongation, respectively. With the exclusion of the lean formula dough, D, due to high variability in its biaxial elongation test, a strong linear correlation between uniaxial and biaxial strain hardening was found ($r = 0.80$). For both elongation tests, formulations E and F exhibited the highest, and A and B the lowest, strain hardening among the formulations. This rheological parameter seems to be reduced and increased by fibre and oil addition, respectively.[41] According to Watanabe *et al.*,[38] it seems that oil is absorbed into the gluten structure, causing protein aggregation. Kokelaar *et al.*[16] did not observe an effect of sodium chloride and emulsifiers on strain hardening. Differences in strain hardening between wheat doughs of different baking quality were found to relate to baking quality, with good breadmaking varieties showing greater strain hardening.[10,14] The strain hardening phenomenon, which is thought to arise mainly from coupling of entanglements of the larger glutenin molecules,[42] limits the growth of large gas cells by locally increasing resistance to elongation, and appears to provide the cells with greater stability against coalescence so that they better retain gas.[10,43–45]

Large differences in fracture stress (σ_{max}) and Hencky strain (ε_H) at fracture stress were observed between doughs, with the $\sigma_{max}/\varepsilon_H$ ratio being from 13.9 to 32.3. Formulations A, B and C, containing inulin, gave the highest $\sigma_{max}/\varepsilon_H$ ratio due to a substantial decrease in extensibility. It is expected that doughs with good strain hardening, high resistance to elongation and high extensibility before break (large fracture strain) should result in a fine and regular crumb texture and large loaf volume.[16]

Baking quality

Breadmaking performance of different formulations was established on the basis of loaf volume, crumb mechanical properties and structure. The highest loaf volume was observed for F containing oil and DMG, whose dough exhibited high resistance, good extensibility and strong strain hardening. Watanabe *et al.*[38] observed a decrease in loaf volume when oil was added to the dough, but their formulation did not contain an emulsifier.

It seems that dough should meet all the three bulk rheological requirements in order to attain a high loaf volume (Table 3).[16] Formulation E gave a lower loaf volume than F because of its lower fracture strain. According to Peressini and Sensidoni,[6] low expansion of dough into bread was observed for fibre-enriched formulations (A, B and C), as expected from rheological characterization, which showed low dough extensibility and/or poor strain hardening for these formulations. Using this criterion, the order of baking quality (high to low) is: F > D = E > B = C > A.

Crumb density (or specific volume) has an enormous effect on the mechanical behaviour of bread crumb.[46] Table 2 shows changes in crumb firmness and Young's modulus for different breads. The observations regarding the mechanical properties of these breads, assessed by the indentation test with a wide range in formulation, were in line with the previously described findings.[46] Fibre-enriched loaves were firmer and had a larger elastic modulus due to low bread volume.[6] Strong linear correlations between crumb mechanical properties and loaf volume were found ($r = -0.93$ for firmness *vs.* volume and $r = -0.95$ for Young's modulus *vs.* volume).[46]

The impact of different formulations on the cellular structure of the crumb was investigated by image analysis. The computed crumb grain features were cell density, mean cell area, cell elongation and cell wall thickness (Table 2).

Cell density was higher for inulin-enriched breads (A, B and C), indicating potentially good incorporation of air within the dough during the long mixing times required for these formulations. Nevertheless, they exhibited the lowest loaf volumes, probably because the expansion of these air cell nuclei was restricted by low extensibility of the dough. In addition, mean cell area was lower for fibre-enriched breads. No significant differences in mean cell area were observed for D, E and F.

Cell elongation refers to irregularity in the crumb texture. Formulations E and F containing oil exhibited the lowest cell elongation values and, therefore, a more isotropic texture. The inulin-enriched breads presented high cell elongation values and in particular B, with its high standard deviation, seems to have a particularly irregular crumb grain. In terms of cell wall thickness, the inulin-enriched formulations gave lower values than E and F. Comparing these results to those of mean cell area, it can be observed that smaller cells tend to have smaller walls.

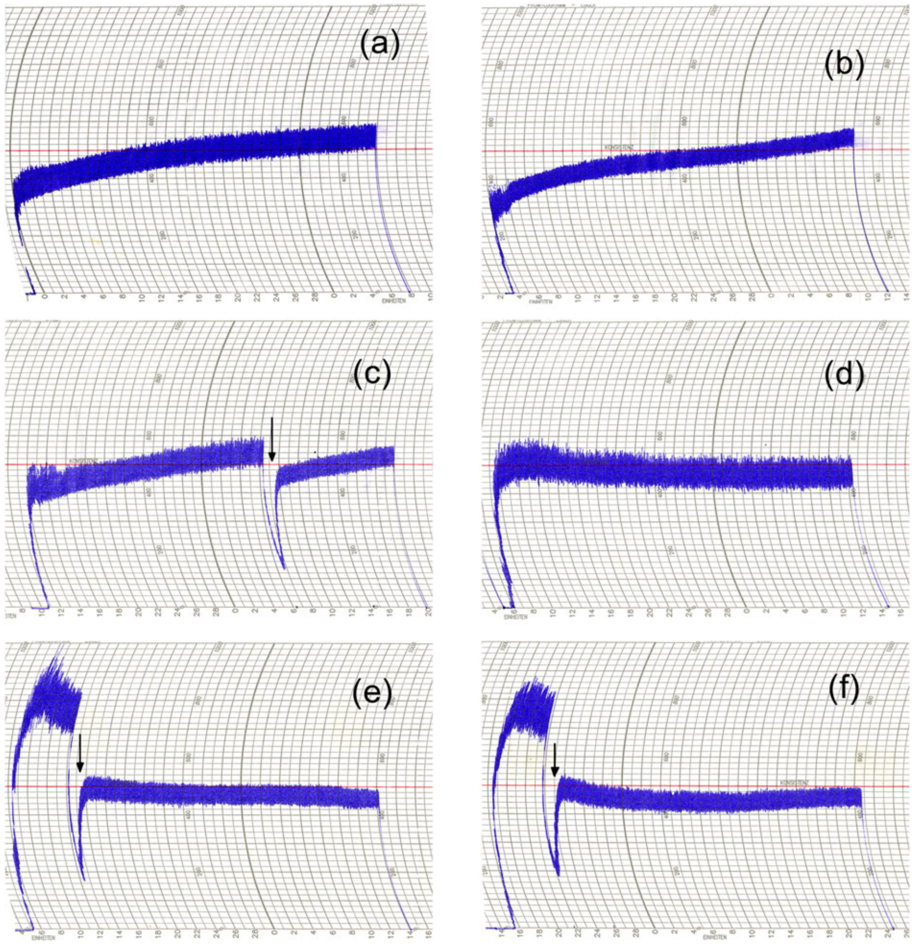

Figure 1. Farinograph curves of doughs of the different formulations. A (a), B (b), C (c), D (d), E (e) and F (f). The arrow indicates oil addition.

Table 2. Density and rheological properties of dough and quality characteristics of bread

Parameter[a]	A	B	C	D	E	F
Dough						
Density (kg m^{-3})	1223a	1196b	1186cd	1199b	1182d	1190c
Uniaxial elongation						
σ_{max} (kPa)	53.5a	33.9cd	37.8bc	39.0bd	27.2c	45.7ab
ε_H (−)	1.67b	1.20c	1.17c	2.08a	1.96ab	2.14a
$\sigma_{max}/\varepsilon_H$ (−)	32.0	28.3	32.3	18.8	13.9	21.4
Area (kPa)	45.0a	27.5b	27.2bc	30.3b	19.1c	29.4b
dln σ_{max}/dε_H (−)	1.25c	1.05d	1.39abc	1.32bc	1.48ab	1.57a
Biaxial elongation						
dln σ_{max}/dε_H (−)	1.97cd	2.03d	2.04d	2.69a	2.34bc	2.52ab
Bread						
Loaf volume (cm^3)	410d	575c	558c	690b	698b	843a
Firmness (kPa)	31.47a	15.94b	14.41b	7.15c	5.66c	4.22c
Young's modulus (kPa)	103.3a	54.2bc	59.1b	24.5bd	20.7cd	14.7d
Crumb grain						
Cell density (number mm^{-2})	92.7a	89.8a	89.2a	74.4c	81.3b	79.3bc
Mean cell area (mm^2)	0.472d	0.667c	0.634bc	0.877a	0.832a	0.800ab
Cell elongation (−)	1.85d	1.80c	1.83bc	1.76a	1.71a	1.69ab
Cell wall thickness (mm)	0.235d	0.270bc	0.269b	0.279ac	0.286a	0.289a

[a] Values within a row followed by the same letter are not significantly different ($P > 0.05$).

Table 3. Comparison of different dough samples on the basis of rheological properties and baking performance

Sample	σ_{max}	ε_H	$\sigma_{max}/\varepsilon_H$	Strain hardening	Loaf volume[a]	Baking performance
A	+++	+	Poor	+/−	↓↓	Very poor
B	++	−	Poor	+/−	↓	Poor
C	++	−	Poor	+	↓	Poor
D	++	++	Good	+	↑	Good
E	+	++	Good	++	↑	Good
F	++	++	Good	++	↑↑	Very good

Mentioned property is: +++ present to a large extent; ++ present to a moderately large extent; + present; +/− more or less present.
[a] ↑↑ very high; ↑ high; ↓ low; ↓↓ very low.

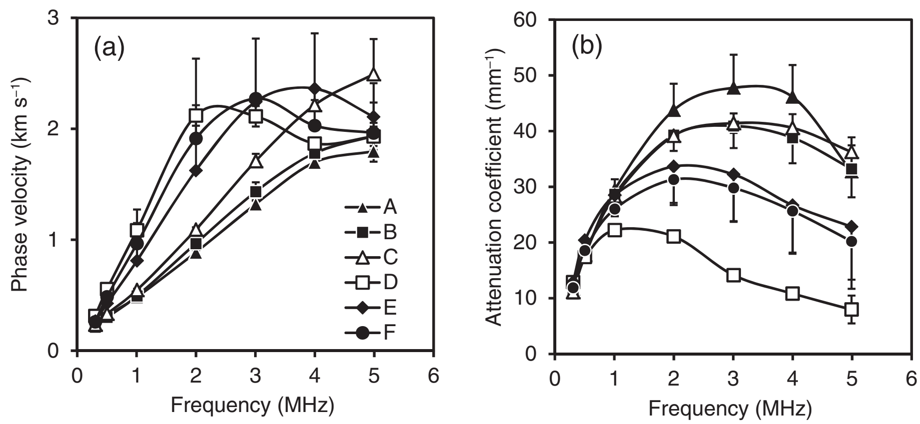

Figure 2. Mean values of ultrasonic phase velocity (a) and attenuation coefficient (b) of doughs of different formulations as a function of frequency. Vertical bar indicates standard deviation.

Ultrasound testing

The mean ultrasonic phase velocity (PV) and the mean attenuation coefficient (At) for each dough formulation are shown in Fig. 2. The variability shown in these figures is associated with the ultrasonic parameter for three replicates of each different dough formulation. It can be seen that variability depends on frequency, being more pronounced at the peak and at the higher frequencies. Furthermore, these high frequencies are closer to the bandwidth limit of the transducer; thus a higher degree of variability is expected, especially for the inulin-containing doughs where higher attenuation contributes to uncertainty in the signal.

The frequency-dependent changes in both phase velocity and attenuation coefficient are very similar to those reported for strong breadmaking flours analysed by transmission experiments.[26,47] The peak in attenuation coefficient, which occurs between 1 and 2 MHz for D, E and F, is indicative of a low-frequency resonance arising from the bubbles entrained into the dough during mixing.[17,26] On the low-frequency side of the peak, velocity and attenuation are lower, indicative of the long-wavelength probing of an effective medium of matrix and bubbles that constitute the dough.[20,26] Ultrasonic velocity at frequencies greater than those of resonance, where dough matrix properties are accessed, is somewhat higher than the velocity of sound in water (1500 m s^{-1}). Formulations A, B and C, all containing inulin and characterized by very long mixing times, show phase velocity values that continue to rise at the higher frequencies and a peak attenuation at higher frequencies (3–3.5 MHz). These features point to one or both of two factors. Bubbles in the inulin-containing doughs could be of smaller average size.[26] Longer mixing times and the altered rheology of these doughs would affect the entrainment and disentrainment dynamics of bubbles in these doughs,[39] thereby potentially forming smaller bubble sizes. Alternatively, the distinct rheological behaviour of the inulin-containing doughs (most noticeably manifest in the large areas under the uniaxial extension stress–strain curves) could also push the resonance peak to higher frequencies.[26]

The differences in large strain properties of the doughs described in previous sections are also evident in small strain ultrasonic measurements. In Fig. 2, attenuation coefficients are substantially different at bubble resonance and at high frequencies for the fibre-enriched doughs. Since dough densities are not very different, and thus the gas content is similar, the increase in attenuation coefficient in the fibre-enriched doughs is likely due to the effect of the fibre on the properties of the dough matrix.

The results for formulations A, B, C, and D show that the reflectance technique is a repeatable means of measuring the ultrasonic properties of wheat flour doughs at frequencies (near resonance) where it is difficult for ultrasound to propagate through the samples in transmission experiments. A possible explanation for the poorer repeatability for formulations E and F might be that the test outcome was affected by external factors, such as laboratory conditions. It is known that the velocity of acoustic waves may be strongly influenced by temperature gradients. It is possible that on the days when the three replicates of formulations E and F were tested there were uncontrolled laboratory conditions – specifically less-regulated temperature control.

PCA and PLS analysis

Results of PCA analysis on the rheological and bread scoring variables are reported in Fig. 3. Observations corresponding to the

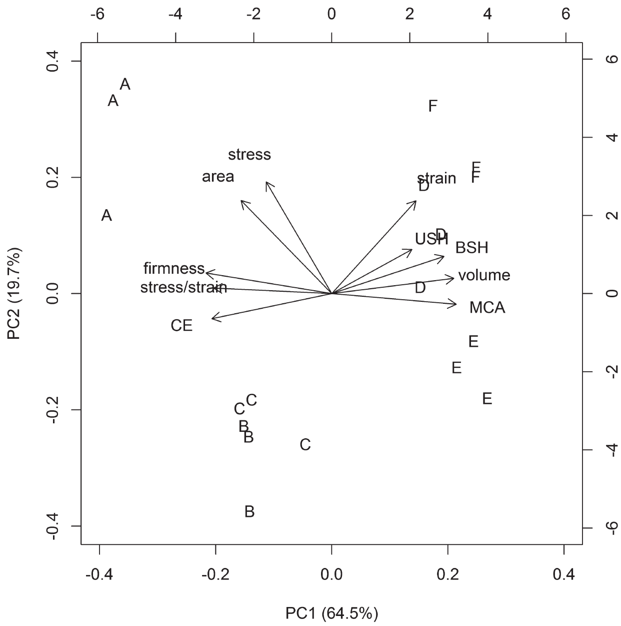

Figure 3. Biplot for dough rheological properties and bread characteristics. Fracture stress (stress), Hencky strain at fracture stress (strain), energy required for uniaxial extension (area), uniaxial (USH) and biaxial strain hardening (BSH), cell elongation (CE) and mean cell area (MCA).

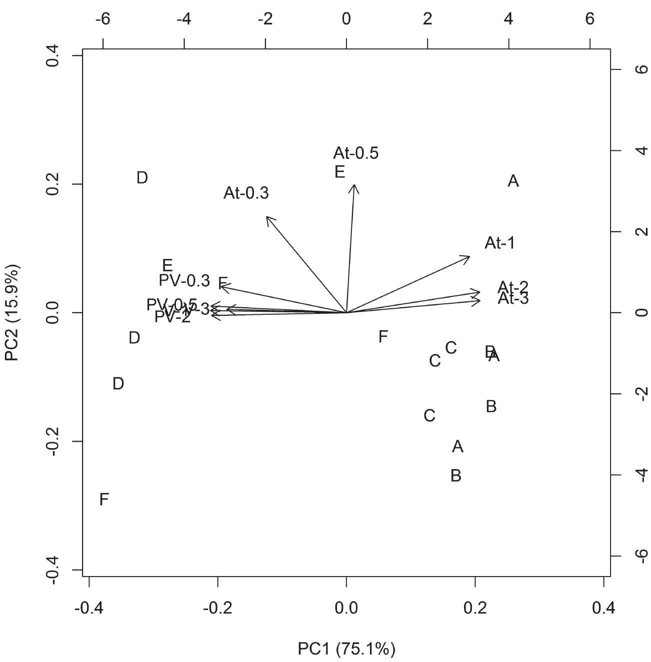

Figure 4. Biplot for dough ultrasonic parameters. Attenuation coefficient at frequencies of 0.3 (At-0.3), 0.5 (At-0.5), 1 (At-1), 2 (At-2) and 3 (At-3) MHz; phase velocity at frequencies of 0.3 (PV-0.3), 0.5 (PV-0.5), 1 (PV-1), 2 (PV-2) and 3 (PV-3) MHz.

three replicates of the same dough formulation are indicated with the same code. The first two components account for 84.2% of the total variation. The first two components are able to clearly identify the different characteristics of the dough formulations, which in most cases are well separated. The first component is positively correlated with mean cell area, loaf volume and biaxial strain hardening, and negatively correlated with crumb firmness,

Table 4. Percentage of variance explained by the PLS regression model with three components for each rheological and bread scoring variable

Variable	% explained variance
Dough	
σ_{max}	40.98
ε_H	66.15
$\sigma_{max}/\varepsilon_H$	78.74
Area	58.19
Uniaxial strain hardening (USH)	35.57
Biaxial strain hardening (BSH)	71.77
Bread	
Loaf volume	74.26
Crumb firmness	75.47
Mean cell area (MCA)	77.06
Cell elongation (CE)	74.51

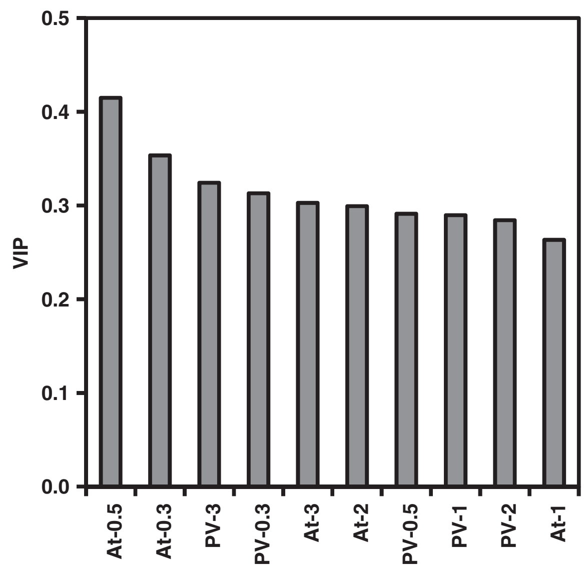

Figure 5. Variable importance in projection (VIP) index. Attenuation coefficient at frequencies of 0.3 (At-0.3), 0.5 (At-0.5), 1 (At-1), 2 (At-2) and 3 (At-3) MHz; phase velocity at frequencies of 0.3 (PV-0.3), 0.5 (PV-0.5), 1 (PV-1), 2 (PV-2) and 3 (PV-3) MHz.

$\sigma_{max}/\varepsilon_H$ and cell elongation, which, considered together, form a group of correlated variables. A second group is identified by the second component, which is more correlated with σ_{max}, area and fracture strain (ε_H).

Results of PCA analysis of ultrasonic velocity and attenuation at different frequencies are reported in Fig. 4. The first two components account for 91% of the total variation. As with conventional quality analyses, the first two components are able to describe the characteristics of dough formulations, though the groups are less characterized than in the previous biplot. All the PV indicators are negatively correlated with the first component, while three of the attenuation parameters – At-1 MHz, At-2 MHz and At-3 MHz, which are at or past the resonance peak – are positively correlated with it.

The second component describes the lower frequency attenuation response of At-0.5 MHz and, to a lesser extent, of At-0.3 MHz. Indeed, while the variables correlated with the first component are highly correlated between them ($r > 0.7$), At-0.3 MHz and At-0.5

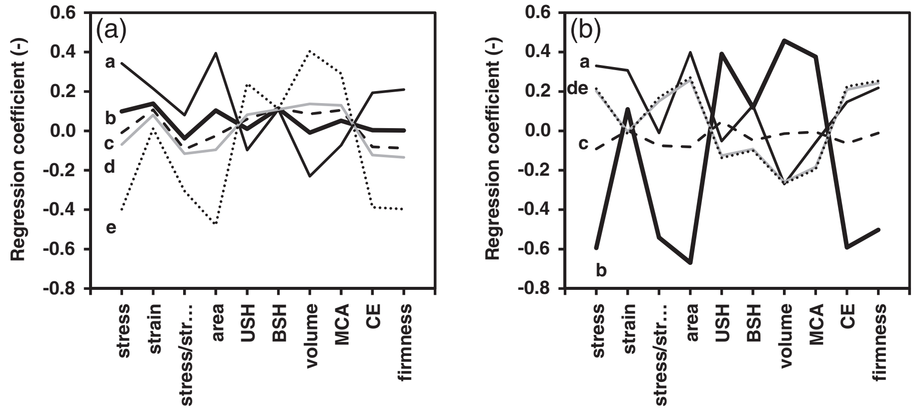

Figure 6. Correlation between dough rheological properties, bread scoring parameters and dough ultrasonic parameters. Phase velocity (a) and attenuation coefficient (b) at frequencies of 0.3 (a), 0.5 (b), 1 (c), 2 (d) and 3 MHz (e). Fracture stress (stress), Hencky strain at fracture stress (strain), energy required for uniaxial extension (area), uniaxial (USH) and biaxial strain hardening (BSH), cell elongation (CE) and mean cell area (MCA).

MHz have correlations with the other variables that are much lower and sometimes negligible.

As regards PLS regression between the two sets of variables, we first identified the number of components while minimizing the cross-validated RMSEP. The best model resulted in one with three components that was able to explain 65.3% of the total variability of the rheological and bread scoring variables (R^2) and to explain 53.9% of the total predicted variability from the ultrasonic parameters (Q^2). The percentage of explained variance of each single **Y** variable for the selected model is reported in Table 4. The percentage of explained variance is satisfactory (>50%) for all the variables except for uniaxial strain hardening and the dough strength parameter σ_{max}.

Figure 5 reports the VIP for each regressor. The attenuation coefficient at 0.5 MHz (At-0.5) appears to be the most relevant ultrasound frequency, followed by the attenuation at 0.3 MHz and, to a lesser extent, the phase velocity at 3 MHz. Even if the variables are highly correlated, the PCA analysis on ultrasound frequencies shows that the correlation of At-0.5 and At-0.3 with the other frequencies is very low. Then, even if it is very difficult to separate the effect of one single variable from the effects of the others and to assign each variable its own importance, we can say that the two attenuation frequencies 0.3 and 0.5 MHz jointly considered are the most relevant to predict rheological and bread scoring variables. The role of the two attenuation frequencies is also evident in Fig. 6, where the regression coefficients relating the **Y** and the **X** variables are reported.

Indeed, At-0.5 is characterized by the highest values of the coefficient, followed by At-0.3. The At-0.5 frequency is negatively related to stress, stress/strain, area, CE and firmness, whereas it is positively related to USH, volume and MCA. Generally, formulations with lower attenuation coefficient values exhibit improved conventional dough quality indices, although interesting strong opposite correlations are apparent for the attenuation coefficient at 0.3 and 0.5 MHz to both uniaxial fracture stress and energy to fracture. Since both these frequencies reside in the bubble resonance region, these pairs of correlations may point to interesting (although as yet undefined) dough matrix–bubble interactions that influence the fracture behaviour of the dough.

Overall, the analysis suggests that ultrasonic parameters acquired from a broadband transducer (where dough properties are interrogated over a broad frequency range) are good predictors of rheological and bread scoring characteristics for a wide range of dough formulations.

CONCLUSIONS

The ultrasonic bubble resonance peak differed considerably depending on dough formulation, with the frequency dependence of the velocity and attenuation coefficient of the inulin-containing doughs being rather distinct from other formulations. Lower frequency attenuation coefficients (0.3–0.5 MHz) had the greatest predictive capacity for dough rheology and bread scoring variables for this wide range of formulations.

REFERENCES

1 Cauvain SP and Young LS, *Technology of Breadmaking*. Springer, New York (2007).
2 MacRitchie F, Cros DL and Wrigley CW, Flour polypeptides related to wheat quality, in *Advances in Cereal Science and Technology*, Vol. 10, ed. by Pomeranz Y. American Association of Cereal Chemists, St Paul, MN, pp. 79–145 (1990).
3 Osborne BG, Fearn T and Hindle PH, *Practical NIR Spectroscopy with Applications in Food and Beverage Analysis* (2nd edn). Addison-Wesley Longman, Harlow, UK (1993).
4 Bloksma AH and Bushuk W, Rheology and chemistry of dough, in *Wheat: Chemistry and Technology*, Vol. 2, ed. by Pomeranz Y. American Association of Cereal Chemists, St Paul, MN, pp. 131–217 (1988).
5 Dobraszczyk BJ and Morgenstern MP, Rheology and the breadmaking process. *J Cereal Sci* **38**:229–445 (2003).
6 Peressini D and Sensidoni A, Effect of soluble dietary fibre addition on rheological and breadmaking properties of wheat doughs. *J Cereal Sci* **49**:190–201 (2009).
7 Watanabe A, Larsson H and Eliasson AC, Effect of physical state of nonpolar lipids on rheology and microstructure of gluten-starch and wheat flour doughs. *Cereal Chem* **79**:203–209 (2002).
8 Zghal MC, Scanlon MG and Sapirstein HD, Prediction of bread crumb density by digital image analysis. *Cereal Chem* **76**:734–742 (1999).
9 Zghal MC, Scanlon MG and Sapirstein HD, Effects of flour strength, baking absorption, and processing conditions on the structure and mechanical properties of bread crumb. *Cereal Chem* **78**:1–7 (2001).
10 van Vliet T, Janssen AM, Bloksma AH and Walstra P, Strain hardening of dough as a requirement for gas retention. *J Texture Stud* **23**:439–460 (1992).
11 Edwards NM, Peressini D, Dexter JE and Mulvaney SJ, Viscoelastic properties of durum wheat and common wheat dough of different strengths. *Rheol Acta* **40**:142–153 (2001).
12 Peressini D, Peighambardoust H, Hamer R, Sensidoni A and van der Goot AJ, Effect of shear rate on microstructure and rheological properties of sheared wheat. *J Cereal Sci* **48**:426–438 (2008).

13 Rao VK, Mulvaney SJ, Dexter JE, Edwards NM and Peressini D, Stress-relaxation properties of mixograph semolina-water doughs from durum wheat cultivars of variable strength in relation to mixing characteristics, bread- and pasta-making performance. *J Cereal Sci* **34**:215–232 (2001).
14 Dobraszczyk BJ and Salmanowicz BP, Comparison of predictions of baking volume using large deformation rheological properties. *J Cereal Sci* **48**:292–301 (2008).
15 Kieffer R, Wieser H, Henderson MH and Graveland A, Correlations of the breadmaking performance of wheat flour with rheological measurements on a micro-scale. *J Cereal Sci* **27**:53–60 (1998).
16 Kokelaar JJ, van Vliet T and Prins A, Strain hardening properties and extensibility of flour and gluten doughs in relation to breadmaking performance. *J Cereal Sci* **24**:199–214 (1996).
17 Scanlon MG and Page JH, Probing the properties of dough with low-intensity ultrasound. *Cereal Chem* **92**:121–133 (2015).
18 Alava JM, Sahi SS, Garcia-Alvares J, Turo A, Chavez JA, Garcia MJ *et al.*, Use of ultrasound for the determination of flour quality. *Ultrasonics* **46**:270–276 (2007).
19 Bellido GG and Hatcher D, Ultrasonic characterization of fresh yellow alkaline noodles. *Food Res Int* **43**:701–708 (2010).
20 Elmehdi HM, Page JH and Scanlon MG, Ultrasonic investigation of the effect of mixing time under reduced pressure on the mechanical properties of bread dough. *Cereal Chem* **81**:504–510 (2004).
21 Garcia-Alvarez J, Salazar J and Rosell CM, Ultrasonic study of wheat flour properties. *Ultrasonics* **51**:223–228 (2011).
22 Létang C, Piau M, Verdier C and Lefebvre L, Characterization of wheat-flour-water doughs: a new method using ultrasound. *Ultrasonics* **39**:133–141 (2001).
23 Ross KA, Pyrak-Nolte LJ and Campanella OH, The use of ultrasound and shear oscillatory tests to characterize the effect of mixing time on the rheological properties of dough. *Food Res Int* **37**:567–577 (2004).
24 Skaf A, Nassar G, Lefebre F and Nongaillard B, A new acoustic technique to monitor bread dough during the fermentation phase. *J Food Eng* **93**:365–378 (2009).
25 Babin P, Della Valle G, Chiron H, Cloetens P, Hoszowska J, Pernot P *et al.*, Fast X-ray tomography analysis of bubble growth and foam setting during breadmaking. *J Cereal Sci* **43**:393–397 (2006).
26 Leroy V, Fan Y, Strybulevych AL, Bellido GG, Page JH and Scanlon MG, Investigating the bubble size distribution in dough using ultrasound, in *Bubbles in Food 2: Novelty, Healthy and Luxury*, ed. by Campbell GM, Scanlon MG and Pyle DL. AACC International, St Paul, MN, pp. 51–60 (2008).
27 Mousia Z, Campbell GM, Pandiella SS and Webb C, Effect of fat level, mixing pressure and temperature on dough expansion capacity during proving. *J Cereal Sci* **46**:139–147 (2007).
28 Mehta KL, Scanlon MG, Sapirstein HD and Page JH, Ultrasonic investigation of the effect of vegetable shortening and mixing time on the mechanical properties of bread dough. *J Food Eng* **74**:E455–461 (2009).
29 Kidmose U, Pedersen L and Nielsen M, Ultrasonics in evaluating rheological properties of dough from different wheat varieties and during ageing. *J Texture Stud* **32**:321–334 (2001).
30 Charalambides MN, Wanigasooriya L, Williams JG, Goh SM and Chakrabarti S, Large deformation extensional rheology of bread dough. *Rheol Acta* **46**:239–248 (2006).
31 Leroy V, Pitura KM, Scanlon MG and Page JH, The complex shear modulus of dough over a wide frequency range. *J Non-Newton Fluid Mech* **165**:475–478 (2010).
32 Strybulevych A, Leroy V, Scanlon MG and Page JH, Characterizing a model food gel containing bubbles and solid inclusions using ultrasound. *Soft Matter* **3**:1388–1394 (2007).
33 Preston KR, Kilborn RH and Black HC, The GRL pilot mill. II. Physical dough and baking properties of flour streams milled from Canadian red spring wheats. *Can Inst Food Sci Technol J* **15**:29–36 (1982).
34 AACC, *Approved Methods of the American Association of Cereal Chemists* (10th edn). American Association of Cereal Chemists, St Paul, MN (2000).
35 Mevik BH, Wehrens R and Liland KH, pls: partial least squares and principal component regression (2013). R package version 2.4-3. [Online]. Available: http://CRAN.R-project.org/package=pls [4 October 2016].
36 R Core Team, *R: A Language and Environment for Statistical Computing* (2013). [Online]. R Foundation for Statistical Computing, Vienna. Available: URL http://www.R-project.org/ [4 October 2016].
37 Wang J, Rosell CM and de Barber CB, Effect of the addition of different fibres on wheat dough performances and bread quality. *Food Chem* **79**:221–226 (2002).
38 Watanabe A, Yokomizo K and Eliasson AC, Effect of physical state of nonpolar lipids on rheology, ultracentrifugation, and microstructure of wheat flour dough. *Cereal Chem* **80**:281–284 (2003).
39 Chin NL and Campbell GM, Dough aeration and rheology. II. Effects of flour type, mixing speed and total work input on aeration and rheology of bread dough. *J Sci Food Agric* **85**:2194–2202 (2005).
40 Chin NL, Martin PJ and Campbell GM, Dough aeration and rheology. III. Effect of the presence of gas bubbles on measured bulk rheology and work input rate. *J Sci Food Agric* **85**:2203–2212 (2005).
41 Cavella S, Romano A, Giancone T and Masi P, The influence of dietary fibres on bubble development during bread making, in *Bubbles in Food 2. Novelty, Healthy and Luxury*, ed. by Campbell GM, Scanlon MG and Pyle DL. AACC International, St Paul, MN, pp. 311–321 (2008).
42 Dobraszczyk BJ, The physics of baking: rheological and polymer molecular structure–function relationships in breadmaking. *J Non-Newton Fluid Mech* **124**:61–69 (2004).
43 Dobraszczyk BJ and Roberts CA, Strain hardening and dough gas cell-wall failure in biaxial extension. *J Cereal Sci* **20**:265–274 (1994).
44 Dobraszczyk BJ, Smewing J, Albertini M, Maesmans G and Schofield JD, Extensional rheology and stability of gas cell walls in bread doughs at elevated temperatures in relation to breadmaking performance. *Cereal Chem* **80**:218–224 (2003).
45 Ng TSK and McKinley GH, Power law gels at finite strains: the nonlinear rheology of gluten gels. *J Rheol* **52**:417–449 (2008).
46 Scanlon MG and Zghal MC, Bread properties and crumb structure. *Food Res Int* **34**:841–864 (2001).
47 Koksel F, Strybulevych A, Page JH and Scanlon MG, Ultrasonic characterization of unyeasted bread dough of different sodium chloride concentrations. *Cereal Chem* **91**:327–332 (2014).

