

Bread Quality Relationship with Rheological Measurements of Wheat Flour Dough

K. Autio,^{1,2} L. Flander,¹ A. Kinnunen,¹ and R. Heinonen¹

ABSTRACT

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The rheological properties of wheat doughs prepared from different flour types, water contents, and mixing times for a total of 20 dough systems were studied. The results were compared with the results of standard baking tests with the same factors. Water and flour type had a significant effect on storage modulus (G') or phase angle measured by an oscillatory test both in the linear viscoelastic region and as a function of stress, and on compressional force measured as a function of time. The correlation of maximum force of dough in compression and G' of dough measured within the linear viscoelastic region was $r = 0.80$. Correlation between the compression and oscillation test improved when all measuring points of the G' stress curve were included ($r = 0.88$). The baking performance of the different doughs varied greatly; loaf volumes ranged from 2.9 to 4.7 mL/g.

Although the water content of the dough correlated with the rheological measurements, the correlation of G' measured in the linear viscoelastic region or maximum force from stress-time curve during compression was poor for bread loaf volumes. Mixing time from 4.5 to 15.5 min did not affect the rheological measurements. No correlation was observed with the maximum force of compression or G' of dough measured in the linear viscoelastic region and baking performance. Good correlation of rheological measurements of doughs and baking performance was obtained when all the data points from force-time curve and whole stress sweep (G' as a function of stress) were evaluated with multivariate partial least squares regression. Correlation of all data points with loaf volume was $r = 0.81$ and 0.72 , respectively, in compression and shear oscillation.

Several different fundamental rheological measurements, differing in terms of magnitude of stress or deformation, in type of deformation (shear, compression, extension, and biaxial extension), or in deformation rate or in terms of the length of time of the constant stress (creep) or deformation (relaxation) have been used to measure the rheological properties of wheat doughs. The measurement should also be sensitive to the water content of doughs because the best mechanical properties are achieved by an optimum flour-to-water ratio. A great number of studies on the relationship of the rheological properties of dough and baking quality have been published. In most cases, very few flour samples have been used and the effect of water content has not been studied.

Oscillatory measurements of wheat doughs in the linear viscoelastic region with strains $<0.1\%$ have been used to study effects of water, ingredients, and flour type. Most rheological measurements on dough have been performed in shear because shear deformation is easier to measure. Oscillatory measurements are very sensitive to water content (Hibberd 1970; Hibberd and Parker 1975; Navickis et al 1982; Dreese et al 1988). Both storage modulus (G') and loss modulus (G'') decrease as the water content of doughs increase. Oscillatory measurements in the linear viscoelastic region have not been able to predict the baking quality of different flours (Amemiya and Menjivar 1992; Safari-Ardi and Phan-Thien 1998). Some studies suggest that these tests can show differences between different baking-quality wheat glutes (He and Hosney 1992; Jansen 1992; Kokelaar 1994). The application of larger strains is more relevant to doughs, therefore high-amplitude oscillatory measurements have also been done (Miller and Hosney 1999). When working within the linear viscoelastic range, data analysis can be conducted with the mathematical theory of linear viscoelasticity. This is not the case in the nonlinear region.

Good baking quality is dependent on several rheological properties: extensibility exceeding a minimum level, strain hardening, and optimal resistance to deformation. Strain hardening can be defined as the occurrence of a sudden increase in the viscosity and in the stress when a certain strain value is reached. Strain hardening behavior of wheat flour doughs has been demonstrated by Schofield and Blair (1933), van Vliet et al (1992), Amemiya and Menjivar

(1992), Janssen et al (1996a,b), Dobraszczyk and Roberts (1994), Kokelaar (1994), Lindborg (1995), and Wikström (1997). Strain hardening has been studied by different methods including biaxial extension tests, in which a cylindrical test piece is compressed between two parallel plates with diameters identical to that of the sample; a modified bubble inflation technique; a stress overshoot test, in which dough is sheared at a fixed shear rate as a function of time; or a method in which the transient stress under a constant extension rate is measured, followed by a stress relaxation measurement after cessation of flow. In the biaxial extension test, Wikström (1994) showed that both the strain and strain rate changed during the measurement. There was no relationship between strain hardening and baking performance using 11 flour samples. On the contrary, when the transient stress was measured under a constant preset strain rate, followed by a stress relaxation measurement after cessation of flow, the onset from stress growth curve and the cut from the relaxation rate plot were closely related to the bread volume of 17 wheat samples.

Increasing automation in the bakery makes it more important than ever that online process control methods will be developed. Many rheological methods, such as stress relaxation (Bohlin 1980; Safari-Ardi and Phan-Thien 1998), creep, and stress overshoot have shown potential in predicting the baking quality of different flours, but they are not well suited for online process control methods.

The aim of the present study was to compare the response of oscillatory and compressional measurements of wheat doughs prepared from different wheat flours, water contents, and mixing times and relate these rheological measurements to baking performance of the flours by multivariate analysis.

MATERIALS AND METHODS

Flour Properties

Four baker flours were obtained from two Finnish bakeries (Baco Ltd., Masala and Leivon Leipomo Ltd., Tampere). Two replicates were made of the chemical analyses of flours. The chemical composition of the flours and quality attributes of flours are shown in Table I.

Moisture content was determined according to standard method 110/1 and wet gluten content with method 137/1 (ICC 1996). Crude protein and ash were analyzed according to standard methods (AOAC 1984). The falling number of flours was determined by Approved Method 56-81B, farinogram by Approved Method 54-21, and extensigram by Approved Method 54-10 (AACC 2000).

¹ VTT Biotechnology, P.O. Box 1500, FIN-02044 VTT, Finland.

² Corresponding author. Phone: +358-9-4565175. Fax: +358-9-4552103. E-Mail: karin.autio@vtt.fi

Data Analysis

The doughs were prepared using a fractional factorial design incorporating four baker flours, three water contents, and three mixing times. Experimental designs were planned and analyzed with Modde for Windows (Umetri Ab, Sweden). Correlations of rheological measurements and baking test were determined with partial least squares (PLS) regression (Unscrambler, Camo As, Norway) using one or a few point values and also using all the data points (rheological measurements).

Baking Tests

The formula consisted of flour (100%), sugar (2%), shortening (2%), salt (1.5%), yeast (instant active dry yeast 1.5%), and water based on the farinograph. All the ingredients were based on 100 parts of flour. The water content of the doughs was -3, 0, or 3% of the farinogram absorption - farinogram drop off (20 BU = 1%; Table II). Drop-off value generally gives the rate of breakdown and strength of a flour: the higher the value, the weaker the flour (D'Appolonia and Kunerth 1984). Flour (600 g) was blended thoroughly with the sugar, yeast, and salt and placed in the spiral mixer (Diosna SP 12 F, Dierks & Söhne GmbH, Osnabrück, Germany). The shortening and water were added and the dough was mixed according to the design of the experiment. The mixing times were 2 min of slow mixing speed (100 rpm). The fast mixing speed (200 rpm) was varied according to the farinogram stability time of flour. The fast mixing

TABLE I
Quality Attributes of Flours

| Attribute | Flour | | | |
|-----------------------------|-------|-------|------|------|
| | 1 | 2 | 3 | 4 |
| Analytical | | | | |
| Moisture (%) | 13.3 | 13.6 | 14.2 | 13.9 |
| Protein (% db) N × 5.7 | 12.2 | 12.0 | 11.8 | 14.2 |
| Ash (% db) | 0.89 | 0.72 | 0.62 | 0.62 |
| Falling number (sec) | 311 | 316 | 364 | 381 |
| Wet gluten (%) ^a | 27.2 | 29.4 | 29.8 | 31.7 |
| Farinograph | | | | |
| Absorption (%) ^a | 60.8 | 57.7 | 60 | 59.6 |
| Development time (min) | 2 | 1.75 | 2.25 | 3.25 |
| Stability (min) | 10.5 | 13.75 | 9.5 | 17 |
| Drop off (BU) ^b | 90 | 70 | 70 | 40 |
| Extensigraph, 45 min | | | | |
| Resistance, max (BU) | 545 | 740 | 465 | 550 |
| Resistance after 5 min (BU) | 435 | 570 | 370 | 400 |
| Extensibility (cm) | 16.1 | 15.6 | 17.5 | 19.4 |
| R 5/E (BU/cm) | 27 | 36.5 | 21.2 | 20.7 |
| Extensigraph, 90 min | | | | |
| Resistance, max (BU) | 790 | over | 520 | 665 |
| Resistance after 5 min (BU) | 735 | 960 | 410 | 515 |
| Extensibility (cm) | 13.8 | 12.9 | 17.2 | 18.4 |
| R 5/E (BU/cm) | 53.5 | 74.6 | 23.8 | 28 |

^a 14% moisture basis.

TABLE II
Water Content and Mixing Time of Doughs
According to the Experimental Design^a

| Flour | w | | | m | | |
|-------|------|---------|------|---------|---------|----------|
| | w- | optimum | w+ | m- | optimum | m+ |
| 1 | 54.6 | 56.3 | 57.9 | 2 + 2.5 | 2 + 5 | 2 + 7.5 |
| 2 | 52.6 | 54.2 | 55.8 | 2 + 3.5 | 2 + 7 | 2 + 10.5 |
| 3 | 54.8 | 56.5 | 58.2 | 2 + 2.5 | 2 + 5 | 2 + 7.5 |
| 4 | 55.9 | 57.6 | 59.3 | 2 + 4.5 | 2 + 8.5 | 2 + 13 |

^a Water content = w, % of flour weight (14% mb); mixing time = m (min).

TABLE III
Correlation Coefficients of Rheological Methods

| Properties Measured | r |
|---|------|
| Hardness vs. storage modulus (G') in the linear region | 0.80 |
| Force-time curve (0-50%) vs. G' stress curve (0.5-1,000 Pa) | 0.88 |

time (min) was -50, 0, or 50% of farinogram stability time/2 (Table II). The temperature of the dough was kept at 26-27°C after mixing by adjusting the temperature of the added water. After the intermediate proof (20 min, 28°C, 80 rh), the dough was scaled into four 150-g pieces, rounded, and molded with bread molder BM 51-B (Werner & Pfleiderer-Haton, Panningen, Netherlands). The breads were placed on baking plates and proofed at 34°C, 80% rh. Proofing times were optimized according to the flour type and were 35 min for flours 1 and 2, 40 min for flour 3, and 30 min for flour 5. The loaves were baked at 200°C for 20 min with 15 sec of steam in the beginning. The loaves were cooled for 2 hr before being weighed. Loaf volume was determined by rapeseed displacement method (Siebert 1971).

Dough Preparation for Rheological Measurements

The doughs for the rheological measurements were prepared as for baking experiments but without yeast.

Rheological Measurements

Two different rheological methods were used. In the first, viscoelastic measurements were made. In the second method, force was measured during the compression 0-50% as a function of time. The viscoelastic measurements were made with a constant stress rheometer (StressTech, Reologica, Lund, Sweden) with parallel-plate geometry (diameter, 20 mm). Two replicate doughs were prepared and three pieces of each dough were measured. The dough sample (1.07 g) was slowly compressed by the upper plate until the gap between the plates was 3.0 mm. Excess dough was removed. Silicon oil was applied around the plate edges to prevent the sample from drying. The sample was allowed to rest to reach a normal force at <0.4 N. The measurements were made at 25°C after dough mixing. Six replicates were made of each sample. G' as a function of stress (stress sweep) was linear up to 10 Pa. The frequency was 1 Hz. The stress sweep was measured at 0.5-1,000 Pa. The standard devi-

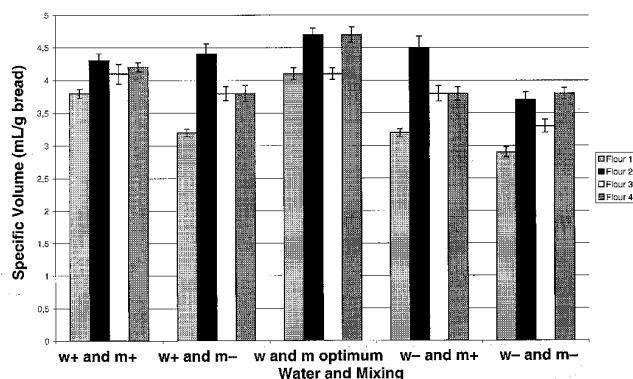


Fig. 1. Effect of water content (w), mixing time (m), and flour type on specific volume of bread dough. Groups indicate flours 1 to 4 as in Table I.

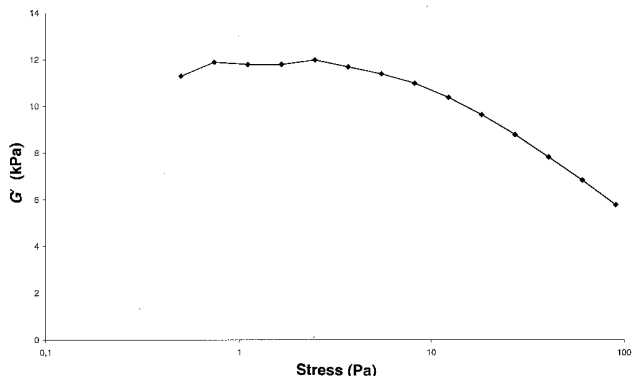


Fig. 2. Typical storage modulus (G') stress curve for wheat dough.

ation after mixing and incubation was 1.5–4.8 and 0.6–2.2, respectively. G' values were taken from the curve corresponding to a stress value of 1 Pa. The compression measurements were performed with a texture analyzer (TA-XTA, Stable Micro Systems, Surrey, Great Britain). A round plastic box with an inner diameter of 68 mm and a height of 20 mm was filled with the dough and the expelled dough was carefully trimmed off with a knife to achieve an even surface. Doughs were compressed with a cylinder (sample area, 314 mm²). Compression range was 50% and the compression rate 2 mm/sec. When the dough was compressed from 0 to 50%, the force as a function of time was registered. The maximum force was taken as a hardness value. The standard deviation after mixing and incubation varied 0.003–0.012 and 0.003–0.020, respectively.

RESULTS AND DISCUSSION

Baking Performance

Various flour quality parameters for the wheat flours used in this study are shown in Table I. Flour protein contents ranged from 11.8 to 14.2%. Although flour 2 had lower protein and wet gluten content (12.0 and 29.4%) than flour 4 (14.2 and 31.7%), it exhibited strong farinograph stability and high extensigraph resistance values. This predicts the good baking quality of the flour and, thus, high specific volume of the bread. The baking performance of different doughs varied greatly. Specific loaf volumes ranged from 2.9 to 4.7 mL/g. The smallest loaf volumes were attained with minimal mixing time and water content and the biggest loaf volumes were attained at optimum mixing time and water content. Results indicate a nonlinear dependence between specific volume, water content and mixing time, when each flour is considered separately (Fig. 1). Hence, we can conclude that the response-factor relationship is curved. Such a curvature can only be adequately represented by a model with quadratic terms. Unfortunately, the design used here does not allow the estimation of quadratic terms.

Rheological Measurements

Two different rheological methods were used. In the first, G' , G'' , and phase angle were measured as a function of stress. A typical G' stress curve for a wheat dough is illustrated in Fig. 2. The stress value where G' is proportional to the stress varies considerably with the nature of material and helps to characterize materials (Ross-Murphy 1988). G' started to decrease heavily after 8–10 Pa, depending on the dough system. The stress value of maximum G' varied in the different doughs at 0.5–2.5 Pa. After this stress value, the G' started to decrease, suggesting that the applied stress had influence on the dough structure. G' values were taken from the curve cor-

responding to stress value of 1 Pa (Fig. 3). The former G' value or all data points of the curve (Fig. 2) were taken for statistical treatments. In the second method, force was measured during the compression at 0–50% as a function of time. A typical force-time curve is illustrated in Fig. 4. The wheat dough deforms easily (low initial slope) and tends to flow. The shape of this curve differs from one material to another (Bourne 1978). The maximum force (peak value, hardness) was taken and used in Fig. 5. These values or all data points of the curve (Fig. 4) were taken for statistical treatments. Both water and flour type had a statistically significant effect on G' value at low deformation (Fig. 3). Several studies have shown that the modulus of the dough, measured at small deformations, is very sensitive to the dough water content.

Both water and flour type had a statistically significant effect on the compressional force of the doughs (Fig. 5). The deformability of sugarfree short doughs increased with increasing water content in

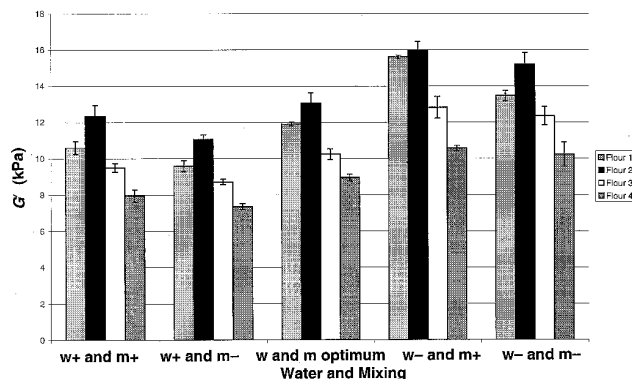


Fig. 3. Effect of water content (w), mixing time (m), and flour type on storage modulus (G') of wheat dough. Groups indicate flours 1 to 4 as in Table I.

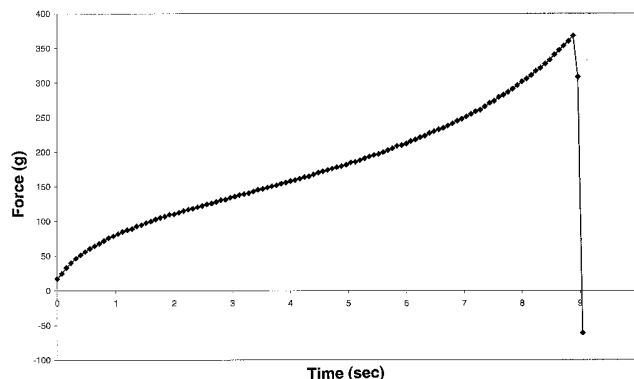


Fig. 4. Typical force-time curve for wheat dough

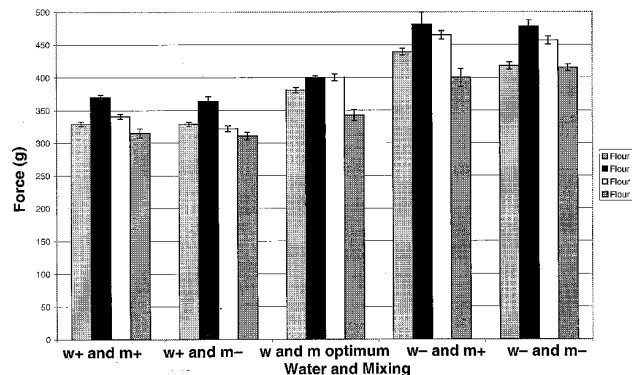


Fig. 5. Effect of water content (w), mixing time (t), and flour type on hardness of wheat dough. Groups indicate flours 1 to 4 as in Table I.

TABLE IV
Correlation Coefficients of Loaf Volume with Rheological Measurements of Dough

| Properties Measured vs. Loaf Volume | <i>r</i> |
|---|----------|
| Storage modulus (G') in the linear region | 0.15 |
| Phase angle in the linear region | 0.28 |
| G' stress curve (0.5–1,000 Pa) | 0.72 |
| Phase angle-stress curve (0.5–1,000 Pa) | 0.65 |
| Hardness | 0.02 |
| Force-time curve (0–50%) | 0.81 |

TABLE V
Correlation Coefficients of Bread Weight with Rheological Measurements of Dough

| Properties Measured vs. Bread Weight | <i>r</i> |
|---|----------|
| Storage modulus (G') in the linear region | 0.67 |
| Phase angle in the linear region | 0.72 |
| G' -stress curve (0.5–1,000 Pa) | 0.91 |
| Phase angle-stress curve (0.5–1,000 Pa) | 0.90 |
| Hardness | 0.68 |
| Force-time curve (0–50%) | 0.76 |

uniaxial compression (Baltasvias et al 1999). The effect of flour type was greater in the small deformation oscillation test than in compression at high deformation, suggesting that the former method is more sensitive than the latter. Especially at high or optimum water contents, the differences in the compressional forces of doughs prepared from different flours were small. The fraction of available water in dough that is incorporated into the gluten phase is strongly dependent on the cultivar (Larsson and Eliasson 1996).

The correlation coefficients between the two rheological methods are shown in Table III. The correlation coefficient between hardness and G' measured in the linear viscoelastic region was $r = 0.80$. Higher correlations ($r > 0.975$) were obtained for rye doughs (Autio et al 1999). The differences between wheat and rye dough are due to the differences in dough structure. In rye dough, the huge flour particles are stuck together by weak, short-range interactions; whereas, in wheat dough, the polypeptide chains are linked together covalently by intermolecular disulfide bridges to form high molecular weight glutenin polymers. Correlation between the compression and oscillation test of wheat doughs improved when all data points of the force-time curve or G' stress curve were included ($r = 0.88$). Mixing times did not have an effect on the rheological properties of doughs.

Relationship Between Dough Rheological Properties and Baking Performance

The correlation coefficients of rheological measurements and loaf volume are presented in Table IV. No correlation was obtained between the maximum force of compression or G' of the dough measured in the linear viscoelastic region and baking performance. Good correlation was achieved between rheological measurements and baking performance when all data points of force-time or G' stress curve were evaluated with PLS multivariate analysis. This and earlier studies suggest that no single rheological parameter has potential in predicting the baking quality of different bread wheat flours. All rheological methods of doughs correlated with bread weight (Table V). The highest correlation was again obtained with rheological methods performed in wide stress-strain ranges.

CONCLUSIONS

The correlation coefficient between hardness and G' in the linear viscoelastic region was $r = 0.80$. Correlation between the compression and oscillation test of wheat doughs improved when all measuring points of the rheological curve were included ($r = 0.88$). Neither G' measured in the linear viscoelastic region nor maximum force of compression have potential in predicting the baking quality of different bread wheat flours. Good correlation was achieved between rheological measurements and baking performance when whole force-time curve or stress sweep were evaluated with PLS multivariate analysis.

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