Assessing Spring Wheat Quality Using the Glutograph Instrument

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ABSTRACT

Wheat proteins, especially the gluten proteins, are the primary determinant of rheological properties and quality differences of wheat flour. The major objective of this study was to use the glutograph, a lesser-used rheological instrument, to evaluate quality differences among a set of 24 hard red spring (HRS) wheats of diverse quality differences. A significant positive relationship was obtained between the stretching (strength) parameter of the glutograph and the following parameters of other rheological instruments: stability of the farinograph, peak time and height of curve at 8 min of the mixograph, height of curve and deformation energy of the alveograph, resistance to extension and area under the curve of the extensigraph, and loaf volume and specific loaf volume of the HRS wheat flours. The relaxation parameter of the glutograph was highly correlated with the length of the alveograph curve and the extensibility of the extensigraph of the wheat flour samples. Also, highly significant correlations of the glutograph parameters were found between whole meals and flours of the HRS wheat. Therefore, the glutograph appears to show good promise for quality evaluation of flour and whole meal samples for assessing dough strength among HRS wheat cultivars.

Proteins are among the primary factors responsible for the variation in wheat quality (39,40). Protein content of wheat grain of a specific cultivar depends on agronomic and environmental factors (4,6,24). Protein quality, on the other hand, is primarily a genotypic trait and can also be affected by certain environmental stress conditions. Wheat proteins comprise an extremely heterogeneous mixture of molecular species with different properties and functions in the wheat grain (7,41). Increase in protein content is normally associated with increased dough strength and improved baking quality of bread wheat (18). The functional properties of wheat depend on the structure of the various types of proteins that form the gluten complex, their interaction with each other, and their interaction with other wheat components (35,39).

Rheological properties are significant in determining the behavior of wheat flour dough during mechanical handling, in addition to their influence on the quality of the finished product. However, the rheological properties of a dough system are analogous to the properties of gluten. These properties depend on the structure of the aggregates and their tendency to interact with each other. Specific nonprotein components of flour interact with specific proteins of gluten. Intermolecular interactions among gluten proteins and between protein and nonprotein components lead to the formation of various aggregates; the most important interactions between these aggregates appear to result from hydrogen bonds (8). The rheological properties of gluten are known to be affected by a) the quality and quantity of the protein fraction in the gluten complex (amino acid composition, molecular weight, and shape); and b) the interaction between different protein components of the gluten complex (disulfide bonds, hydrogen bonds, and hydrophobic interactions) (21).

Several instruments are used to obtain empirical information on mixing. Two commonly used instruments, the farinograph and the mixograph, record the resistance of dough to the mixing blades during prolonged mixing (38). During the mixing process, many physicochemical changes occur, and the different flours have different responses (15).

Protein quality measurement using lower-cost accessible equipment and small samples (such as with the glutograph equipment) would enable wheat-breeding programs, researchers, and end-users to perform the same tests, allowing direct comparison of protein quality measurements with improved understanding of quality requirements. Traditionally, wheat dough rheological properties have been determined using dough-mixing instruments, such as the farinograph or mixograph, or using large strain (nonlinear) descriptive rheological methods, such as with the extensigraph or alveograph (5,22). These testing methods have led to the use of a number of physical indicators of dough strength, in addition to the basic definition of ultimate strength as stress at rupture. These methods are still useful, especially for determination of the relative strength and extensibility of cultivars, but require relatively large samples.

The glutograph measures the stretching and elastic properties of wet gluten. The measuring system consists of two parallel, round, corrugated plates mounted at a defined distance opposite each other. One of these plates deflects against the other one, stretching the sample. There is only one type of glutograph, and a wet gluten sample is needed for analyses. Wheat flour (10 g) is used to obtain gluten with a glutomatic machine (Perten Instruments AB, Huddinge, Sweden). The time required for one glutograph test (including washing out the starch and forming a wet gluten ball on the glutomatic machine) is about 7 min.

Different values can be obtained from the glutograph profile, such as the shear time (determines the extension of sample) and relaxation time (determines the elasticity of sample). Sietz (37) described the glutograph as a new method to test gluten quality, such as the extensibility and elasticity of washed wet or dry gluten. Research comparing farinograph and extensigraph parameters with the glutograph parameters was carried out by Sietz (37). He concluded that, in spite of the glutograph being a good instrument for testing of gluten quality, it cannot replace more sensitive tests like the extensigraph but it is a good complement as a rapid test. Johansson and Svensson (17) used the glutograph as one of various technological tests to evaluate the functional value of the high-molecular-weight glutenin subunit 21* (HMW-GS 21*) to different baking quality characteristics of

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Swedish wheats. They found that the glutograph deformation time (function of the time during extension and relaxation) was very long and did indicate a gluten strength too high for Swedish baking conditions. The same authors (18) investigated the effect of weather and nitrogen application rate on bread volume, protein concentration, and gluten strength of spring and winter Swedish wheats. They concluded that the higher nitrogen fertilizer rate led to lower glutograph values (decreased gluten strength). Also, spring wheats showed higher gluten strength than winter wheats. Influence of both the genotype and the environment on different spring wheat cultivars showed a high glutograph value, which means an increase in gluten strength (19).

Quick and efficient wheat flour quality evaluation in breeding programs and in industry—where there is a need to analyze many samples in a short time—is needed. Therefore, the objectives of this study were a) to determine the correlations between the parameters of the glutograph and other standard protein quality testing instruments using a set of selected HRS wheats; and b) to use the glutograph as a potential tool to evaluate gluten quality.

MATERIALS AND METHODS

Materials

Twenty-four HRS wheat cultivars grown in North Dakota in 2005 were chosen on the basis of their wide quality differences (wheat quality report, Plant Sciences Department, North Dakota State University [NDSU], Fargo, ND, U.S.A.). The cultivars chosen were as follows: AC-Amazon, Alsen (13), Briggs, Dapps (25), Fryer, Glenn (ND 747) (27), Granger (SD 3546), Granite, Gunner, Knudson, ND 800 (now named Howard) (28), ND 803, ND 805 (now named Faller) (29), ND 806, ND 807, Oklee, Oxen, Parshall, Polaris, Reeder, Saturn, Steele-ND (26), Trooper, and MN 97803 (Ulen). In addition, one commercial HRS wheat flour was obtained from the mill in Grand Forks, ND, U.S.A., and used as the control.

Methods

Sample Cleaning

A Carter-Day dockage tester (Carter-Day Co., Minneapolis, MN, U.S.A.) was used to clean the HRS wheat samples. Further, samples were scoured using a Forster scourer (Forster Manufacturing Co., Wichita, KS, U.S.A.).

Milling

The HRS wheat cultivars were tempered to 15.5% moisture content for 24 h, and then milled on a Buhler laboratory experimental mill according to a standard procedure for HRS wheat used at the Department of Plant Sciences at NDSU adapted from AACC International Method 26-20 (1). After milling, flour samples were placed at room temperature to be matured for a week. Then the flour was stored at 4°C until used. The whole meal samples were obtained by grinding HRS wheat cultivars in a falling number laboratory mill 3100 (Perten Instruments AB, Huddinge, Sweden) with a 0.8-mm screen.

Physical and Chemical Analyses of HRS Wheat Flours

Approved Methods of the American Association of Cereal Chemists (2) was used to determine moisture (Method 44-15A); protein (Method 46-30) using a Leco protein analyzer (conversion factor $N \times 5.7$); ash (Method 08-01); wet gluten and gluten index (Method 38-12A); falling number (Method 56-81B); farinograph (Method 54-28A); mixograph (Method 54-40A); extensigraph (Method 54-10); and alveograph (Method 54-30A).

Glutograph

The procedure was carried out according to the manual of the manufacturer (Brabender GmbH & Co., Duisburg, Germany) of the Glutograph-E: wet gluten from 10 g of flour was used for measuring the stretching and elastic properties of the dough to obtain the following data: a) shear time or stretching (STR) (s), time to reach the deflection or shear angle (determines the extension of the dough); and b) relaxation (RX) (Brabender units [BU]), recovery of the sample after 10 s (determines the elasticity of the dough).

Baking Quality Evaluation of HRS Wheat Flours

Evaluation of the bread-baking quality of the HRS wheat flours was carried out according to the standard method (straight dough) used at the Department of Plant Sciences at NDSU as follows: a) flour (14% moisture basis [mb]), 100 g; b) yeast (instant), 3 g; c) sugar, 5 g; d) salt, 1 g; e) α-amylase (Doh-Tone), 1 mL (0.3 g/100 mL of water); f) ammonium phosphate, 1 mL (10 g/100 ml of water); g) ascorbic acid (20 ppm/1 mL), 1 mL (0.2 g/100 mL of water); and h) water (optimum amount based on farinograph absorption and adjusted as follows: farinograph absorption was reduced by the amount of 3 mL of α-amylase, ammonium phosphate, and ascorbic acid that was already added before addition of the water).

After baking, the loaves were cooled at room temperature for 30 min, and the loaf volume was measured by rapeseed displacement. The bread scoring was done by an experienced scorer at the Department of Plant Sciences at NDSU.

Data Analysis

Completely randomized design (CRD) was used for the statistical analyses for all data of selected HRS wheats. Each analysis was based on three replicates. All statistical analyses were conducted using SAS programs (34). Significant differences between group means were analyzed by Duncan's multiple-range test. A level of significance of 95% was used throughout the statistical analyses. Pearson's correlation coefficients were used to measure the strength of the linear correlation between two variables.

RESULTS AND DISCUSSION

Chemical Composition of HRS Wheat Flours

The results of moisture content, protein content, ash content, wet gluten content, gluten index, and falling number of the HRS wheat flours used in this study, including a commercial flour as a control, are given in Table I. All flours showed many statistically significant differences in their chemical composition because of different cultivars, environmental conditions, and/or flour extractions. The variations in the decline in protein from wheat to flour are due to conditions of the milling process and differences in flour yield between cultivars. The highest flour-protein content cultivars, Steele-ND, Saturn, Granger, Fryer, and Trooper, had the highest wet gluten contents. Ash content ranged from 0.39% in Oklee and Trooper to 0.65% for MN-97803. The falling number ranged from 329 to 681 s. These high falling number values indicate sound and unsprouted wheats. A high falling number indicates low α-amylase activity (31).

Gluten index (GI) is defined as the ratio of wet gluten remaining on the centrifuge screen and the total gluten centrifuged. Cubadda et al. (10) concluded that GI is an excellent small-scale method to evaluate gluten strength in durum wheat. In order to evaluate the latter conclusion of Cubadda et al. (10) for spring wheats, we ran correlations between GI and the rheological parameters of the various instruments used in this study. Our results (Table II) showed that GI was highly significantly and positively associated with gluten-strength-related parameters of the five rheological instruments. AC-Amazon had the highest gluten index value, while Briggs, Oklee, and Reeder had the lowest values. Thus, a high GI could indicate a strong gluten structure in the dough of HRS wheat flours.

Farinograph and Mixograph Properties of HRS Wheat Flours

In order to make comparisons with the relatively new glutograph instrument for use in wheat quality evaluation, data had to be collected on the 24 HRS wheat cultivars with the traditional rheological instruments that are used, such as the farinograph, mixograph, extensigraph, and alveograph. Data from these latter instruments are reported in the following sections to show the diverse quality differences among the 24 HRS wheat cultivars as a good set of samples with which to make valid comparisons.

Farinograph and mixograph evaluations of HRS wheat flours are shown in Table III. Raw data (Table III) from these two instruments are given as representative of these rheological instruments to illustrate the wide range of quality differences. Water absorption (WA) of flour ranged from 61% (Polaris) to 76.2% (ND 807). Bushuk et al. (9) estimated that 45.5% of the total water in dough is absorbed by starch, 31.2% by proteins, and 23.4% by pentosans. Both damaged starch and proteins absorb half the amount of water of their weight, while pentosans can be hydrated 15 times their weight (9). Thus, WA may not be directly related to gluten strength and may be influenced more by other factors, such as starch damage and pentosans contents. Dough development time (DDT) is an indicator of flour protein strength. Strong flours require longer DDTs than weaker flours (14). Therefore, comparing DDTs can determine the relative strength of different flours (12). Farinograph DDTs of samples ranged from 3.9 to 39.7 min. Cultivars Reeder and Parshall had the shortest DDTs, while cultivars Trooper and AC-Amazon had the longest DDTs. It was noticed that the cultivars with the longest DDTs hydrated quickly and showed two peak times before dough breakdown. The second peak time is more accurate, representing the DDT of this type of dough. Stability (ST) is a better index of flour quality; the longer the stability, the stronger the resistance to extension (30). Farinograph ST of dough ranged from 4.4 (Reeder) to 46 min (Trooper). Mixing tolerance index (MTI) is an indicator of dough strength; higher values indicate weaker flours. All doughs eventually break down with sustained mixing, and the more rapidly breakdown occurs, the less mechanical abuse the flour can tolerate (33). However, high ST and low MTI values are a desirable combination for good mixing properties (36). In the present study, cultivars Saturn, Trooper, AC-Amazon, and Fryer significantly had the lowest MTI values (higher stability) than the rest of the cultivars.

Mixograph data showed significant differences among cultivars (Table III). The mixograph evaluates the mixing properties of gluten development in dough (5). Peak height (PH) tends to be positively related to the flour's protein content (at a constant water absorption) (30,33). Results of PH values and protein content of the cultivars in this study are generally consistent with Pyler's (33) description of mixograph results. Peak times (PT) and height of curve at 8 min (H-8min) of flours ranged from 7.9 min and 5.4 mixograph units (MU) for AC-Amazon to 2.2 min and 4.4 MU for Reeder, respectively. These results are also consistent with the values of the gluten index and farinograph ST of these same cultivars.

Generally, there were large differences in all values for both the farinograph and mixograph rheological tests among the flours. These wide differences in rheological properties are needed when comparing parameters of the glutograph instrument to establish relationships of rheological properties between the other instruments.

Table I. Chemical composition of hard red spring (HRS) wheat flours[x]

Cultivar	Moisture (%)	Protein[y] (%)	Ash[y] (%)	Falling Number (s)	Wet Gluten[y] (%)	Gluten Index[y]
AC-Amazon	14.7 a	12.2 p	0.48 fg	484 ij	31.0 mn	100.2 a
Alsen	12.6 f	12.4 o	0.63 ab	329 m	31.7 m	92.9 ef
Briggs	13.3 cde	13.7 kl	0.56 cd	561 def	38.2 hi	55.2 m
Dapps	14.5 a	14.6 i	0.42 h	500 hi	39.2 fg	86.9 gh
Fryer	13.3 cde	16.9 d	0.56 cd	681 a	47.0 b	67.7 l
Glenn	13.4 cd	14.9 gh	0.63 ab	464 ijk	39.6 ef	92.2 ef
Granger	13.3 cde	17.3 c	0.57 c	590 cde	47.8 ab	73.6 k
Granite	13.2 de	14.9 fg	0.61 b	384 l	39.2 fg	76.1 k
Gunner	13.9 b	13.2 n	0.61 b	563 def	36.6 j	83.0 ij
Knudson	13.4 cd	12.4 o	0.63 ab	461 jk	29.8 o	98.2 ab
MN-97803	13.3 cde	13.6 l	0.65 a	467 ijk	37.3 ij	68.6 l
ND 800	13.5 c	14.7 hi	0.46 g	556 efg	40.2 de	83.1 ij
ND 803	12.6 f	14.1 j	0.50 f	553 fg	37.0 j	81.7 j
ND 805	13.1 e	13.4 m	0.46 g	535 fg	35.0 k	94.8 cde
ND 806	13.3 cde	15.1 f	0.50 f	636 b	39.2 fg	86.7 gh
ND 807	12.8 f	14.8 ghi	0.48 fg	481 ij	38.2 hi	84.7 hi
Oklee	14.6 a	13.1 n	0.39 i	525 gh	37.1 j	53.2 m
Oxen	13.8 b	11.8 q	0.55 cde	470 ijk	30.5 no	95.8 bcd
Parshall	14.5 a	11.5 r	0.41 h	441 k	31.5 m	94.3 de
Polaris	13.4 cde	13.7 kl	0.48 fg	440 k	38.4 gh	87.5 g
Reeder	12.8 f	12.3 op	0.61 b	389 l	34.0 l	55.0 m
Saturn	12.6 f	17.6 b	0.53 e	566 def	45.8 c	75.0 k
Steele-ND	13.4 cde	17.9 a	0.54 de	602 c	48.6 a	68.7 l
Trooper	14.0 b	16.1 e	0.39 i	596 cd	41.0 d	91.0 f
Control[z]	14.0 b	13.8 k	0.46 g	248 n	36.4 k	97.2 bc

[x] Values followed by the same letter in the same column are not significantly different from each other ($P < 0.05$).
[y] Based on 14% moisture.
[z] Commercial HRS wheat flour obtained from the mill in Grand Forks, ND, U.S.A.

Table II. Correlation coefficients between rheological parameters[y] and gluten index of hard red spring (HRS) wheat flours

Parameters of Rheological Instruments	Gluten Index
Farinograph	
WA	–0.209
DDT	–0.041
ST	0.332**[z]
MTI	–0.203
Mixograph	
PH	0.202
PT	0.485***
H-8min	0.529***
Alveograph	
P	0.331**
W	0.548***
L	0.0711
Extensigraph	
RE 45	0.589***
RE 90	0.618***
RE 135	0.617***
EX 45	0.039
EX 90	–0.108
EX 135	–0.171
AUC 45	0.612***
AUC 90	0.688***
AUC 135	0.709***
Glutograph	
STR	0.832***
RX	–0.054

[y] Water absorption (WA), dough development time (DDT), stability (ST), mixing tolerance index (MTI), peak height (PH), peak time (PT), height of curve at 8 min (H-8min), maximum overpressure (P), deformation energy (W), length of curve (L), resistance to extension (RE), extensibility (EX), area under the curve (AUC), stretching (STR), and relaxation (RX).
[z] ** and *** indicate significance at $P < 0.01$ and $P < 0.001$, respectively.

Extensigraph and Alveograph Properties of HRS Wheat Flours

The differences between the rheological property measurements of the farinograph and mixograph and of the extensigraph and alveograph are that these latter instruments measure the rheological properties of a dough that has been developed and rested, while the farinograph and mixograph measure dough while it is being mixed and developed. Generally, the extensigraph measures the extent to which properly developed gluten can be extended or sheeted and the ability of gluten to retain gas (resistance to extension). Good bread-baking flour has a much greater resistance to extension than poor bread-baking flour (11). The values of resistance to extension (RE), extensibility (EX), and area under the curve (AUC) of flour dough in this study obtained after 45, 90, and 135 min of proofing were determined (data not shown). The RE of the dough in this study at different rest times ranged from 158 BU in the cultivar Briggs (weak) to 1,000 BU in AC-Amazon (strong). The AUC at 45 min of rest time corresponded with the RE of the same cultivars: it ranged from 48 to 258 cm^2 in Briggs and AC-Amazon, respectively. AUC and RE are used to indicate dough strength (32). Therefore, cultivars with large areas (AC-Amazon, Glenn, Dapps, Granger, Knudson, ND 805, Oxen, and Trooper) indicate stronger wheat flours, and cultivars with smaller areas (Briggs, Oklee, and Reeder) indicate weaker wheat flours.

These results agree with the classification system of extensigraph by Preston and Hoseney (32), as they reported that AUCs less than 80 cm^2 could be classified as weak dough. In this study, AUC values between 120 and 200 cm^2 could be considered strong dough. Therefore, the wide range in values of extensigraph parameters among the HRS wheat flour doughs is useful for comparison purposes between the glutograph and other instrument parameters.

The alveograph is used to measure RE and EX by blowing air through a stretched dough piece, forming a bubble that then ruptures. Thus, the alveograph is somewhat analogous to the extensigraph because both procedures use a rested dough and both use an absorption based on the farinograph. The raw data of the 24 HRS wheat samples were determined for comparisons (data not shown). The alveogram values of maximum overpressure (P) and deformation energy (mechanical work) in 10^3 ergs per g of dough (W) were higher for samples AC-Amazon, Trooper, Glenn, and Dapps and lower in values of length of curve (extensibility) (L); whereas samples of Briggs, Reeder, and Oklee had the opposite values of P, W, and L compared with the previous samples. These results support the data from the extensigraph reported earlier and they were used to compare with glutograph parameters.

Comparison of Data from the Glutograph of HRS Wheat Flours and Whole Meals

The recommended sample for the glutograph is flour. However, we wanted to see whether a whole meal sample could also be used. Hence, we compared both flour and whole meal from the same cultivars. Glutograph stretching time, (STR, determines the extension of the sample) is inversely proportional to relaxation (RX, determines the elasticity of the sample) of the gluten ball at 10 s. Glutograph data for both flour and whole meals are shown in Table IV. The highest STR (125 s, the maximum value that the glutograph registers) values were obtained for AC-Amazon, Trooper, Knudson, ND 805, and Glenn, while AC-Amazon had the lowest RX value. The data of glutograph STR are consistent with data in Table III of farinograph DDT and ST, of mixograph PT and H-8min, of extensigraph RE and AUC, and of alveograph P and W. The data of glutograph RX are also consistent with farinograph MTI, extensigraph EX, and alveograph L. Moreover, these data showed that STR and RX of HRS wheat flours were highly correlated with both stretching and relaxation data of HRS whole wheat meals (Fig. 1).

Table III. Farinograph and mixograph data of hard red spring (HRS) wheat flours[x]

	Farinograph Parameters				Mixograph Parameters		
Cultivar	Water Absorption (%)	Dough Development Time (min)	Stability (min)	Mixing Tolerance Index (BU)[y]	Peak Height (MU)[y]	Peak Time (min)	Height of Curve at 8 min (MU)[y]
AC-Amazon	62.8 p	26.0 b	36.7 b	23.3 lm	5.4 hi	7.9 a	5.4 a
Alsen	69.5 h	4.4 m	6.3 lm	80.0 a	5.5 ghi	3.2 ijk	4.9 e–h
Briggs	68.1 j	5.5 l	5.9 m	65.0 b	5.7 e–h	2.4 m	4.6 ijk
Dapps	69.6 h	8.2 def	14.2 e	31.7 i–l	6.0 bcd	4.2 ef	5.3 abc
Fryer	71.2 d	7.7 e–h	16.0 d	20.7 m	6.2 b	2.8 kl	5.1 b–e
Glenn	71.0 e	9.2 d	12.0 f	40.0 f–j	6.1 bc	4.4 ef	5.3 ab
Granger	72.7 b	7.2 f–k	11.1 fg	22.3 lm	6.2 bc	2.9 kl	5.2 a–d
Granite	69.5 h	7.3 f–j	10.9 fg	45.0 efg	6.1 bc	3.5 hi	5.0 def
Gunner	67.5 k	6.7 g–l	10.4 fgh	46.7 efg	5.3 i	3.8 gh	4.7 hij
Knudson	67.5 k	8.7 de	10.5 fgh	40.0 f–j	5.6 f–i	4.6 de	5.0 c–f
MN-97803	67.5 k	6.4 i–l	6.3 lm	53.3 cde	5.6 f–i	3.4 hij	4.7 g–j
ND 800	69.5 h	6.0 kl	11.8 f	30.7 jkl	6.0 b–e	3.2 ijk	4.9 d–g
ND 803	71.2 d	6.0 kl	8.3 ijk	40.7 f–i	5.5 ghi	2.6 lm	4.6 ijk
ND 805	67.5 k	6.6 h–l	8.6 ij	60.0 bc	5.4 hi	3.2 ijk	4.6 ijk
ND 806	68.0 j	6.4 i–l	11.7 f	30.0 kl	5.4 hi	3.1 ijk	4.5 jkl
ND 807	76.2 a	8.3 def	10.7 fgh	37.7 g–k	6.7 a	2.8 kl	5.3 ab
Oklee	66.6 l	7.5 f–i	7.1 klm	48.3 def	5.0 j	3.3 h–k	4.3 l
Oxen	64.8 n	6.1 jkl	9.7 ghi	41.7 fgh	6.0 bcd	4.0 fg	5.2 a–d
Parshall	70.0 g	4.2 m	7.7 jkl	51.7 cde	5.3 i	3.5 hi	4.8 f–i
Polaris	61.0 q	5.6 l	9.2 hi	56.7 bcd	5.9 b–f	3.3 ijk	4.9 e–h
Reeder	68.5 i	3.9 m	4.4 n	81.7 a	4.9 j	2.2 m	4.4 kl
Saturn	66.0 m	12.3 c	20.9 c	6.7 n	4.9 j	6.6 b	4.6 ijk
Steele-ND	72.2 c	7.9 efg	11.3 fg	33.3 h–k	6.0 bcd	2.7 jkl	4.9 d–g
Trooper	70.2 f	39.7 a	46.0 a	18.3 m	5.8 d–g	6.0 c	5.4 a
Control[z]	64.0 o	6.3 i–l	13.5 e	31.7 i–l	5.9 c–f	4.9 d	5.2 a–d

[x] Values followed by the same letter in the same column are not significantly different from each other ($P < 0.05$).
[y] BU = Brabender units, and MU = mixograph units.
[z] Commercial HRS wheat flour obtained from the mill in Grand Forks, ND, U.S.A.

These observations indicate that it is possible to test the quality of cultivars through bypassing the milling step to obtain flour and using instead a whole meal sample. This could be very advantageous for elevator stations and breeding programs in terms of saving in the cost of milling and also saving on time required to test samples.

Relationship Between Parameters of Glutograph and Other Rheological Instruments of HRS Wheat Flours

The results of correlation coefficients between the parameters of the physical dough-testing instruments with glutograph parameters of HRS wheat flours show that some parameters gave much better correlations with glutograph than other parameters (Table V). The farinograph parameters, such as WA, DDT, and MTI, showed negative and positive correlations, but none of these correlation coefficients were significantly correlated with glutograph parameters. Farinograph ST was positively and significantly correlated with glutograph STR, while it was negatively and significantly correlated with glutograph RX. The mixograph PH was positively but not significantly correlated with both glutograph parameters STR and RX; whereas PT and H-8min were positively and highly significantly correlated with STR. The mixograph PT showed negative and significant correlation with glutograph RX. The correlation coefficient of alveograph P and W correlated positively and significantly with the STR parameter of the glutograph. Alveograph P and W were negatively and not

Table IV. Glutograph data of hard red spring (HRS) wheat flours and whole meals[x]

	Stretching (s)		Relaxation (BU)[y]	
Cultivars	Flour	Whole Meal	Flour	Whole Meal
AC-Amazon	125 a	125 a	393 i	453 g
Alsen	108 ab	125 a	596 e–h	494 fg
Briggs	8 j	13 hij	567 fgh	604 a–d
Dapps	110 ab	108 ab	649 abc	657 a
Fryer	17 ij	11 ij	589 e–h	607 abc
Glenn	125 a	125 a	604 c–g	521 ef
Granger	17 ij	15 hij	588 e–h	576 bcd
Granite	94 bc	124 a	666 ab	638 a
Gunner	48 fg	57 efg	600 c–g	620 abc
Knudson	125 a	125 a	625 b–e	551 de
MN-97803	61 ef	45 fgh	648 a–d	619 abc
ND 800	42 fgh	37 g–j	597 d–h	621 abc
ND 803	84 cd	77 b–f	607 c–g	614 abc
ND 805	125 a	125 a	595 e–h	552 de
ND 806	68 de	75 c–f	621 b–e	636 a
ND 807	55 efg	50 fg	612 c–f	624 abc
Oklee	7 j	7 j	547 h	578 bcd
Oxen	101 abc	106 abc	694 a	660 a
Parshall	62 def	69 d–g	618 b–f	638 a
Polaris	94 bc	90 bcd	689 a	612 abc
Reeder	22 ij	38 g–j	575 e–h	633 ab
Saturn	35 ghi	41 ghi	559 gh	569 cde
Steele-ND	17 ij	16 hij	555 gh	573 cde
Trooper	125 a	82 b–e	604 c–g	636 a
Control[z]	118 a	--	603 c–g	--

[x] Values followed by the same letter in the same column are not significantly different from each other ($P < 0.05$).
[y] BU = Brabender units.
[z] Commercial HRS wheat flour obtained from the mill in Grand Forks, ND, U.S.A.

Table V. Correlation coefficients of rheological parameters[x] between glutograph and other instruments for testing hard red spring (HRS) wheat flours

Parameters of Rheological Instruments	Glutograph Parameters: Stretching (s)	Glutograph Parameters: Relaxation (BU)[y]
Farinograph		
WA	–0.291	0.221
DDT	0.089	0.228
ST	0.578**[z]	–0.431*
MTI	–0.309	0.092
Mixograph		
PH	0.116	0.319
PT	0.687***	–0.515**
H-8min	0.630***	–0.107
Alveograph		
P	0.524**	–0.233
W	0.448*	–0.073
L	0.224	0.427*
Extensigraph		
RE 45	0.809***	–0.436*
RE 90	0.845***	–0.341
RE 135	0.848***	—0.326
EX 45	–0.144	0.507**
EX 90	–0.391	0.613**
EX 135	–0.443*	0.517**
AUC 45	0.818***	–0.331
AUC 90	0.698***	–0.099
AUC 135	0.889***	–0.076

[x] Water absorption (WA), dough development time (DDT), stability (ST), mixing tolerance index (MTI), peak height (PH), peak time (PT), height of curve at 8 min (H-8min), maximum overpressure (P), deformation energy (W), length of curve (L), resistance to extension (RE), extensibility (EX), and area under the curve (AUC).
[y] BU = Brabender units.
[z] *, **, and *** indicate significance at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

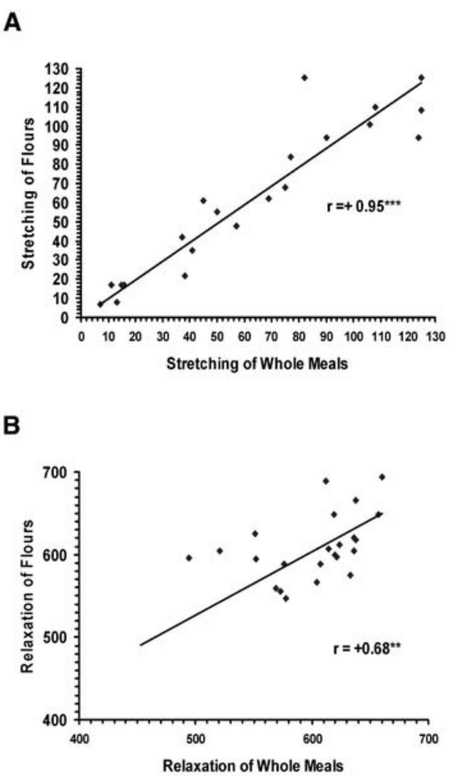

Fig. 1. A, Correlation between stretching parameter of the glutograph of HRS wheat whole meals and flours. B, Correlation between relaxation parameter of the glutograph of HRS wheat whole meals and flours.

significantly correlated with the RX parameter of the glutograph. The alveogram L was positively correlated with glutograph STR but not at a significant level, while it was positively and significantly correlated with glutograph RX. The extensigraph parameters at three different proofing times showed a mixture of positive and negative correlation coefficients with glutograph parameters; highly positive and significant correlations were obtained between extensigraph RE and AUC with glutograph STR. The extensigraph RE and AUC parameters were negatively but not significantly correlated with glutograph RX, except extensigraph RE but only at 45 min, which was significant. The extensigraph EX at 45 and 90 min were negatively but not significantly correlated with glutograph STR, except that extensigraph EX at 135 min was the only one that was significant. It should be noted also that all extensigraph EX parameters at 45, 90, and 135 min were positively and significantly correlated with glutograph RX.

Generally, this data provides evidence that the STR parameter (dough strength parameter) of the glutograph strongly corresponds to the following dough strength parameters of the other rheological instruments: ST (farinograph); PT and H-8min (mixograph); P and W (alveograph); and RE and AUC (extensigraph). In contrast, the RX parameter (extensibility parameter) of the glutograph corresponds more to EX (of extensigraph) and L (of alveograph) than to ST, PT, and RE due to their negative correlations. Thus, glutograph dough strength parameters could possibly be used to evaluate flour instead of other dough strength parameters obtained from the other standard rheological dough testing instruments, such as the extensigraph, alveograph, farinograph, and mixograph. However, a larger number of HRS wheat genotypes (a larger sample set) with diverse quality differences need to be evaluated to confirm this possibility.

Evaluation of Bread-Baking Quality of HRS Wheat Flours

Table VI shows the baking quality data of HRS wheat flours. Loaf volume ranged from 767 (ND 803) to 1,127 (Saturn) cm^3 with a mean of 903 cm^3. Most studies indicated good positive correlations between dough strength and loaf volume (22,23). Loaf weight ranged from 130.6 (AC-Amazon) to 140.6 (Granger) g. The differences in loaf weights are reflected in the differences in genotypes and environmental conditions. Specific loaf volume was calculated by dividing the loaf volume by loaf weight and reported in cubic centimeters per gram. Specific loaf volume is affected by many factors (e.g., flour quality, ingredients, and processing conditions). Our data showed that when loaf volume is increased, the loaf weight is decreased and specific loaf volume is increased for some cultivars. For example, Saturn had 1,127-cm^3 loaf volume, 131.2-g loaf weight, and 8.6-cm^3/g specific loaf volume compared with ND 803. External characteristics of loaves include crust color and symmetry (which means appearance and size of the loaf with more emphasis on the uniformity and the break and shred of the loaf's crust).

The internal characteristics of the loaf include crumb color, grain, and texture. These characteristics of bread were graded on a scale of 1 to 10 (by an experienced evaluator), ranging from least favorable to most favorable. All loaves had a 10 score of crust color, but they varied in scores of other characteristics. However, cultivars AC-Amazon, Dapps, Glenn, and Trooper had the highest scores in crust color, symmetry, crumb color, grain, and texture. Cultivars Briggs, Fryer, Steele-ND, and Reeder had the lowest loaf score in both external and internal characteristics, although Fryer and Steele exhibited stronger dough-mixing properties. In earlier published studies, poor baking performance of extra-strong cultivars was attributed to the strong nature of gluten protein that makes the dough more elastic and less extensible, which prevent dough expansion (16,20). However, in this study, the wide variation in baking quality among this limited set of samples provided a good initial data set for correlation studies with the glutograph and other rheological instruments. At the same time, these baking quality data support the rheological properties data of all the instruments used in this study. For example, high values of farinograph ST and glutograph STR parameters of Trooper were associated with high values of baking results.

Table VI. Baking quality data of hard red spring (HRS) wheat flours[x]

Cultivar	Loaf Volume (cm^3)	Loaf Weight (g)	Specific Volume (cm^3/g)	Crust Color[y]	Symmetry[y]	Crumb Color	Grain/ Texture[y]
AC-Amazon	868 e–h	130.6 k	6.7 e–h	10.0 a	8.0 c	7.3 fg	8.0 b
Alsen	853 e–i	135.7 c–g	6.3 h–k	10.0 a	6.3 d	5.8 l	5.2 hi
Briggs	783 ij	138.1 bcd	5.7 kl	10.0 a	4.7 e	7.0 ghi	5.3 ghi
Dapps	1,013 b	135.5 d–g	7.5 c	10.0 a	9.3 ab	9.5 a	9.0 a
Fryer	785 ij	140.3 ab	5.6 kl	10.0 a	4.0 ef	6.0 kl	5.3 ghi
Glenn	1,087 a	134.8 e–h	8.1 b	10.0 a	10.0 a	9.3 ab	9.0 a
Granger	837 f–j	140.6 a	5.9 i–l	10.0 a	6.0 d	6.7 ij	5.8 efg
Granite	840 f–j	136.6 cde	6.1 h–k	10.0 a	9.0 b	6.0 kl	6.0 ef
Gunner	870 e–h	134.5 e–h	6.5 f–i	10.0 a	6.7 d	6.0 kl	6.0 ef
Knudson	890 def	133.8 f–i	6.7 e–h	10.0 a	9.3 ab	6.3 jk	6.3 de
MN-97803	903 c–f	135.0 efg	6.7 e–h	10.0 a	6.3 d	6.0 kl	5.8 efg
ND 800	903 c–f	136.5 cde	6.6 e–h	10.0 a	7.7 c	8.0 de	6.0 ef
ND 803	767 j	139.2 ab	5.5 l	10.0 a	3.7 f	7.2 gh	5.7 fgh
ND 805	1,002 b	133.4 g–j	7.5 c	10.0 a	10.0 a	8.2 cd	6.7 cd
ND 806	872 e–h	135.9 c–g	6.4 f–i	10.0 a	6.7 d	6.8 hi	5.8 efg
ND 807	882 d–g	134.4 e–h	6.6 fgh	10.0 a	6.7 d	6.8 hi	5.8 efg
Oklee	897 def	134.8 e–h	6.7 e–h	10.0 a	9.0 b	7.7 ef	6.7 cd
Oxen	910 c–f	132.4 h–k	6.9 d–g	10.0 a	9.7 ab	8.3 cd	6.7 cd
Parshall	973 bc	135.7 c–g	7.2 cde	10.0 a	9.3 ab	8.5 c	8.3 b
Polaris	957 bcd	131.6 ijk	7.3 cd	10.0 a	10.0 a	4.8 m	7.2 c
Reeder	797 hij	138.2 abc	5.8 jkl	10.0 a	4.3 ef	5.0 m	4.8 i
Saturn	1,127 a	131.2 k	8.6 a	10.0 a	10.0 a	8.0 de	8.3 b
Steele-ND	810 g–j	139.7 ab	5.8 jkl	10.0 a	3.7 f	5.0 m	4.8 i
Trooper	1,013 b	136.2 c–f	7.4 c	10.0 a	10.0 a	9.5 a	9.0 a
Control[z]	920 cde	131.5 ijk	7.0 c–f	10.0 a	9.0 b	9.0 b	9.0 a

[x] Values followed by the same letter in the same column are not significantly different from each other ($P < 0.05$).
[y] Grades on a scale of 1 to 10 using subjective evaluation by an experienced baker.
[z] Commercial HRS wheat flour obtained from the mill in Grand Forks, ND, U.S.A.

Relationship Between Parameters of Glutograph and Other Rheological Instruments, and Bread-Baking Quality of HRS Wheat Flours

The standard physical dough-testing instruments (farinograph, mixograph, alveograph, and extensigraph) are used to predict baking performance and the behavior of the dough during processing before baking (11). The correlation coefficients between the parameters of these four physical dough-testing instruments, plus the glutograph with bread-baking quality of HRS wheat flours, are shown in Table VII. The farinograph WA and MTI were negatively associated with loaf and specific loaf volumes, whereas they were positively associated with loaf weight. The opposite was true in that DDT and ST were positively and significantly associated with loaf and specific loaf volumes, whereas they were negatively and significantly associated with loaf weight.

The mixograph PH showed negative and positive but not significant correlations with loaf volume and loaf weight, respectively. PT and H-8min showed positive and negative correlations with loaf volume and loaf weight, respectively, at a highly significant level with PT only.

The alveograph P and W were positively, significantly correlated with loaf volume and negatively, significantly correlated with loaf weight. The L parameter had a lowpositive and nonsignificant relationship with bread-baking quality.

The extensigraph RE and AUC parameters at three different proofing times were positively and highly significantly correlated with loaf volume and specific loaf volume, while they were negatively and highly significantly correlated with loaf weight. The EX parameter at different proofing showed either negative or low-positive correlations with loaf volume and specific loaf volume but not at a significant level. In contrast, the EX showed positive correlations with loaf weight at a significant level.

The relationship obtained from the glutograph parameters with bread baking was similar to those obtained from the previous instruments. The glutograph STR (strength parameter) was highly significantly and positively correlated with loaf volume while it was negatively correlated with loaf weight. Glutograph RX parameter was negatively and nonsignificantly correlated with bread-baking quality.

Generally, the correlation coefficients data showed that the rheological dough strength indicator parameters from the four commonly used instruments (farinograph, mixograph, extensigraph, and alveograph) and the glutograph were significantly and positively associated with loaf volume and specific loaf volume. In contrast, these strength parameters were significantly and negatively associated with loaf weight. These results are in agreement with the findings of MacRitchie et al. (23) that there is a positive correlation between dough strength and loaf volume. Also, Autio et al. (3) found a good correlation between rheological measurements of the farinograph and extensigraph and baking performance of hard wheat.

Results from the present study demonstrated that flour of the HRS wheat cultivars could be classified based on overall rheological properties as follows: very strong (AC-Amazon and Trooper); strong (Dapps, Fryer, Glenn, Granger, Knudson, Oxen, Saturn, Steele-ND, and the control); medium (Granite, Gunner, MN 97803, ND 800, ND 803, ND 805, ND 806, ND 807, Parshall, and Polaris); weak (Alsen and Oklee); and very weak (Briggs and Reeder). The functional properties data also follow the rheological properties data showing that the stronger cultivars had better baking characteristics.

The glutograph parameters have been significantly correlated with the strength parameters of the major rheological instruments currently used to screen wheat germplasm in most breeding programs, such as at NDSU. Based on our findings, for certain tests, where gluten strength is evaluated as a functional quality, the glutograph can replace most of these instruments used for this test. Also, the glutograph can be very advantageous in breeding/screening programs, particularly when only smaller samples are available (for example, in early segregating generations screening) and because the length of time required for the glutograph test is much shorter.

Table VII. Correlation coefficients between rheological parameters[y] and bread baking of HRS wheat flours

Parameters of Rheological Instruments	Loaf Volume	Loaf Weight	Specific Loaf Volume
Farinograph			
WA	–0.199	0.654***[z]	0.299**
DDT	0.490***	0.027	0.450***
ST	0.291	0.207	0.299**
MTI	–0.268*	0.077	0.263*
Mixograph			
PH	–0.124	0.161	0.146
PT	0.502***	0.600***	0.560***
H-8min	0.171	0.159	0.178
Alveograph			
P	0.234*	0.293*	0.268*
W	0.536***	0.253*	0.524***
L	0.191	0.074	0.150
Extensograph			
RE 45	0.386***	–0.514	0.438***
RE 90	0.415***	–0.521***	0.464***
RE 135	0.407***	0.248*	0.460***
EX 45	0.074	0.359**	0.027
EX 90	–0.036	0.452***	0.099
EX 135	–0.141	–0.431***	–0.207
AUC 45	0.460***	–0.405***	0.489***
AUC 90	0.545***	–0.335**	0.557***
AUC 135	0.453***	–0.525***	0.461***
Glutograph			
STR	0.401***	–0.037	0.444***
RX	–0.027	0.037	0.018

[y] Water absorption (WA), dough development time (DDT), stability (ST), mixing tolerance index (MTI), peak height (PH), peak time (PT), height of curve at 8 min (H-8min), maximum overpressure (P), deformation energy (W), length of curve (L), resistance to extension (RE), extensibility (EX), area under the curve (AUC), stretching (ST), and relaxation (RX).

[z] *, **, and *** indicate significance at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

CONCLUSION

Rheological properties of 24 HRS wheat flours were evaluated. These wheat genotypes exhibited different mixing and baking characteristics, although some had similar protein content. Using classical methodologies and tools, chemical composition, rheological properties, and baking results in this study demonstrated that flour of the 24 HRS wheat cultivars could be classified based on protein quality as follows: very strong (AC-Amazon and Trooper); strong (Dapps, Fryer, Glenn, Granger, Knudson, Oxen, Saturn, Steele, and the control); medium (Granite, Gunner, MN 97803, ND 800, ND 803, ND 805, ND 806, ND 807, Parshall, and Polaris); weak (Alsen and Oklee); and very weak (Briggs and Reeder). Gluten index was significantly correlated to all rheological dough strength-related parameters.

It was hypothesized that the glutograph instrument might help in the evaluation of gluten quality and functional properties to replace certain tests of other classical or traditionally used rheological instruments. A direct relationship between stretching (strength parameter) of the glutograph and dough strength parameters of the farinograph, mixograph, extensigraph, and alveograph was found for flour samples. Also, the results showed a positive and significant relationship between the stretching parameter of the glutograph and loaf volume and specific loaf volume. The relaxation parameter of the glutograph was highly correlated with the length of the alveograph curve and extensibility of the extensigraph for the HRS wheat samples.

In an attempt to determine whether HRS wheat whole meal could be used as the starting material for the glutograph test, glutograph parameters showed highly significant correlations between flours and whole meals of HRS wheat cultivars. However, more research is needed with more HRS wheat cultivars and breeding lines to evaluate the suitability of whole meal samples for the glutograph test.

This is the first extensive study to investigate the relationship between the glutograph and other rheological standard testing instruments. The glutograph parameters could have potential usefulness in rapid quality tests since the method is technically simple, reduces the length of time and cost of milling, and requires a small amount of flour or meal to do small-scale tests that may be used to predict the gluten strength and end-use quality of wheat germplasm in breeding programs and wheat quality at country elevators.

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