Comparison of Quality Characteristics and Breadmaking Functionality of Hard Red Winter and Hard Red Spring Wheat

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ABSTRACT

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Various whole-kernel, milling, flour, dough, and breadmaking quality parameters were compared between hard red winter (HRW) and hard red spring (HRS) wheat. From the 50 quality parameters evaluated, values of only nine quality characteristics were found to be similar for both classes. These were test weight, grain moisture content, kernel size, polyphenol oxidase content, average gluten index, insoluble polymeric protein (%), free nonpolar lipids, loaf volume potential, and mixograph tolerance. Some of the quality characteristics that had significantly higher levels in HRS than in HRW wheat samples included grain protein content, grain hardness, most milling and flour quality measurements, most dough physicochemical properties, and most baking characteristics. When HRW and HRS wheat samples were grouped to be within the same wheat protein content range (11.4–15.8%), the average value of many grain and breadmaking quality characteristics were similar for both wheat classes but significant differences still existed. Values that were higher for HRW wheat flour were color *b**, free polar lipids content, falling number, and farinograph tolerance. Values that were higher for HRS wheat flour were geometric mean diameter, quantity of insoluble polymeric proteins and gliadins, mixograph mix time, alveograph configuration ratio, dough weight, crumb grain score, and SDS sedimentation volume. This research showed that the grain and flour quality of HRS wheat generally exceeds that of HRW wheat whether or not samples are grouped to include a similar protein content range.

Growing diversity in the wheat marketplace continues to change wheat, *Triticum aestivum* L. and *T. durum*, into a highly specialized grain product that demands specific quality traits and functionality. In response, wheat-producing countries have used various means of meeting consumer demands such as choosing wheat cultivars with specific quality traits and implementing identity preservation practices (Dahl and Wilson 2000). In the United States, the official inspection system continues to require identification of wheat by market class, which gives an indication of grain hardness, color, and the growing region, thereby providing some information on end use functionality. The six wheat market classes are hard red winter (HRW), hard red spring (HRS), soft red winter, soft white, hard white, and durum wheat.

HRW and HRS wheat are the classes of choice for breadmaking. Finney (1965) provided a general definition of good quality wheat suitable for milling and bread production. For good milling quality, wheat should have normal bolting or sifting properties and a normal flour yield with a normal quantity of ash. A flour of good quality for breadmaking was defined as having high water absorption, medium to medium-long mixing requirement, satisfactory mixing tolerance, good loaf volume potential, and yield a loaf with good internal crumb grain and color. If the wheat is used for making noodles, it should have a low polyphenol oxidase (PPO) content. PPO present in mature wheat kernels has been implicated in undesirable darkening and discoloration in noodles (Jukanti et al 2004).

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The claim that the HRS wheat class is superior to the HRW wheat class dates back to the 1930s. Larmour (1940) made an extensive comparison of HRW and HRS wheat by examining opinions and existing data. That study concluded that although the belief was prevalent that HRS wheat was superior to HRW wheat in baking quality, a survey of published work of many scientists who had used both classes of wheat in their studies failed to provide any consistent support for this view. To date, conflicting claims as to which wheat class is better still exists. Several researchers have shown that, compared with HRW wheat, HRS is the superior wheat class, generally due to higher protein content, while others have shown no distinct quality difference between the two wheat classes. The marketing system may contribute to this inconclusive data because wheat is marketed by class, not by quality. Boland et al (2005) stated that Montana's semi-arid climate encourages the production of high protein content levels in spring wheat. However, HRS wheat grown under high rainfall areas on the West Coast may have significantly lower protein content and quite different quality than the same HRS cultivar grown in lower rainfall areas of the upper Midwest.

Endo et al (1990a) used reversed-phase high performance liquid chromatography (RP-HPLC) to analyze 15 HRW and 15 HRS wheat samples with flour protein content of 12.0–14.4%. Total peak areas for the more hydrophobic peaks were larger for HRS than for HRW wheat flour. Comparison of milling and analytical properties showed that HRS wheat had a higher total flour yield and milling score than HRW wheat. Additionally, ratios of total amount of break flour to reduction flour were lower for HRS than for HRW wheat, although a somewhat higher damaged starch content and ratio of starch tailings to total isolated starch occurred for HRS wheat. Their research showed little difference in the ratio of free lipid to total lipid content between the two wheat classes. Huebner et al (1995) used RP-HPLC to quantitatively analyze gliadins from HRS and HRW wheat. They concluded that quantitative differences in protein compositions of HRS and HRW wheat were primarily genetic and environmental. In a later study, Huebner et al (1997) showed different correlations between loaf volume and γ-gliadin amounts for HRS and HRW wheat flour, suggesting further subtle differences between the two wheat classes. With conflicting results as to which wheat class performs better, they recommended that additional studies of HRS and HRW wheat be done to confirm and extend these observations. Bruckner et al (2001) compared bread quality of white flour and whole grain flour for HRS and HRW wheat. They showed that correlations between protein content and protein-dependent quality traits, including baking water absorption and loaf volume in white flour and whole meal, were higher for HRW wheat than for HRS wheat. Chung et al (2003) showed that HRS wheat has significantly higher mean values of protein and gluten content, kernel hardness, and loaf volume but lower gluten index than hard winter wheat. Their findings were based on data collected over three years using 12 pure cultivars of each hard winter (11 red and one white) and HRS wheat grown in a unique environment in California that allows for synchronous grain fill of all genotypes, thus removing a normally strong environmental component and allowing a better investigation of genetic component differences.

The need to differentiate between classes was also shown in studies that segregated wheat based on wheat classes. For example, Endo et al (1990b) used RP-HPLC and milling results to compare qualitative and quantitative differences between HRS and HRW wheat. Cluster analysis of normalized chromatographic data separated 15 HRS and 15 HRW wheat samples by class, with HRS wheat forming a more compact cluster than HRW wheat. Lookhart et al (1993) used RP-HPLC to analyze gliadins extracted from grain harvested from 12 HRW and 12 HRS wheat cultivars grown in a common environment. Cluster, principal, and canonical analyses were used with canonical discriminate analysis allocating all cultivars to their correct classes, except for the HRW cultivars TAM 105 and TAM 107.

The work reported herein seeks to build on these previous findings by including commercial samples, testing a larger population of samples, and comparing additional quality parameters. The objective of this study was to compare 50 whole kernel, milling, flour, dough, and breadmaking quality characteristics from 100 commercially available HRW and 100 HRS wheat samples. Additional analysis entails a comparison of quality parameters for all HRS and HRW samples falling within the same wheat grain protein content range (11.4–15.8%).

MATERIALS AND METHODS

Wheat Samples

One hundred HRW and 100 HRS wheat samples were collected and provided by the Federal Grain Inspection Service (FGIS) Technical Center, Kansas City, MO, which is part of the U.S. Department of Agriculture (USDA), Grain Inspection, Packers, and Stockyards Administration (GIPSA). These samples were part of the 2002 and 2003 crop years and were obtained from domestic and export markets and from some pure cultivars. Sample size was ≈1 kg. Two HRS samples were discarded due to insect infestation. About 25% of the HRS and 17% of the HRW wheat samples came from the Pacific Northwest; the remaining samples came from the Great Plains. For HRS wheat, Parshall, Alsen, Oxen, McNeal, Reeder, Amidon, Gunner, 2375, Ernest, and Fortuna were used as pure samples, and then each was blended 50:50 separately with Parshall. Also, each sample was blended 50:50 with McNeal, with the exception of Oxen. In addition, 2375 and Amidon were each blended 25:75 and 75:25 with McNeal. Thus, for HRS wheat, there were 10 pure cultivars and 20 blends. For HRW samples, Ike, Karl 92, Arapahoe, Millennium, 2174, Akron, Jagger, 2137, Prower 99, and Tam 110 were used as pure cultivar samples. The following samples were then combined into 50:50 blends: Akron and Prower 99, Arapahoe and Millennium, Jagger and 2174, Karl 92 and 2137, and Tam 110 and Ike. The following HRW samples were combined into 25:75, 50:50, and 75:25 blends: 2137 and Akron, Ike and Prower 99, Jagger and Arapahoe, Karl 92 and 2174, and Tam 110 and Millennium. Thus, for HRW wheat, there were 10 pure samples and 20 blends. The remaining 70 HRW and 68 HRS samples were obtained from commercial sources and consequently blended during typical handling, shipping, and storage processes. Because they were commercial samples, the cultivars comprising these blends were unknown. The pure cultivars selected represent ≈70% of the seeded acres in Kansas, Montana, and North Dakota. Thus, it is expected that the pure cultivars will also be represented in the commercial samples.

To address concerns of observed differences across these wheat classes being primarily due to protein content differences, a subset of the HRW and HRS samples within a common grain protein content range (11.4–15.8% adjusted to 14% moisture content) was selected for further comparison. Those that did not fall within this protein content range were taken out of this subset. This subset contained 73 HRW and 75 HRS wheat samples.

Analytical Methods

Wheat samples were analyzed for 50 grain, milling, flour, dough, and breadmaking quality characteristics (Table I). All whole grain quality characteristics were analyzed by GIPSA. CII Laboratory Services, Kansas City, MO, conducted alveograph tests. All other tests were conducted at the USDA, Agricultural Research Service (ARS), the Grain Marketing and Production Research Center (GMPRC), Manhattan, KS. Quality characteristics included in this study were identified by GIPSA as important to their customers and those that are standard quality parameters measured by the USDA, ARS, GMPRC, Hard Winter Wheat Quality Laboratory for evaluating hard winter wheat cultivars before commercial release.

Grain quality. Grain quality parameters included test weight, whole-grain protein content, single kernel hardness, single kernel moisture content, single kernel size, and wheat ash content. Test weight was measured using Approved Method 55-10 (test wt/bu) reported as lb/bu (1.29 kg/hL) (AACC International 2000). Protein content of whole grain wheat was determined using Approved Method 39-25 (near-infrared reflectance method for protein content in whole-grain wheat). Reported protein contents were corrected to 14% moisture content. Grain hardness was determined by Approved Method 55-31 (single kernel characterization system [SKCS] for wheat kernel texture). The SKCS 4100 instrument (Perten, Springfield, IL) was used to measure single kernel grain hardness, moisture content, and diameter. Grain and flour ash contents were determined using Approved Method 08-01 (ash, basic method) and were corrected to 14% moisture content.

Milling and flour quality. Milling and flour quality indicators were flour yield, flour protein content, flour ash content, flour color, flour particle geometric mean diameter (GMD), starch particle GMD, polyphenol oxidase content, falling number, SDS sedimentation volume, total gluten, gluten index, insoluble polymeric proteins, soluble polymeric proteins, gliadin proteins, total polymeric proteins, and free lipids and the nonpolar and polar lipid fractions.

Approved Method 26-10A (experimental milling; introduction, equipment, sample preparation, and tempering) (AACC International 2000) was used for experimental milling with the Brabender Quadrumat Sr. experimental mill. Flour milling yield was calculated on the basis of total recovered products and corrected to 14% moisture content. Flour protein content was measured using Approved Method 39-11 (near-infrared reflectance method for protein determination in wheat flour) and corrected to 14% moisture content. Grain and flour ash contents were determined by Approved Method 08-01 (ash, basic method) and was corrected to 14% moisture content. Flour color (lightness [L*]; amount of red and green color [a*]; and amount of yellow and blue color [b*]) was determined using a colorimeter (CR-300, Minolta, Osaka, Japan).

Particle size distribution of flour and isolated starch samples was analyzed using a laser light scattering particle size instrument (Beckman/Coulter 13 320, Fullerton, CA) equipped with application software (v. 4.21, Beckman/Coulter). Starch was isolated from flour following the procedure described by Bechtel and Wilson (2000). Samples were placed into the instrument's tornado dry module, and particle size was measured. The universal liquid module with water as the suspending agent was used to measure starch particle size. The instrument is capable of measuring sizes from 0.1 to 2,000 µm. The size distribution was calculated by assuming the particles are spherical. The GMD reported here is the particle size where half of the particles are smaller, or larger, than this value.

Polyphenol oxidase content was determined using a modification of Approved Method 22-85 (measurement of polyphenol oxidase in wheat kernels) (AACC International 2000) using 75 mg of wheat meal and 10 min of vortex time. Falling number was determined by Approved Method 56-81B (determination of falling number) and was corrected to 14% moisture content.

The SDS sedimentation volume was measured by a modification of Approved Method 56-70 (SDS sedimentation test for durum wheat) (AACC International 2000) with sedimentation values corrected to 14% moisture content. Modifications included using 2 g of flour placed in a 100-mL graduated cylinder where 20 mL of water containing bromophenyl blue is added and mechanically shaken. SDS reagent (20 mL) was added and cylinders were mixed, followed by adding 10 mL of lactic acid reagent and then mixed again. The same 20-min settling time was used before sedimentation volume was determined.

Wet gluten and gluten index were determined using Approved Method 38-12 (wet gluten and gluten index) (AACC International 2000) and corrected to 14% moisture content. Protein characterization used the procedure outlined by Bean et al (1998) to determine quantity of insoluble polymeric proteins, soluble polymeric proteins, gliadin proteins, and total polymeric proteins. Free lipids were extracted by a Soxhlet apparatus with petroleum ether as an extractant using the procedure reported by Chung et al (1980). The extracted free lipids were fractionated into nonpolar and polar lipid fractions using a solid-phase extraction (SPE) system as reported by Ohm and Chung (1999) and Hubbard et al (2004).

TABLE I
Comparison of Quality Characteristics of HRW and HRS Wheat Samples[a]

	Hard Red Winter (n = 100)				Hard Red Spring (n = 98)			
Quality Characteristics	Avg	SD	Min	Max	Avg	SD	Min	Max
Test weight, lb/bu (1.29 kg/hL)	61.6a	1.20	57.3	65.0	61.4a	1.72	56.2	65.1
Grain protein content, %, 14% mb	12.6a	1.66	9.20	15.8	14.6b	1.59	11.4	19.3
Grain moisture content, %	10.6a	0.92	8.60	12.4	11.1a	1.00	8.62	13.1
Single kernel hardness index	73.6a	4.60	59.2	82.6	78.2b	4.56	67.0	87.6
Single kernel diameter, avg mm	2.25a	0.14	1.88	2.71	2.39a	0.17	2.04	2.88
Flour yield, extraction, %	65.9a	1.27	63.1	69.5	67.0b	2.05	59.7	71.3
Wheat ash content, 14% mb	1.54a	0.10	1.30	1.93	1.67b	0.11	1.27	1.93
Flour ash content, 14% mb	0.43a	0.03	0.36	0.50	0.45b	0.04	0.39	0.55
Flour protein content, 14% mb	11.3a	1.66	8.24	14.8	13.2b	1.53	10.6	17.8
Flour brightness (color L*)	92.4a	0.34	91.7	93.2	92.1b	0.34	91.3	92.9
Flour red/green color (color a*)	–1.45a	0.23	–1.99	–0.65	–1.23b	0.23	–1.92	–0.81
Flour yellow/blue color (color b*)	9.60a	0.67	7.54	11.4	9.38b	0.70	7.76	11.1
Flour particle size GMD, 50% vol, µm	83.8a	2.44	78.7	91.8	89.2b	2.46	82.0	94.5
Starch particle size GMD, 50% vol, µm	15.4a	1.65	11.6	23.8	12.3b	1.71	8.00	15.9
Polyphenol oxidase, au/min/mL	0.45a	0.08	0.20	0.65	0.47a	0.09	0.26	0.75
Falling number, sec	565a	101	278	861	440b	81.6	209	589
SDS sedimentation volume, mL	35.2a	4.33	24.0	43.0	41.1b	2.79	30.0	45.0
Average total gluten, g/10 g of flour	3.03a	0.53	1.99	4.30	3.62b	0.43	2.68	4.72
Average gluten index, %	95.2a	3.31	79.2	99.2	95.8a	3.96	77.8	99.4
Insoluble polymeric proteins, mg	10.6a	1.67	6.6	15.9	12.5b	1.86	8.2	19.1
Soluble polymeric proteins, mg	4.0a	0.83	2.6	6.2	4.4b	0.62	2.5	6.0
Gliadin proteins, mg	12.0a	1.92	6.8	15.7	14.5b	2.05	9.0	19.8
Total polymeric proteins, mg	14.6a	2.33	10.3	20.6	16.9b	2.09	11.0	23.7
Insoluble polymeric proteins, % protein	38.2a	2.32	32.3	44.3	38.2a	3.47	29.4	54.6
Soluble polymeric proteins, % protein	14.4a	1.54	11.5	18.4	13.6b	1.46	9.18	17.7
Gliadin proteins, % protein	43.2a	2.21	29.5	47.5	44.1b	2.28	33.5	50.1
Total polymeric proteins, % protein	52.5a	2.10	48.0	58.4	51.7b	2.52	45.9	63.8
Free lipids, mg/10 g of flour, db	84.2a	4.9	70.2	97.3	82.3b	6.2	67.0	103.0
Free polar lipids, mg/10 g of flour, db	18.6a	3.4	11.4	28.3	15.8b	4.3	6.3	32.4
Free nonpolar lipids, mg/10 g of flour, db	65.6a	4.6	55.8	78.8	66.5a	5.2	52.6	83.3
Mixograph water absorption, %	61.8a	2.42	56.9	67.0	65.7b	2.14	61.0	71.7
Mixograph mix time, min	3.33a	0.67	2.50	6.13	3.81b	0.98	1.84	7.75
Mixograph tolerance (score 0–6)	3.82a	0.91	1.00	6.00	4.00a	1.11	1.00	6.00
Farinograph absorption, %	60.9a	2.27	55.5	68.2	66.0b	2.31	59.8	73.1
Farinograph development time, min	8.28a	4.54	1.20	23.0	13.7b	6.91	5.20	44.5
Farinograph stability, min	15.0a	4.06	3.00	22.0	18.2b	4.33	9.80	31.9
Farinograph mixing tolerance, min	19.6a	11.4	0.00	54.0	15.6b	9.54	0.00	37.0
Farinograph breakdown, min	14.6a	5.76	2.90	25.4	21.1b	7.14	8.80	49.5
Alveograph peak height (P), mm	105a	15.2	73.0	145	118b	17.4	68.0	159
Alveograph length (L), mm	101a	31.3	37.0	174	126b	25.2	66.0	191
Alveograph swelling index, mL	22.1a	3.52	13.5	29.4	24.9b	2.55	18.1	30.8
Alveograph work, 10^{-4} J	350a	83.5	208	573	500b	105	109	793
Alveograph configuration ratio (P/L)	1.20a	0.57	0.48	3.94	0.99b	0.32	0.36	2.21
Baking water absorption, %	62.1a	1.78	58.2	66.4	65.5b	1.73	60.5	70.6
Baking mix time, min	4.13a	0.85	2.33	6.75	5.21b	1.26	2.29	10.3
Crumb grain score (score 0–6)	3.43a	0.66	1.70	5.00	3.73b	0.64	2.00	5.00
Dough weight, g	171a	1.81	167	176	175b	1.47	171	178
Loaf volume of pup loaf, cm^3	842a	84.6	685	1,060	964b	88.5	803	1,238
Loaf specific volume, cm^3/g	5.64a	0.56	4.62	7.13	6.40b	0.58	5.31	8.24
Loaf vol potential, cm^3/% protein	65.1a	1.91	52.0	77.9	65.2a	3.63	55.7	73.4

[a] Values followed by the same letter in the same row are not significantly different (P < 0.05).

Dough physicochemical properties. Physicochemical properties of dough were evaluated using a mixograph, farinograph, and alveograph. Approved Method 54-40A (mixograph method) (AACC International 2000) was used for 10 g of flour to obtain mixograph parameters including water absorption, mix time, and tolerance. Approved Method 54-21 (farinograph method for flour) was used for 10 g of flour to obtain farinograph parameters including water absorption, development time, stability, tolerance, and breakdown. Approved Method 54-30A (alveograph method for soft and hard wheat flour) was used to determine alveograph parameters including peak height, length, swelling index, deformation energy, and configuration ratio. Dough weight was also measured. Williams (1997) summarized the guidelines for interpretations of these test results which were used as a basis to categorize samples. For example, for the farinograph test, flour with development time and stability time of ≤1 min is categorized as weak, while those with development time of 3–5 min and stability time of 8–14 min are considered strong flours.

Experimental breadmaking properties. Breadmaking characteristics of a pup loaf of bread baked using 100 g of wheat flour were evaluated using Approved Method 10-10B (optimized straight-dough breadmaking method) (AACC International 2000) modified to use an oven temperature of 425°F and baked for 18 min. Breadmaking qualities assessed were baking water absorption, baking mix time, crumb grain score (rated as 0–6 with 6 being excellent), loaf volume, specific loaf volume, and loaf volume potential. Specific loaf volume (cm^3/g) is the loaf volume divided by the loaf weight and accounts for differences in loaf weights. Loaf volume potential (cm^3/% flour protein content) is the increase in loaf volume as flour protein content increases by 1 percentage point as calculated from equations published by Chung et al (2002), which are mathematical expressions of graphs published by Finney (1985).

Statistical Analysis

To test differences in quality characteristics across HRW and HRS wheat samples, the *t*-test (5% probability level) was used. Additionally, linear regression plots and equations for selected quality characteristics of HRW and HRS wheat samples in the 11.4–15.8% protein content range were generated and compared using tests of homogeneity of regression coefficients (5% level of significance). Correlations among quality characteristics and the relationships between quality characteristics and end use quality measures are reported only when needed to support the findings reported here. A more complete analysis of correlations and relationships are presented by Dowell et al (2006) and also are the subject of current investigations.

RESULTS AND DISCUSSION

Comparison of HRS and HRW Wheat

Table I summarizes quality characteristics of the 100 HRW and 98 HRS wheat samples used in this study. A comparison of means showed that only nine of the 50 quality parameters evaluated were similar ($P \leq 0.05$) across wheat classes. These were test weight, grain moisture content, and kernel size for wheat quality parameters, and polyphenol oxidase content, average gluten index, free nonpolar lipid content, insoluble polymeric proteins (%), mixograph tolerance, and loaf volume potential for flour quality parameters. Quality characteristics that were higher for HRS wheat than HRW wheat included grain and flour protein content, grain hardness, flour yield and particle size GMD, average total gluten content, insoluble and soluble polymeric proteins, gliadin proteins, most dough quality measurements, and most baking quality measurements. On the other hand, HRW wheat flour had higher color L^* and b^* values, starch particle size GMD, falling number, % soluble polymeric proteins, % total polymeric proteins, free lipid and its polar lipid contents, farinograph mixing tolerance, and alveograph configuration ratio compared with HRS wheat flour.

Whole-kernel quality. Test weight, which provides an indication of flour yield, soundness, and density of the wheat, was similar for both classes and averaged ≈61 lb/bu. All samples had test weights >56 lb/bu, indicating that all of the samples had high potential for good flour extraction yield.

Grain and flour protein content is considered an important quality characteristic of wheat that provides an indication of final quality and functionality. Grain protein content of HRW wheat averaged 12.6%, while HRS wheat was higher at 14.6% (Table I). Seventeen percent of the HRS wheat samples had higher grain protein content than the highest protein content for the HRW wheat samples. In addition, 30% of the HRW samples had lower grain protein content than the lowest grain protein content value for the HRS samples.

Moisture content is not a wheat-grade determinant but is important for providing information used for pricing the commodity and is essential information when storing or processing the wheat. Samples had equilibrated to ambient moisture content; the moisture content of the HRW and HRS wheat samples were similar at 10.6 and 11.1%, respectively.

The average hardness index, as measured by SKCS, was 73.6 and 78.2 for HRW and HRS wheat, respectively. It should be noted that while these wheat classes were significantly different at the 5% probability level, the mean hardness index values still categorized both wheat classes as hard wheat. The lowest hardness index for HRS was 67.0, while 7% of the HRW samples had hardness index values <67.0. The highest hardness index for the HRW was 82.6, while 12% of the HRS samples had hardness index values >82.6. Measurements of single kernel diameter using SKCS showed that the HRW wheat kernels were similar in mean diameter to HRS wheat kernels (2.25 vs. 2.39 mm, respectively).

Milling and flour quality. The same mill settings were used to mill both HRW and HRS wheat classes. The mean flour yield for HRS wheat (67.0%) was significantly higher compared with HRW wheat (65.9%). This difference in flour yield will have both economic and quality implications.

The mean wheat ash content was significantly higher for HRS wheat (1.67 %) than for HRW wheat (1.54%). The resulting flour also had significantly higher mean ash content for HRS wheat (0.45%) than HRW wheat (0.43%). The higher flour ash content of HRS may also be partly due to the higher flour yield of HRS wheat, which may mean that more bran portions were left in the HRS flour than in the HRW flour.

It is expected that ≈1 percentage point of wheat grain protein content will be lost to the feed fraction when the wheat is milled to flour (Halverson and Zeleny 1988). The loss in protein content during milling was 0.7–1.8 percentage points for HRW and 0.7–2.4 percentage points for HRS wheat samples, indicating a better protein conversion for the HRW wheat class.

The HRS wheat flour samples had higher mean protein content (13.2%) than the HRW samples (11.3%), which is consistent with the results shown for grain protein content. Twelve percent of HRW and 82% of HRS wheat samples had flour protein content >13%.

The HRW wheat samples yielded flour with a significantly higher mean L^* value (92.4) than the HRS wheat samples (92.1), indicating that the HRW wheat produced flour with lighter color than the HRS wheat samples. The negative value of a^* was larger for HRW (–1.45) than for HRS (–1.23) wheat samples, indicating that the HRW wheat flour had a larger green component than the HRS wheat flour. The mean b^* value was larger for HRW (9.60) than for the HRS (9.38) wheat flour, indicating that the HRW wheat flour was more yellow than the HRS wheat flour. Again, these results may be partly attributed to the differences discussed earlier on flour yield; other parameters such as the wheat cultivar and flour particle size also affect flour color.

The flour GMD was significantly larger for the HRS wheat (89.2 μm) than the HRW wheat (83.8 μm); this indicates that the HRW wheat flour contained more fine particles when compared with HRS wheat flour. This may be due to the lower grain hardness index for HRW than for HRS wheat grain. Conversely, starch particle GMD was significantly larger for the HRW wheat (15.4 μm) than the HRS wheat (12.3 μm), which may again be due to HRW grains being softer than HRS wheat, producing a lower quantity of damaged starch and tailings during the milling process.

The HRW wheat flour had a PPO content of 0.20 to 0.65 au/min/mL; the HRS wheat flour had PPO content of 0.26 to 0.75 au/min/mL. The similar PPO levels for HRW and HRS wheat flour samples indicated that both wheat classes would have similar effects on darkening noodle color that may be caused by PPO.

The falling number used to indicate α-amylase activity, which is an indicator of preharvest sprouting, was 278–861 sec for HRW wheat flour (mean 565 sec), and 209–589 sec for HRS wheat flour (mean 440 sec). Falling numbers >200 sec generally indicate little α-amylase activity (Perten 1964) and includes all samples in this study. Although the falling number for HRW wheat was higher than for HRS wheat, the higher value probably is of no practical significance.

The SDS sedimentation test has been highly correlated with the breadmaking quality of hard wheat (Axford et al 1979). The SDS sedimentation volume of HRW wheat flour was 24–43 mL (mean 35.2 mL), while significantly higher values for HRS wheat flour were 30–45 mL (mean 41.1 mL).

Mean average gluten content of HRS wheat was significantly higher (3.62 g/10 g of flour) than HRW wheat (3.03 g/10 g of flour). Gluten index measurement based on the Glutomatic apparatus provides an indication of gluten strength (whether the wheat dough properties are strong, normal, or weak). There was no significant difference in mean gluten indexes for HRW and HRS wheat samples (95.2 vs. 95.8 g/g of flour, respectively).

All flour protein quality measurements showed that HRS had greater quantities of gliadins and glutenins. These greater values are reflected in greater dough physical property measurements shown in Table I. Mean insoluble polymeric protein content was significantly higher for HRS than for HRW wheat flour samples (12.5 vs. 10.6 mg). Soluble polymeric proteins were significantly higher for HRS (4.4 mg) than for HRW (4.0 mg) wheat. Gliadin content was significantly higher for HRS (14.5 mg) than HRW wheat (12.0 mg). Also, total flour polymeric protein content was significantly higher for HRS (16.9 mg) than for HRW (14.6 mg) wheat, indicating better overall dough physical properties. These higher values were primarily due to the higher protein content of HRS wheat flour compared with HRW wheat flour samples.

Free lipid and the polar lipid contents were higher for HRW wheat flour when compared with HRS wheat flour, whereas free nonpolar lipid contents were similar for the two wheat classes. Pomeranz (1988) reviewed the importance of lipids in the baking process, but generally lipid contents were not correlated to baking quality. However, Chung et al (1982) showed that loaf volume increased with free polar lipid contents that are naturally present in a particular cultivar, but their study utilized mostly pure wheat cultivars grown at various locations in Kansas. This correlation of free polar lipid contents to loaf volume or to any of the other quality parameters was not observed in our study for either HRW or HRS wheat samples, which may likely be due to differences in wheat cultivars used. This study used pure commercial wheat cultivars and blends of commercial samples, while the study of Chung et al (1982) used pure wheat breeding lines under evaluation for the Kansas State University breeding programs.

Dough quality. The mixograph is the common method adopted by hard wheat breeding programs in the United States for evaluating physicochemical properties of dough and breadmaking potential. Water absorption and mix time of HRS were significantly higher than for HRW wheat flour, while the mixograph tolerance was similar for both wheat classes. The higher mean mixograph water absorption of HRS (65.7%) compared with HRW (61.8%) essentially equates to higher profit for a loaf of bread baked from HRS wheat flour when compared with bread baked from HRW wheat flour. This is likely mainly due to the higher flour protein content in HRS versus HRW wheat flour, which results in a higher water absorption requirement. The range of mixograph mix times or time to dough development peak was 2.5–6.13 min for HRW and 1.84–7.75 min for HRS wheat flour, respectively. This indicated that flour strength of samples from both wheat classes based on mixing times ranged from medium to extra-long flour (Williams 1997). Mixing tolerance was 1.0–6.0 for both HRW and HRS wheat, indicating that flours of both wheat classes ranged in strength from weak to extra-strong with ≈75% having satisfactory to outstanding tolerance to overmixing.

All farinograph test parameters had significantly higher values for HRS than for HRW wheat flour, except for farinograph mixing tolerance. Mean farinograph development time was significantly longer for HRS wheat (13.7 min, range of 5.2–44.5 min) compared with HRW wheat (8.28 min, range of 1.20–23.0 min). Based on development time, the HRW wheat samples had 21% medium-strong flour and 79% extra-strong flour. On the other hand, the HRS wheat sample set consisted of 100% extra-strong flour. Mean farinograph stability time was likewise significantly higher for HRS wheat flour (18.2 min, range of 9.8–31.9 min) than HRW wheat flour (15.0 min, range of 3.0–22.0 min). Using stability time as a basis, the HRW sample set consisted of 6% medium-strong flour, 54% strong flour, and 40% extra-strong flour. The HRS sample set consisted of 37% strong flour and 63% extra-strong flour.

The alveograph test is effective in identifying flours of weak to medium strength and, thus, has been favored for soft wheat. However, the alveograph test does not differentiate well among flours with farinogram stability of >15 min. It should be noted that 56 and 80% of the sample set of HRS and HRW wheat, respectively, showed farinograph stability >15 min.

All alveograph test parameters showed significantly higher values for HRS wheat flour than for HRW wheat flour, except for the mean configuration ratio, where it was higher for HRW wheat than for HRS wheat. Mean peak height for HRS wheat flour was 118 mm, while HRW wheat flour was 105 mm. Mean length was 126 mm for HRS wheat flour and 101 mm for HRW wheat flour. Mean swelling index was 24.9 mL for HRS wheat flour and 22.1 mL for HRW wheat flour. Alveograph deformation energy, or work, was 500 J for HRS wheat flour and 350 J for HRW wheat flour. Work value ranges were 109–793 J for HRS wheat flour and 208–573 J for HRW wheat flour, indicating that both sample classes included weak to extra-strong flours. Mean configuration ratio of 0.99 (range 0.36–2.21) for HRS wheat was significantly lower than for HRW wheat (mean 1.20, range 0.48–3.94).

Breadmaking quality. HRS wheat flour had significantly higher mean baking water absorption (65.5%) than HRW wheat flour (62.1%). Because water is the cheapest ingredient in breadmaking, this difference translates to higher economic return for using HRS wheat flour, provided that the prices of those two wheat classes were the same. However, this improvement is at least partially offset by the increase in mean mixing time required to achieve optimal dough for HRS wheat flour (5.21 min) versus HRW wheat flour (4.13 min). Mean crumb grain scores of pup loaf breads baked with HRW and HRS wheat flour samples were both good, although HRS wheat flour bread was significantly higher (3.73) compared with HRW wheat flour bread (3.43). This score includes some degree of subjectivity due to being graded by an expert basing a score on visual observation.

Mean HRS wheat flour loaf volume was significantly higher (964 cm^3) than for HRW wheat flour (842 cm^3). Thirty percent of the HRW wheat flour samples had loaves with a volume lower than the smallest loaf of the HRS wheat flour set, which may be explained by 30% of HRW wheat grain samples having lower protein contents than the lowest protein content of HRS wheat grain samples. Ten percent of the HRS wheat flour samples had loaf volumes higher than the largest loaf of the HRW wheat flour set, although 17% of HRS wheat samples had protein contents that were higher than the highest protein content for the HRW wheat grain set.

Mean specific loaf volume was significantly higher for HRS wheat flour than for HRW wheat flour, 6.40 vs. 5.64 cm^3/g. Loaf-volume potential, which takes into account differences in flour protein contents, was the same for HRW and HRS wheat. This was the only breadmaking parameter in this study that was similar for both wheat classes. HRW wheat flour had a mean loaf volume potential of 65.1 cm^3/% flour protein content compared with HRS wheat flour at 65.2 cm^3/% flour protein content, indicating that at similar protein levels, HRW and HRS wheat flours will have similar loaf volume.

Comparison of HRW and HRS Wheat: Grouped by Protein Content

Quality characteristics of samples selected based on a common protein content range (11.4–15.8%) are summarized in Table II. Many quality parameters that were significantly different in the previous analyses, shown in Table I, were now similar when samples within a common protein content range were compared. However, HRS wheat flour had a lower color *b** value, lower falling number, greater SDS sedimentation volume, fewer free polar lipids, more insoluble polymeric proteins and gliadins, greater flour particle GMD, longer mixograph mix time, larger alveograph configuration ratio, lower farinograph mixing tolerance, higher dough weight, and a better crumb score than HRW wheat flour.

To further assess the effect of wheat grain protein content on quality parameters, linear regression models were generated for those dough and bread characteristics that were correlated to wheat

TABLE II
Comparison of Quality Characteristics of HRW and HRS Wheat Samples Selected From Only the 11.4-15.8% Protein Content Range

	Hard Red Winter (*n* = 73)				Hard Red Spring (*n* = 75)			
Quality Characteristics	Avg	SD	Min	Max	Avg	SD	Min	Max
Test weight, lb/bu (1.29 kg/hL)	61.3a	1.04	57.3	63.3	61.9a	1.35	59.2	65.1
Grain protein content, %, 14% mb	13.4a	1.19	11.4	15.8	14.1a	1.17	11.4	15.8
Grain moisture content, %	9.59a	0.38	8.64	10.22	9.67a	0.58	8.24	10.8
Single kernel hardness index	74.5a	4.34	59.2	82.6	77.8a	4.16	66.9	86.7
Single kernel diameter, avg mm	2.20a	0.10	1.88	2.45	2.42a	0.16	2.11	2.88
Flour yield, extraction, %	65.7a	1.26	63.1	69.5	66.5a	1.74	62.5	71.3
Wheat ash content, 14% mb	1.55a	0.10	1.39	1.93	1.65a	0.10	1.27	1.86
Flour ash content, 14% mb	0.43a	0.03	0.36	0.50	0.44a	0.03	0.39	0.55
Flour protein content, 14% mb	12.1a	1.23	10.2	14.8	12.7a	1.08	10.6	14.5
Flour brightness (color *L**)	92.3a	0.24	91.7	93.0	92.2a	0.33	91.3	92.9
Flour red/green color (color *a**)	–1.38a	0.20	–1.90	–0.65	–1.27a	0.22	–1.92	–0.96
Flour yellow/blue color (color *b**)	9.58a	0.63	7.54	11.1	9.44b	0.74	7.76	11.1
Flour particle size GMD, 50% vol, µm	83.8a	2.45	78.7	91.8	89.0b	2.46	82.0	94.5
Starch particle size GMD, 50% vol, µm	15.4a	1.26	13.1	19.9	12.0a	1.73	8.00	15.9
Polyphenol oxidase, au/min/mL	0.46a	0.08	0.27	0.65	0.46a	0.09	0.28	0.75
Falling number, sec	584a	96.0	278	792	423b	77.3	209	569
SDS sedimentation volume, mL	36.9a	3.37	30.0	43.0	40.9b	2.97	30.0	45.0
Average total gluten, g/10 g of flour	3.28a	0.39	2.54	4.30	3.48a	0.34	2.68	4.32
Average gluten index, %	94.3a	3.31	79.2	99.2	96.0a	3.99	77.8	99.4
Insoluble polymeric proteins, mg	11.1a	1.18	10.1	15.9	11.9b	1.17	9.1	15.6
Soluble polymeric proteins, mg	4.3a	0.68	3.3	6.2	4.3a	0.49	3.6	6.0
Gliadin proteins, mg	12.7a	1.12	11.6	15.7	13.7b	1.46	11.7	19.8
Total polymeric proteins, mg	15.4a	1.55	13.8	20.6	16.2a	1.28	14.6	20.6
Insoluble polymeric proteins, % protein	38.0a	2.31	33.5	44.3	37.8a	3.07	29.4	52.0
Soluble polymeric proteins, % protein	14.6a	1.50	11.5	18.4	13.8a	1.32	10.1	17.7
Gliadin proteins, % protein	43.5a	1.72	39.4	47.5	44.1a	2.04	34.8	50.0
Total polymeric proteins, % protein	52.6a	1.99	48.0	57.1	51.6a	2.26	45.9	62.1
Free lipids, mg/10 g of flour, db	83.3a	4.9	70.2	96.1	82.2a	6.0	67.0	103.0
Free polar lipids, mg/10 g of flour, db	17.8a	2.40	13.2	25.4	16.2b	4.2	7.6	32.4
Free nonpolar lipids, mg/10 g of flour, db	65.6a	4.60	55.8	77.9	65.9a	4.6	52.6	83.3
Mixograph water absorption, %	62.8a	1.94	60.0	67.0	65.0a	1.70	61.0	68.1
Mixograph mix time, min	3.51a	0.61	2.26	5.50	3.66b	0.89	1.84	5.88
Mixograph tolerance (score 0–6)	3.73a	0.87	1.00	6.00	3.89a	1.10	1.00	6.00
Farinograph absorption, %	61.5a	2.15	57.4	68.2	65.3a	1.61	59.8	68.6
Farinograph development time, min	9.83a	3.80	1.20	23.0	11.7a	4.00	5.20	22.0
Farinograph stability, min	16.1a	3.11	8.90	22.0	17.6a	4.00	9.80	23.9
Farinograph mixing tolerance, min	17.1a	9.71	0.00	43.0	16.7b	9.66	0.00	37.0
Farinograph breakdown, min	16.6a	4.46	3.50	25.4	19.2a	4.90	8.80	25.0
Alveograph peak height (*P*), mm	103a	14.5	73.0	136	117a	17.7	68.0	159
Alveograph length (*L*), mm	114a	24.8	72.0	174	123a	25.0	66.0	191
Alveograph swelling index, mL	23.7a	2.57	18.9	29.4	24.5a	2.55	18.1	30.8
Alveograph work, 10^{-4} J	385a	69.8	258	573	477a	94.6	109	655
Alveograph configuration ratio (*P/L*)	0.96a	0.31	0.48	1.87	1.02b	0.34	0.36	2.21
Baking water absorption, %	62.6a	1.62	58.2	66.4	65.0a	1.35	60.5	67.5
Baking mix time, min	4.33a	0.84	2.71	6.75	4.91a	1.15	2.29	8.13
Crumb grain score (score 0–6)	3.59a	0.61	2.20	5.00	3.77b	0.61	2.40	5.00
Dough weight, g	172a	1.51	167	175	174b	1.28	171	176
Loaf volume of pup loaf, cm^3	879a	63.5	733	1,060	937a	62.9	803	1,048
Loaf specific volume, cm^3/g	5.89a	0.42	4.92	7.13	6.23a	0.42	5.31	6.93
Loaf vol potential, cm^3/% protein	64.0a	4.77	52.0	72.4	65.7a	3.41	55.7	73.4

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

protein content with $r \geq 0.7$. Those quality parameters were water absorption, alveograph test parameters (length, swelling index, and work), loaf volume, specific loaf volume, SDS sedimentation volume, and average total gluten content.

The plots of regression lines comparing HRW and HRS wheat samples for mixograph water absorption, farinograph water absorption, and baking water absorption are shown in Fig. 1A–C. As expected, water absorption increased with grain protein content. The estimated linear relationships between various water absorption measures and grain protein content based on the intercept showed that HRS wheat flour had significantly higher ($\alpha = 0.05$) water absorption values than HRW wheat flour samples. The test of homogeneity of regression coefficients showed that the rate of increase in baking water absorption due to an incremental change in protein content is not different across HRW and HRS wheat flour samples. Results showed, as an example, that HRW wheat with a grain protein content of 14% would have baking water absorption similar to that of HRS wheat with a grain protein content of 12% when using the same milling procedure. Modifications to the milling procedure may allow HRW wheat flour to be comparable in water absorption to HRS wheat. Water absorption is a key parameter in the purchase of flour for breadmaking (Webb and Owens 2003) and can be influenced by wheat cultivar and by the amount and type of grinding performed during milling. Milling damages a portion of the starch granules, which increases water absorption. Bushuk (1966) reported that damaged starch absorbs water about three times better than undamaged starch. Sluimer (2005) summarized the effect of varying extraction rates (100–66%) using the same starting material and showed that water absorption increases with increasing extraction rate. Thus the example presented earlier, where there is a 2% difference in grain protein content but similar water absorption requirement, may be explained by differences in flour extraction yield and presumably higher starch damage content in HRS than in HRW wheat flours. Starch damage was not included as a quality parameter in this study and should be considered in future work.

Figure 2 summarizes three parameters of alveograph testing (length, swelling index, and work) for HRW and HRS wheat flour samples within the same grain protein content range. The test of homogeneity of regression coefficients showed that the rate of

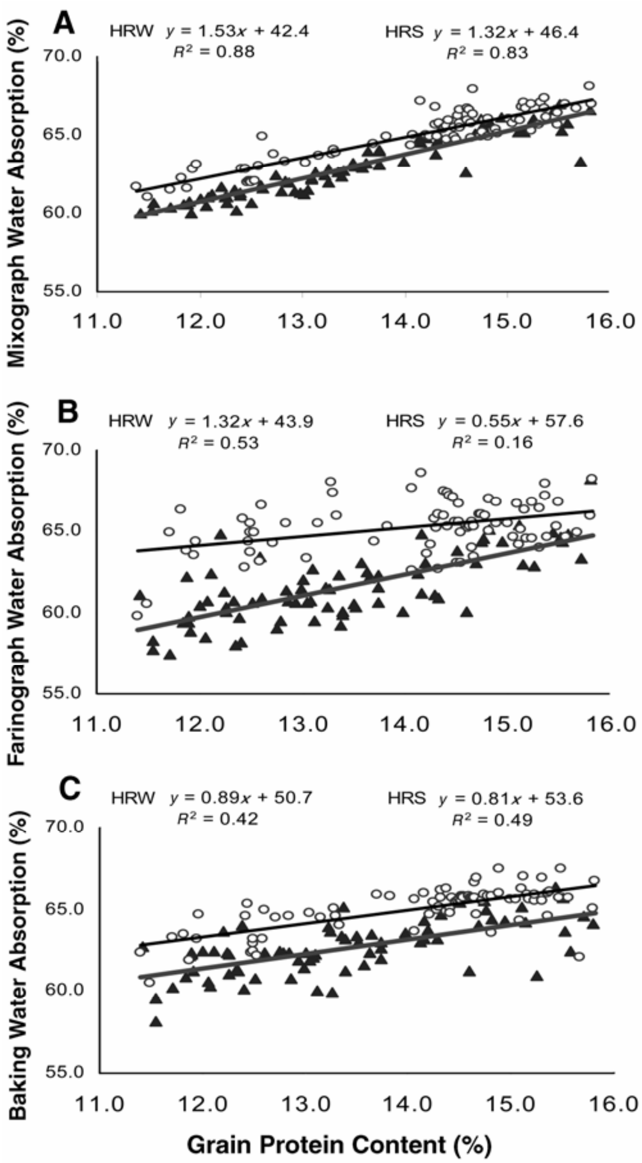

Fig. 1. Linear relationships between selected water absorption parameters and grain protein content of hard red winter (HRW) (▲) and hard red spring (HRS) (○) wheat samples. **A,** Mixograph water absorption; **B,** farinograph water absorption; and **C,** baking water absorption.

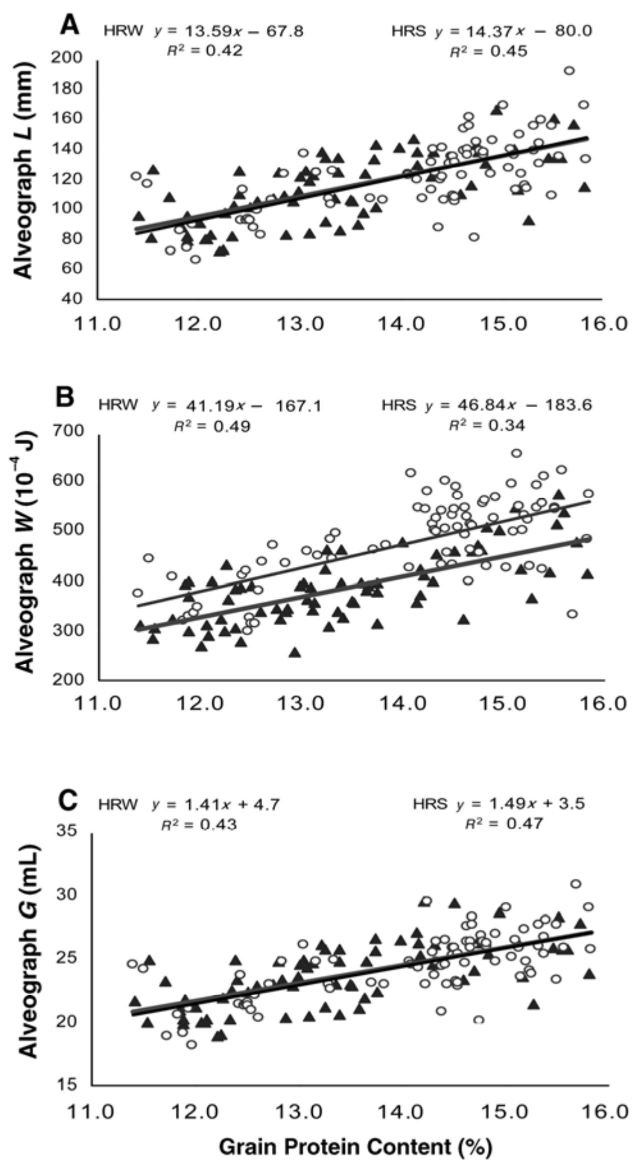

Fig. 2. Linear relationships between selected alveograph quality parameters and grain protein content of hard red winter (HRW) (▲) and hard red spring (HRS) (○) wheat samples. **A,** Alveograph length (*L*); **B,** alveograph work (*W*); and **C,** alveograph swelling index (*G*).

change in the three alveograph test parameters due to an incremental change in grain protein content was not different across HRW and HRS wheat flour samples. This indicates that the overall tenacity, extensibility, and strength of HRW and HRS wheat flour samples were similar. Additionally, these three alveograph parameters had similar intercepts for HRW and HRS wheat. It should be noted that these parameters were significantly higher for HRS wheat flour compared with HRW wheat flour when protein content range was not the same for both classes, providing an indication of the strong effect of significantly higher protein content of the original set of HRS wheat samples on three alveograph parameters. Other parameters plotted to compare differences between HRW and HRS wheat samples across the same grain protein content range were loaf volume, specific loaf volume, SDS sedimentation volume, and average total gluten content (Fig. 3A–D). The test of homogeneity of regression coefficients showed that the rate of increase in loaf volume, specific loaf volume, and average total gluten content due to an incremental change in grain protein content was not significantly different across HRW and HRS wheat samples; the rate of increase in SDS sedimentation volume was significantly lower for HRS wheat compared with HRW wheat flour. However, this may be an indication that the modified SDS sedimentation test may not be a sensitive test for HRS wheat flour samples. The intercepts of loaf volume, specific loaf volume, and average total gluten content were similar for HRS and HRW wheat flour samples. The intercept for SDS sedimentation volume was significantly higher for HRS than for HRW wheat flour samples. This suggests that SDS sedimentation volume was not affected solely by protein content but perhaps also by some nonprotein components such as pentosans, damaged starch, tailings, or other parameters.

The SDS sedimentation volume for HRS wheat flour showed lower correlations to grain protein content (r = 0.5) compared with HRW wheat flour (r = 0.75) but both showed an increasing trend in SDS sedimentation at increasing grain protein content with HRS wheat flour being significantly higher than HRW wheat flour. The higher SDS sedimentation volume of HRS wheat flour indicates that HRS wheat flour samples are supposed to have better gluten quality than HRW wheat flour, even though the average total gluten and gluten index were similar. The difference in SDS sedimentation volume of HRS and HRW wheat flours narrowed as protein content increased. The SDS sedimentation test was developed for differentiating protein quality, but as discussed above, results indicated that the SDS sedimentation volume may not be controlled by protein quality alone. However, the contribution of other nonprotein components to swelling volume is not clearly understood and should be studied further.

CONCLUSIONS

Currently, there is no official wheat classification system based on specific end use that exists in the United States. Wheat class has been a major basis for determining wheat end-product functionality. While HRS and HRW wheats are both considered best for breadmaking, HRS is generally priced higher than HRW wheat (U.S. Wheat Associates 2006) mainly because it is perceived by some to be superior to HRW wheat.

This study showed that when including the range of all HRS and HRW wheat samples used in this study, there were numerous quality parameters where HRS wheat was better than HRW wheat. Of the 50 quality parameters evaluated, only nine were similar for both wheat classes. The generally higher protein content of HRS wheat has been cited as a major reason for the superiority of HRS to HRW wheat. When we selected wheat from HRS and HRW classes within a common grain protein content range (11.4–15.8%) and compared the same 50 quality parameters, HRS wheat quality parameters such as the quantity of gliadins and insoluble polymeric proteins, mixograph mix time, alveograph configuration ratio, dough weight, crumb grain score, and SDS sedimentation volume were still superior to HRW wheat.

Some of the HRW wheat flour factors that were inferior to the HRS wheat flour (such as water absorption) can possibly be improved by changes in grain processing (such as in milling). This

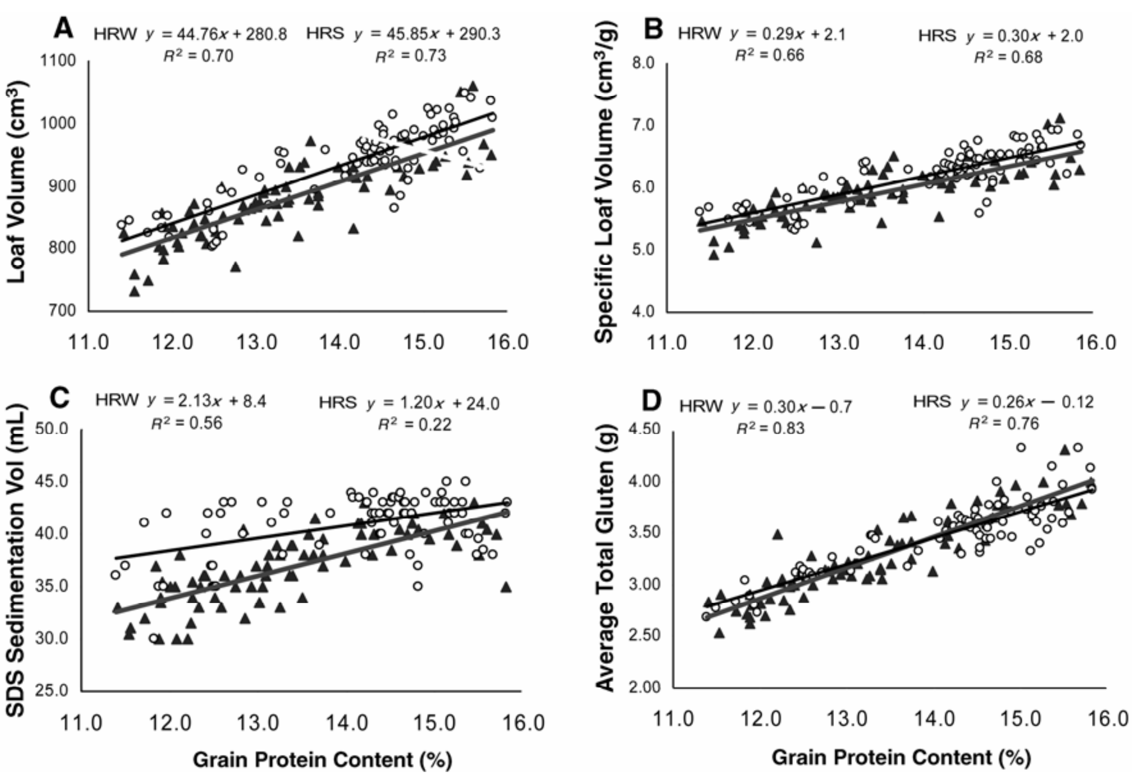

Fig. 3. Linear relationships between selected quality parameters and grain protein content of hard red winter (HRW) (▲) and hard red spring (HRS) (○) wheat samples. **A,** Loaf volume; **B,** specific loaf volume; **C,** SDS sedimentation volume; and **D,** average total gluten.

study did not include starch damage, but this should be included in future studies.

Currently, the market provides a premium for HRS wheat, which this study shows is generally superior in quality to HRW wheat. However, there are some HRS wheat cultivars that do not perform as well as HRW wheat and they still receive a better price by virtue of being classified as HRS wheat. As the market becomes highly specialized and oriented toward consumer preferences, the best way to respond to these changes may be to classify all hard wheat based on protein content or other quality measurements that better reflects end use functionality.

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LITERATURE CITED

AACC International. 2000. Approved Methods of the American Association of Cereal Chemists, 10th Ed. Methods 08-01, 10-10B, 22-85, 26-10A, 38-12, 39-11, 39-25, 54-21, 54-30A, 54-40A, 55-10, 55-31, 56-70, and 56-81B. The Association: St. Paul, MN.

Axford, D. W. E., McDermott, E. E., and Redman, D. G. 1979. Note on the sodium dodecyl sulfate test of breadmaking quality: Comparison with Pelshenke and Zeleny tests. Cereal Chem. 56:582-583.

Bean, S. R., Lyne, R. K., Tilley, K. A., Chung, O. K., and Lookhart, G. L. 1998. A rapid method for quantitation of insoluble polymeric proteins in flour. Cereal Chem. 75:374-379.

Bechtel, D. B., and Wilson, J. D. 2000. Variability in a starch isolation method and automated digital image analysis system used for the study of starch size distributions in wheat flour. Cereal Chem. 77:401-405.

Bruckner, P. L., Habernicht, D., Carlson, G. R., Wichman, D. M., and Talbert, L. E. 2001. Comparative bread quality of white flour and whole grain flour for hard red spring and winter wheat. Crop Sci. 41:1917-1920.

Boland, M., Brester, G. W., and Taylor, M. R. 2005. An overview of the wheat gluten industry. Agricultural Marketing Policy Center—Briefing No. 75. Available online at http://www.ampc.montana.edu/briefings/briefing75.pdf. Montana State University: Boseman, MT.

Bushuk, W. 1966. Distribution of water in dough and bread. Baker's Dig. 40:38-40.

Chung, O. K., Pomeranz, Y., Jacobs, R. M., and Howard, B. G, 1980. Lipid extraction conditions to differentiate among hard red winter wheats that vary in breadmaking. J. Food Sci. 45:1168-1174.

Chung, O. K., Pomeranz, Y., and Finney, K. F. 1982. Relation of polar lipid content to mixing requirement and loaf volume potential of hard red winter wheat flour. Cereal Chem. 59:14-20.

Chung, O. K., Ohm, J. B., Guo, A. M., Deyoe, C. W., Lookhart, G. L., and Ponte, J. G., Jr. 2002. Free lipids in air-classified high-protein fractions of hard winter wheat flours and their effects on breadmaking quality. Cereal Chem. 79:774-778.

Chung, O. K., Ohm, J. B., Lookhart, G. L., and Bruns, R. F. 2003. Quality characteristics of hard winter and spring wheats grown under an overwintering condition. J. Cereal Sci. 37:91-99.

Dahl, B. L., and Wilson, W. W. 2000. Grades/classes of hard wheats exported from North America: Analysis of growth and market segments. Rev. Agric. Econ. 22:172-191.

Dowell, F. E., Maghirang, E. B., Xie, F., Lookhart, G. L., Pierce, R. O., Seabourn, B. W., Bean, S. R., Wilson, J. D., and Chung, O. K. 2006. Predicting wheat quality characteristics and functionality using near-infrared spectroscopy. Cereal Chem. 83:529-536.

Endo, S., Okada, K., Nagao, S., and D'Appolonia, B. L. 1990a. Quality characteristics of hard red spring and winter wheats: I. Differentiation by reversed-phase high performance liquid chromatography and milling properties. Cereal Chem. 67:480-485.

Endo, S., Okada, K., Nagao, S., and D'Appolonia, B. L. 1990b. Quality characteristics of hard red spring and winter wheats: II. Statistical evaluations of reversed-phase high-performance liquid chromatography and milling data. Cereal Chem. 67:486-489.

Finney, K. F. 1965. Evaluation of wheat quality. Pages 73-82 in: Food Quality: Effects of Production Practices and Processing. Publication No. 77. AAAS: Washington, DC.

Finney, K. F. 1985. Experimental breadmaking studies, functional (breadmaking) properties, and related gluten protein fractions. Cereal Foods World 30:794-801.

Halverson, J., and Zeleny, L. 1988. Criteria of wheat quality. Pages 69-91 in: Wheat Chemistry and Technology, Vol. II, 3rd Ed. Y. Pomeranz, ed. AACC International: St Paul, MN.

Hubbard, J. D., Downing, J. M., Ram, M. S., and Chung, O. K. 2004. Lipid extraction from wheat flour using supercritical fluid extraction. Cereal Chem. 81:693-698.

Huebner, F. R., Nelsen, T. C., and Bietz J. A. 1995. Differences among gliadins from spring and winter wheat cultivars. Cereal Chem. 72:341-343.

Huebner, F. R., Nelsen, T. C., Chung, O. K., and Bietz, J. A. 1997. Protein distributions among hard red winter wheat cultivars as related to environment and baking quality. Cereal Chem. 74:123-128.

Jukanti, A. K., Bruckner, P. L., and Fischer, A. M. 2004. Evaluation of wheat polyphenol oxidase genes. Cereal Chem. 81:481-485.

Larmour, R. K. 1940. A comparison of hard red winter and hard red spring wheats. Bull. No. 289, Agricultural Experiment Station. Kansas State College of Agriculture and Applied Science: Manhattan, KS.

Lookhart, G. L., Cox, T. S., and Chung, O. K. 1993. Statistical analyses of gliadin reversed-phase high-performance liquid chromatography patterns of hard red spring and hard red winter wheat cultivars grown in a common environment: Classification indices. Cereal Chem. 70:430-434.

Ohm, J. B., and Chung, O. K. 1999. Estimation of free glycolipids in wheat flour by high performance liquid chromatography. Cereal Chem 76:873-876.

Perten, H. 1964. Application of the falling number method for evaluating alpha-amylase activity. Cereal Chem. 41:127-140.

Pomeranz, Y. 1988. Composition and functionality of wheat flour components. Pages 219-370 in: Wheat Chemistry and Technology, Vol. II, 3rd Ed. Y. Pomeranz, ed. AACC International: St Paul, MN.

Sluimer, P. 2005. Principles of Breadmaking: Functionality of Raw Material and Process Steps. AACC International: St Paul, MN.

U.S. Wheat Associates. 2006. Price Report History. Available online at http://www.uswheat.org/ priceReports. USW: Washington, DC.

Webb, C., and Owens, G. W. 2003. Milling and flour quality. Pages 200-219 in: Bread Making—Improving Quality. S. P. Cauvain, ed. CRC Press: Boca Raton, FL.

Williams, P. C. 1997. Variety development and quality control of wheat in Canada. Available online at http://www.grainscanada.gc.ca/Cdngrain/VarietyDev/variety1-e.htm. Canadian Grain Commission: Winnipeg, Manitoba.

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