Relation of Wheat Hardness to Air-Classification Yields and Flour Particle Size Distribution

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ABSTRACT

Hardness of 14 wheats was related to particle size distribution determined by Buhler milling. Hard and soft wheats differed in percentage of flour that passed through a 270-mesh screen (53-μm opening) but was retained on a 325-mesh screen (44-μm opening), in percentage of flour that passed through a 325-mesh screen, and in mean flour particle size after 10 min of screening. Effects on particle size of varying the amount of flour screened and length of time on a Ro-Tap sieve shaker were studied. Hard and soft wheats also were distinctly different in percentage of coarse residue (>30 μm) from air classification of flour and from flour pin-milled at 9,000 rpm or at 9,000 followed by 14,000 rpm. Hard red spring wheats appeared to differ from hard red winter wheats in percent <15-μm fraction from air classification of flour further pin-milled at 9,000 rpm and three times at 14,000 rpm, and also in percentage of 24–30-μm fraction. Thus, >30-μm fraction from air classification or screening of flour distinguishes hard and soft wheats, whereas the <15-μm fraction from air classification also differentiated hard red spring from hard red winter wheats.

Although wheat hardness has no universally accepted definition, hardness has been equated with vitreosity, texture, or amount of force necessary to crush the kernel. Ten methods of evaluating wheat hardness have been used.

1) Measuring the force to crush or shear kernels. Pomeranz et al (1988) used a single-kernel compression instrument equipped with a semiautomated kernel feeder to crush individual kernels between two flat surfaces. They calculated a hardness score from kernel thickness, kernel deformation, and force to deform the kernel. Eckhoff et al (1988) evaluated hardness by shearing individual kernels and recording the associated force breakage curves.

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2) Abrasion. Taylor et al (1939), Stenvert (1972), Kuhlman et al (1979), and Obuchowski and Bushuk (1980) determined wheat hardness by measuring the quantity of wheat worn off in a barley pearler. Bran appears to play a predominant role in attritional abrasion of wheat kernels in pearling.

3) Determining work to grind kernels. Miller et al (1981b, 1982) measured hardness by work required to grind wheat in a modified Brabender hardness tester. Obuchowski and Bushuk (1980) and Greenway (1969) determined hardness by a wheat hardness index, calculated from the maximum torque produced during grinding divided by percent yield of flour.

4) Measuring starch damage or diastatic activity. Stenvert (1972) used a Buhler experimental mill to obtain flour, and he related hardness to percentage of starch damage and diastatic activity.

5) Determining flour yield or surface area. Anderson et al (1966) demonstrated that flour yield or flour fraction surface area, determined by the Brabender tester or the pin mill, can rate wheats according to kernel hardness.

6) Measuring speed reduction of a mill during grinding.

Williams et al (1987) determined wheat hardness by measuring speed reduction of a Udy cyclone grinder during grinding.

7) Determining grinding time. Miller et al (1981a, 1982), Sampson et al (1983), and Kosmolak (1978) related wheat hardness to time required to grind wheat in a Brabender automatic micro hardness tester, a Wiley laboratory mill, and a Brabender grinder, respectively.

8) Analyzing vibrations produced by grinding grain. Massie and Norris (*personal communication*, 1989) developed an instrument that electronically registers grain vibrations produced by grinding. Hard grains grind louder at high sound frequencies than soft ones. A computer linked to the instrument translates the measurement into a hardness score.

9) Near-infrared reflectance (NIR) analysis after grinding. Williams (1979), Miller et al (1982), Sampson et al (1983), Pomeranz et al (1985), Williams and Sobering (1986a), Gaines et al (1987), and Norris et al (1989) correlated NIR with particle size index of ground wheat, which can rank wheat according to hardness. An NIR method to determine wheat hardness based on the procedure of Williams and Sobering (1986a) appeared recently as AACC method 39-70 (AACC 1983).

10) Measuring particle size of ground wheat. There have been numerous studies of wheat particle size. Cutler and Brinson (1935) used a Wiley mill equipped with a 1-mm mesh sieve to grind wheat, and separated the meal by 60-mesh (246-μm) and 270-mesh sieves (53-μm opening) into three fractions.

Worzella and Cutler (1939) conducted a critical study of techniques for measuring granulation of wheat meal. Fifty grams of wheat were ground in a Labconco mill; 2.5 g of the resulting meal was screened for 1 hr through standard 60- and 270-mesh wire sieves. The percentage of meal that passed through the 270-mesh sieve (53-μm opening) is defined as particle size index. A low index indicates a coarse meal, and a high index indicates a fine meal.

Symes (1961) used the finest setting of a Labconco mill to grind 10 g of wheat and sieved the meal on no. 15 silk (aperture 75 μm) for 5 min. The percentage of meal passing through the silk was also defined as a particle size index.

Miller et al (1982) ground wheat in a Brabender micro hardness tester and calculated the percentage of meal that passed through a U.S. no. 140 (106-μm opening) sieve using a sonic sifter. A higher percentage of soft wheat meal passed through a no. 140 sieve than did hard wheat meal.

Obuchowski and Bushuk (1980) milled wheat in a Brabender Quadramat Junior mill and sieved the product on a sieve shaker with 125-μm sieve openings.

Williams and Sobering (1986b) used a Falling Number KT-30 burr mill fitted with a no. 2 (fine) burr to grind wheat. Meal was sieved through a 200-mesh screen (74-μm opening) for 10 min in a Ro-Tap sieve shaker. Percentage of meal that passed through the screen (particle size index) clearly differentiates varieties of various hardness. A particle size index method for determining wheat hardness based on the method of Williams and Sobering (1986b) appeared recently as AACC method 55-30 (AACC 1983).

Yamazaki and Donelson (1983) ground wheat in a Labconco heavy duty grinder with special burrs. The meal was separated by a 425-μm screen by sifting for 30 sec on a rotary sifter. Particle size index was defined as the percentage of meal passing through the screen.

These studies related wheat hardness to meal particle size from different grinders and usually a single screen (of different openings); they did not determine flour particle size distribution. Few studies have related hardness to amounts of various flour fractions. Also, changes in breeding strategies (including release of varieties having multiple biotypes, earlier selection, and crosses between hard and soft wheats) are making traditional differences between hard and soft wheats less clear. For example, Brule is a hard red winter wheat but has some soft parents in its pedigree, and it contains both hard and semihard kernels (Schmidt et al 1983). Also, Arkan is a hard red winter wheat derived from a cross between hard and soft wheats (Martin et al 1983). Such wheats may be impossible to categorize as hard or soft by traditional visual classification criteria of kernel size, shape, and color.

The objectives of this study are to better relate wheat hardness to flour particle size distribution, and to use resulting information in an attempt to distinguish hard spring from hard winter wheats.

MATERIALS AND METHODS

Wheats

Arthur soft red winter (SRW), Hart SRW, and Ruler SRW wheats were grown at Wooster, OH, in 1984. Daws soft white winter (SWW) wheat came from Washington in 1981. Arkan hard red winter (HRW), Centurk 78 HRW, Newton HRW, and Sage HRW wheats were grown in 1984 in Manhattan, KS. Brule HRW came from Lincoln, NE, in 1987. Scout 66 HRW was from Manhattan, KS, in 1986. Len hard red spring (HRS) came from Fargo, ND, in 1987. Marshall HRS wheat was from St. Paul, MN, and from Fargo, ND, in 1988. Wheaton HRS wheat came from St. Paul, MN, in 1988. All wheats were stored at 1°C upon arrival. All wheats were clean and sound when received. Besides the usual HRS, HRW, and SRW wheats, two problem HRW wheats (Brule and Arkan) and a harder than usual SWW wheat (Daws) were also included in our study.

Buhler Milling and Pin-Milling

Hard wheats were tempered to 15.5% moisture overnight and then to 16.0% for 0.5 hr before milling in a Buhler pneumatic laboratory flour mill (Buhler, Uzwil, Switzerland) in a constant-temperature and constant humidity milling laboratory (25°C and 48% relative humidity). Soft wheats were tempered to 14% moisture overnight and then to 14.5% for 0.5 hr before Buhler milling. Straight-grade flour (subsequently called flour) was the combined break and reduction flour fractions from the Buhler mill. An Alpine 160Z laboratory pin mill (Augsburg, Germany) at 9,000 and 14,000 rpm (the two lowest speed settings) was used for further grinding flours from Buhler milling before air classification for some experiments.

Air Classification

A Pillsbury laboratory air classifier (Pillsbury Mills Inc., Minneapolis, MN) was used to separate flour. Each pass of material through the classifier produces one fine and one coarse fraction. For a five-part separation, the classifier was adjusted for cut points of 15, 18, 24, and 30 μm in successive passes to obtain four fine fractions with progressively increasing particle size and a coarse residue. Flour was further pin-milled at 9,000 and three times at 14,000 rpm before five-part air classification. For a two-part separation, the classifier was adjusted to a 30-μm cutpoint to separate flour or pin-milled flour into a coarse residue and a fine fraction. Buhler flour was air classified, then the flour was pin-milled at 9,000 rpm and air classified. The flour then was remilled at 14,000 rpm and air classified, then remilled at 14,000 rpm for two more times before air classification. Since air classification is time-consuming and needs a large sample, no replication was performed.

Screening

A Ro-Tap Testing Sieve Shaker (W. S. Tyler Co., Cleveland, OH) with six 8-in. diameter brass screens separated wheat flours (10, 15, and 20 g) from the Buhler mill into seven fractions after 5, 10, 20, and 30 min of shaking and tapping. The screens used were 100, 140, 170, 200, 270, and 325 mesh (149-, 100-, 88-, 74-, 53-, and 44-μm openings, respectively). The sum of the products by weight of each fraction and average particle size for that fraction divided by the total weight of all fractions gives the mean particle size of each flour. Average particle sizes used for this calculation were 155, 125, 94, 81, 64, 49, and 22 μm, respectively, for fractions on 100, through 100 on 140, through 140 on 170, through 170 on 200, through 200 on 270, through 270 on 325, and through 325 mesh. The average size of the on 100-mesh fraction (155 μm) is the average of 160 and 149 μm. In a separate Ro-Tap screening, all Scout 66 flour passed through an 80-mesh screen

(160-μm opening). It is assumed that other hard wheat flours and soft wheat flours, which have smaller particle size than hard wheat flours (see Results and Discussion), also passed through an 80-mesh screen. Replicate screening analyses were carried out on all samples, except sample availability limited some screenings to single experiments (no standard deviation in tables).

NIR

NIR measurements were made with a Pacific Scientific 6250 near-infrared spectrophotometer (Silver Springs, MD). AACC method 39-70 (1983) for determining wheat hardness by NIR was used. Ten standard wheats from the Federal Grain Inspection Service were used to calibrate the instrument. A Udy cyclone mill with a 1-mm screen was used to grind the wheats. The best fit for hardness was $-274.14 - 1{,}152.08\,[\log(1/R)]_{1{,}680} + 1{,}546.24\,[\log(1/R)]_{2{,}230}$, where subscripts denote wavelengths in nanometers of measured reflectance (R). The same formula was then used to obtain NIR hardness values for other wheats.

Analyses

Protein in triplicate was determined by AACC approved methods (1983), and crude protein was calculated from Kjeldahl N $\times$ 5.7. Moisture was determined in triplicate by a Brabender Moisture/Volatiles tester, type SAS (C. W. Brabender Instruments, Inc., Hackensack, NJ) after wheat was cracked in an Enterprise model 00 grain mill (Philadelphia, PA).

Statistical correlations are Pearson's coefficients with probability values representing the probability of a zero coefficient. Coefficient of variation is 100 times standard deviation divided by mean. In linear regression procedure, r^2 is the proportionate reduction of total variation associated with the use of the independent variable.

RESULTS AND DISCUSSION

Effect of Sample Size and Time of Shaking on Wheat Flour Particle Size Distribution

A hard wheat flour (Scout 66) and a soft wheat flour (Daws) were used to study effects of sample size (10, 15, and 20 g) and time of shaking (5, 10, 20, and 30 min) on wheat flour particle size distribution (Table I). Linear regression procedures showed no significant difference in percentage of screened fractions or of mean particle size for 10, 15, and 20 g of Scout 66 flour shaken for 10 min except that there was an increasing trend for the 49-μm fraction with increasing sample size ($r^2 = 0.84$, $P = 0.08$). Mean particle size of Daws flour screened for 10 min declined as sample size increased ($r^2 = 0.91$, $P = 0.04$). There was a decreasing trend for the 94-μm fraction with increasing sample size of Daws flour screened for 10 min ($r^2 = 0.87$, $P = 0.07$).

Linear regression showed that increasing screening time for 15 g of Daws flour (Table I) increased the 22-μm fraction ($P = 0.01$, $r^2 = 0.75$) and 49-μm fraction ($P < 0.10$, $r^2 = 0.45$) and decreased the 94-μm ($P = 0.01$, $r^2 = 0.75$) and 155-μm ($P = 0.09$, $r^2 = 0.47$) fractions and mean particle size ($P < 0.01$, $r^2 = 0.83$). The effect of increasing shaking time (Table I) for 15 g of Scout 66 flour indicated increase in the 81-μm ($P < 0.01$, $r^2 = 0.77$) fraction and decrease in the 155-μm fraction ($P < 0.01$, $r^2 = 0.85$).

Particle Size Distribution of Wheat Flours

Table II gives percentage by weight of each screened fraction, the calculated mean particle size for each wheat flour after 10 min of shaking, and NIR hardness values for each wheat studied. Hard and soft wheat flours exhibit major differences in particle size distributions, as seen in percent 49- and 22-μm fractions and mean particle size. Although Arkan flour has atypical percentages of 94- and 64-μm fractions compared with other hard wheats, it is also clearly different from soft wheats. Except for Brule, percent of 155- and 125-μm fractions also separates hard and soft wheats. Apparently, Brule behaves both as a hard and a soft wheat, consistent with the fact that Brule actually contains both hard and soft wheat kernels (Schmidt et al 1983; P. J. Mattern, *personal communication*). These results (Table II) show no significant difference between particle size distributions of HRS and HRW wheat varieties.

Percentages of 22-, 49-, 125-, and 155-μm fractions and mean particle size after 10 min of screening were correlated with NIR hardness ($P < 0.01$, Table III) and percentage of 81-μm fraction was correlated with NIR hardness ($P < 0.05$). Percent 49-μm fraction, percent 155-μm fraction, and mean particle size after 20 min of screening were correlated with NIR hardness ($P < 0.01$, Table III), and percent 125 μm fraction was correlated with NIR hardness. Percentages of 49-, 125-, and 155-μm fractions and mean flour particle size after 30 min screening were correlated ($P < 0.01$) with NIR hardness (Table III).

After 20 min of screening, percent 155- and 49-μm fraction and mean flour particle size differentiated four hard (including Brule) and four soft wheats (Table IV). After 30 min of screening, percent 125- and 49-μm fraction and mean flour particle size differentiated all hard and soft wheats except Brule (Table V).

Mean flour particle size and percent 155-μm fraction generally decrease as screening time increases from 10 to 30 min (Tables

TABLE I
Effect of Sample Size and Time of Shaking on Particle Size Distribution of Wheat Flour from Buhler Mill[a]

Sample (g)	Time on Shaker (min)	% of Screened Fractions (by average size) 22 μm	49 μm	64 μm	81 μm	94 μm	125 μm	155 μm	Mean Particle Size (μm)
Scout 66									
10	10	1.3 ...	7.0 ...	5.4 ...	7.5 ...	15.8 ...	25.2 ...	37.7 ...	118 ...
15	10	3.5 (1.2)	8.8 (0.2)	7.9 (0.2)	4.1 (0.2)	12.3 (1.5)	26.3 (0.3)	37.1 (0.7)	115 (1.4)
20	10	3.7 ...	9.3 ...	5.8 ...	3.9 ...	14.2 ...	25.9 ...	37.1 ...	116 ...
Daws									
10	10	0.3 ...	6.0 ...	6.8 ...	9.0 ...	26.9 ...	23.9 ...	26.9 ...	112 ...
15	10	4.2 (2.0)	13.0 (1.6)	7.2 (2.1)	4.5 (0.8)	20.8 (2.3)	21.1 (0.8)	29.4 (0.8)	107 (0.7)
20	10	2.2 ...	13.4 ...	16.0 ...	4.9 ...	15.1 ...	22.9 ...	25.4 ...	104 ...
Scout 66									
15	5	0.1 ...	2.4 ...	2.3 ...	3.7 ...	26.3 ...	25.3 ...	39.8 ...	124 ...
15	10	3.5 (1.2)	8.8 (0.2)	7.9 (0.2)	4.1 (0.2)	12.3 (1.5)	26.3 (0.3)	37.1 (0.7)	115 (1.4)
15	20	2.3 (0.2)	8.6 (1.0)	7.0 (1.6)	5.6 (0.9)	15.7 (3.3)	27.9 (0.0)	32.9 (0.4)	114 (1.5)
15	30	2.3 (0.9)	8.5 (0.0)	9.4 (0.9)	6.4 (0.4)	13.8 (0.1)	27.3 (0.6)	32.4 (0.2)	113 (0.5)
Daws									
15	5	0.2 ...	3.7 ...	8.6 ...	6.7 ...	26.9 ...	22.0 ...	32.0 ...	115 ...
15	10	4.2 (2.0)	12.9 (1.6)	7.1 (2.1)	4.4 (0.8)	20.8 (2.3)	21.0 (0.8)	29.4 (0.8)	107 (0.7)
15	20	11.7 (2.0)	16.1 (0.3)	5.4 (1.4)	4.7 (0.2)	14.2 (5.8)	23.8 (1.0)	24.3 (2.8)	98 (0.6)
15	30	13.5 (3.3)	16.3 (4.4)	6.7 (0.1)	4.9 (0.1)	9.2 (1.1)	23.6 (0.9)	25.8 (1.1)	97 (0.1)

[a] Determined on a Ro-Tap shaker with 8-in. diameter screens. Values in parentheses indicate standard deviation of duplicate samples. Percent recovery ranged from 94.3 to 95.7% for each screening. Values in table were based on 100% recovery.

II, IV, V). Rates of decrease appear similar for HRS, HRW, and soft winter wheats.

Coefficients of variation of percent by weight of each screened fraction ranged from 3.0 for the 155-μm fraction to 23.3 for the 22-μm fraction (average 13.7) for four flours (Centurk 78, Newton, Scout 66, and Daws) screened 10 min compared with 1.2 for mean particle size. Corresponding coefficients of variation ranged from 2.7 for the 125-μm fraction to 30.5 for the 22-μm fraction (average 16.1) for 16 flours screened 20 min, compared with 1.4 for mean particle size. After 30 min of screening 13 flours, coefficients of variation ranged from 2.4 for the 125-μm fraction to 24.8 for the 22-μm fraction (average 10.2), and 0.8 for mean particle size. Overall, average coefficients of variation ranged from 2.6 for the 125-μm fraction to 26.0 for the 22-μm fraction (average 12.3) for 23 flours screened 10, 20, and 30 min, compared with 1.0 for mean particle size. Thus, mean particle size is more reproducible than percentages of individual screened fractions.

Break Flour Yield from Wheat and Percent Coarse Residue of Wheat Flour from Two-Part Air-Classification

Yields of break flour and coarse residue from air-classification of flours were examined in an attempt to relate wheat hardness and yield (Table VI). Break flour yield as a percentage of straight flour and break flour yield as a percentage of total products (flour + shorts + bran) were correlated ($r = -0.535$, $r = -0.578$, respectively, both $P < 0.05$) with NIR hardness.

TABLE II
Particle Size Distribution of Wheat Flours from a Buhler Mill (10-min screening)[a]

		% of Screened Fractions (by average size)[c]								
Wheat	Class[b]	22 μm	49 μm	64 μm	81 μm	94 μm	125 μm	155 μm	MPS[d] (μm)	NIR[e] Hardness
Len	HRS	2.3 ...	7.8 ...	10.7 ...	3.4 ...	10.5 ...	26.4 ...	38.9 ...	117 ...	70
Marshall (ND)	HRS	2.8 ...	6.3 ...	8.1 ...	3.3 ...	16.2 ...	27.8 ...	35.6 ...	117 ...	62
Marshall (MN)	HRS	3.7 ...	7.8 ...	9.6 ...	5.4 ...	10.6 ...	27.8 ...	35.1 ...	114 ...	62
Wheaton	HRS	1.9 ...	7.6 ...	8.2 ...	4.3 ...	17.8 ...	23.3 ...	36.9 ...	116 ...	68
Centurk 78	HRW	3.6 (0.3)	8.0 (1.1)	6.0 (1.1)	4.4 (1.2)	14.2 (2.7)	24.0 (1.2)	39.7 (1.6)	117 (1.4)	56
Newton	HRW	3.4 (0.1)	8.3 (1.8)	3.9 (1.2)	5.2 (1.0)	20.4 (4.0)	25.5 (1.0)	33.2 (1.1)	114 (1.8)	44
Sage	HRW	4.0 ...	8.7 ...	8.9 ...	5.9 ...	10.8 ...	23.8 ...	38.1 ...	114 ...	67
Scout 66	HRW	3.5 (1.2)	8.8 (0.2)	7.9 (0.2)	4.0 (0.2)	12.3 (1.5)	26.3 (0.3)	37.1 (0.7)	115 (1.4)	51
Arkan	HRW	1.0 ...	4.1 ...	1.5 ...	2.7 ...	28.8 ...	26.6 ...	35.3 ...	120 ...	60
Brule	HRW	3.0 ...	9.9 ...	7.8 ...	6.8 ...	19.2 ...	22.8 ...	30.4 ...	110 ...	46
Daws	SWW	4.2 (2.0)	12.9 (1.6)	7.1 (2.1)	4.4 (0.8)	20.8 (2.3)	21.0 (0.8)	29.4 (0.8)	107 (0.7)	31
Hart	SRW	6.0 ...	13.4 ...	6.7 ...	6.6 ...	20.0 ...	22.0 ...	25.2 ...	103 ...	18
Ruler	SRW	6.3 ...	27.9 ...	11.6 ...	6.8 ...	14.6 ...	14.4 ...	18.3 ...	88 ...	12
Arthur	SRW	5.6 ...	16.4 ...	7.9 ...	4.1 ...	11.6 ...	22.9 ...	31.3 ...	106 ...	26

[a] For each sample, 15 g of flour was used.
[b] HRS, hard red spring; HRW, hard red winter; SWW, soft white winter; and SRW, soft red winter.
[c] Values in parentheses are standard deviations of duplicate samples.
[d] Mean particle size.
[e] Near-infrared reflectance spectroscopy.

TABLE III
Correlation Coefficients of Buhler Flour Screened Fraction Percentages Versus Near-Infrared Reflectance Hardness

	Fraction							
Screening Time	22 μm	49 μm	64 μm	81 μm	94 μm	125 μm	155 μm	Mean Particle Size
10 min ($n = 14$)	−0.835**[a]	−0.829**	−0.070	−0.514*	−0.157	0.753**	0.898**	0.876**
20 min ($n = 8$)	−0.456	0.946**	−0.442	−0.350	0.304	0.749*	0.883**	0.953**
30 min ($n = 14$)	−0.504	−0.720**	0.024	−0.136	−0.240	0.855**	0.720**	0.781**

[a] * = Significant at $P < 0.05$; ** = significant at 0.01 level.

TABLE IV
Particle Size Distribution of Wheat Flours from a Buhler Mill (20-min screening)[a]

		% of Screened Fractions (by average size)[c]							
Wheat	Class[b]	22 μm	49 μm	64 μm	81 μm	94 μm	125 μm	155 μm	Mean Particle Size (μm)
Centurk 78	HRW	4.9 (1.3)	8.8 (1.2)	9.0 (0.4)	7.5 (0.5)	8.9 (1.4)	25.4 (0.6)	35.5 (0.9)	112 (0.2)
Newton	HRW	9.6 (0.8)	10.4 (0.6)	8.3 (0.5)	4.9 (0.4)	11.0 (0.5)	25.7 (0.9)	30.1 (0.7)	106 (0.3)
Scout 66	HRW	2.3 (0.2)	8.6 (1.0)	7.0 (1.6)	5.6 (0.9)	15.7 (3.3)	27.9 (0.0)	32.9 (0.4)	114 (1.5)
Brule	HRW	3.2 (2.3)	9.5 (3.7)	8.3 (1.5)	8.1 (0.7)	20.7 (7.7)	23.3 (1.4)	26.9 (0.9)	108 (3.7)
Daws	SWW	11.7 (2.0)	16.1 (0.3)	5.4 (1.4)	4.7 (0.2)	14.2 (5.8)	23.8 (1.0)	24.3 (2.8)	98 (0.6)
Hart	SRW	14.1 ...	17.9 ...	7.0 ...	6.9 ...	9.9 ...	21.3 ...	23.0 ...	93 ...
Ruler	SRW	3.6 (1.8)	25.5 (8.8)	19.1 (13.8)	10.9 (2.3)	20.6 (1.6)	11.4 (0.0)	9.0 (0.7)	82 (1.9)
Arthur	SRW	10.3 ...	15.2 ...	7.1 ...	5.4 ...	10.4 ...	25.3 ...	26.3 ...	101 ...

[a] 15 g of each sample was screened.
[b] HRW, hard red winter; SWW, soft white winter; SRW, soft red winter.
[c] Values in parentheses are standard deviations of duplicate samples.

Percentages of coarse residue of flour and pin-milled flour decreased with successive passes through the air classifier (Table VI). When flour was passed through the air classifier at minimum feed rate to separate it into coarse residue (>30 μm) and a fine fraction, some fine particles were trapped in the coarse residue. When the coarse residue was passed through the air classifier again at the same setting, some trapped fine particles from the coarse residue were separated into the fine fraction. When the remaining coarse residue was again air classified, still more trapped fine particles from coarse residue were released into the fine fraction. Additional air classification generally did not further affect the amount of coarse residue.

Hard wheat flours had higher percentages of coarse residue than did soft wheat flours (Table VI). Brule yielded the lowest percentage of coarse residue among hard wheat flours; it resembled soft wheat flours, especially when pin-milled (once at 9,000 and once at 14,000 rpm) before air classification. Air classification differentiates hard and soft wheats by percent coarse residue of flour (one, two, and three passes), of flour pin-milled at 9,000 rpm (one, two, and three passes), and of flour pin-milled at 9,000 and at 14,000 rpm (two and three passes). These percentages of coarse residues from air classification correlate ($P < 0.01$) with NIR hardness (Table VI).

Five-Part Air Classification of Wheat Flour

Table VII shows yields of air-classified fractions from flours pin-milled at 9,000 rpm and three times at 14,000 rpm. HRS and HRW wheats differ in percentage of <15-μm fraction and, except for Brule, in percentage of 24–30-μm fraction.

Overall, hard and soft wheats are less clearly differentiated on the basis of these air classification data than by sieving (Tables II–IV, V). Nevertheless, soft wheats differ from hard red spring

TABLE V
Particle Size Distribution of Wheat Flours from a Buhler Mill (30-min screening)[a]

Wheat	Class[b]	% of Screened Fractions (by average size)[c] 22 μm	49 μm	64 μm	81 μm	94 μm	125 μm	155 μm	Mean Particle Size (μm)
Len	HRS	1.3 (0.4)	7.4 (0.1)	10.1 (0.2)	6.1 (0.6)	12.7 (1.4)	32.1 (1.6)	30.4 (2.2)	114 (0.6)
Marshall (ND)	HRS	3.8 (0.6)	7.7 (0.8)	10.3 (0.4)	6.2 (0.2)	11.3 (0.5)	33.1 (0.9)	27.7 (1.3)	111 (0.6)
Marshall (MN)	HRS	1.0 (0.4)	6.0 (1.0)	5.5 (1.3)	6.1 (1.4)	21.2 (4.3)	30.0 (0.5)	30.3 (0.2)	116 (1.2)
Wheaton	HRS	1.4 (0.1)	9.0 (1.4)	9.5 (3.2)	6.9 (1.6)	15.8 (2.8)	30.3 (0.9)	27.1 (1.0)	111 (1.6)
Centurk 78	HRW	5.6 (0.8)	9.6 (0.3)	9.6 (0.3)	5.5 (0.2)	10.3 (0.4)	27.3 (0.7)	32.0 (0.1)	110 (0.8)
Newton	HRW	3.4 (0.7)	10.7 (1.4)	4.7 (1.5)	6.7 (1.2)	19.2 (2.7)	27.1 (0.1)	28.1 (0.6)	110 (1.2)
Sage	HRW	3.5 (1.2)	11.1 (0.2)	12.3 (0.3)	5.8 (0.2)	10.7 (1.3)	29.9 (1.1)	26.5 (0.5)	107 (1.1)
Scout 66	HRW	2.3 (0.9)	8.5 (0.0)	9.4 (0.9)	6.4 (0.4)	13.8 (0.1)	27.3 (0.6)	32.4 (0.2)	113 (0.5)
Arkan	HRW	1.7 (0.6)	10.5 (0.6)	9.3 (0.4)	5.6 (0.5)	13.9 (2.0)	29.2 (0.4)	29.9 (0.3)	112 (0.8)
Brule	HRW	3.6 (0.4)	13.6 (0.2)	10.5 (0.2)	8.2 (0.6)	15.4 (0.8)	23.8 (0.4)	24.9 (0.5)	104 (0.3)
Daws	SWW	13.5 (3.3)	16.3 (4.4)	6.7 (0.1)	4.9 (0.1)	9.2 (1.1)	23.6 (0.9)	25.8 (1.1)	97 (0.1)
Hart	SRW	3.2 (0.8)	12.0 (0.5)	13.0 (3.7)	7.2 (1.1)	19.9 (0.9)	23.4 (0.1)	21.4 (0.2)	102 (0.2)
Ruler	SRW	6.1 (1.5)	42.4 (6.2)	10.9 (1.1)	5.8 (0.0)	15.6 (3.6)	11.4 (0.3)	7.7 (0.3)	75 (1.5)
Arthur	SRW	4.2 ...	16.2 ...	5.6 ...	7.1 ...	14.9 ...	25.7 ...	26.3 ...	105 ...

[a] 15 g of each sample was screened.
[b] HRS, hard red spring; HRW, hard red winter; SWW, soft white winter; SRW, soft red winter.
[c] Values in parentheses are standard deviations of duplicate samples.

TABLE VI
Break Flour Yield from Wheat and Percent Coarse Residue[a] of Wheat Flour from Two-Part Air Classification

		Break Flour as %		% Coarse Residue from Air Classifier									
				Buhler Pass no.			1 × 9,000, Pass no.			1 × 9,000 and 1 × 14,000, Pass no.			
Wheat	Class[b]	Straight Flour	Total Products[c]	1	2	3	1	2	3	1	2	3	NIR[d] Hardness
Hart	SRW	31.1	18.5	57.3	40.9	34.1	35.7	21.6	16.8	23.9	8.2	4.3	18
Ruler	SRW	37.0	21.7	41.4	24.3	18.4	29.7	13.9	9.2	23.0	7.2	3.1	12
Daws	SWW	35.0	21.5	62.3	48.1	41.6	43.9	29.9	25.0	28.7	12.8	8.6	31
Arthur	SRW	29.9	20.2	61.3	47.6	42.1	41.9	28.6	23.0	26.1	10.1	6.0	26
Sage	HRW	32.0	17.0	83.9	74.7	69.0	67.6	57.3	53.5	46.7	32.6	28.1	67
Arkan	HRW	28.6	16.1	82.7	74.3	69.0	69.8	59.8	54.8	47.0	32.6	27.4	60
Scout 66	HRW	27.9	18.2	78.9	68.6	62.6	63.1	50.9	44.5	42.9	27.7	21.7	51
Newton	HRW	27.5	17.5	73.9	...	...	56.7	...	...	40.1	...	...	44
Centurk 78	HRW	25.5	14.5	81.4	...	...	67.9	...	...	49.1	...	...	56
Brule	HRW	35.4	23.3	67.8	52.8	45.3	48.0	35.3	30.2	28.2	13.6	9.1	46
Wheaton	HRS	31.7	20.0	78.6	70.7	66.5	68.1	59.4	54.5	48.3	35.9	28.6	68
Len	HRS	28.6	13.5	82.5	74.3	69.6	67.8	58.8	54.6	46.9	34.6	30.5	70
Marshall (ND)	HRS	26.9	17.7	82.7	73.3	68.4	66.4	57.4	53.1	43.1	30.7	25.9	62
Marshall (MN)	HRS	27.6	17.9	80.6	71.7	66.8	66.1	56.3	52.3	43.2	29.8	24.6	62
Correlation coefficients vs. NIR hardness[e]		−0.535*	−0.578*	0.932**	0.962**	0.963**	0.966**	0.979**	0.981**	0.926**	0.961**	0.963**	...

[a] Coarse residue is >30 μm.
[b] SRW, soft red winter; SWW, soft white winter; HRW, hard red winter; and HRS, hard red spring.
[c] Total products = flour + shorts + bran.
[d] Near-infrared reflectance spectroscopy.
[e] * = Significant at $P < 0.05$; ** = significant at $P < 0.01$.

TABLE VII
Five-Part Air Classification of Buhler Flour Further Pin-Milled at 9,000 and Three Times at 14,000 rpm[a]

Wheat	Class[b]	% Fraction (μm range)			NIR[c] Hardness	% Protein (as-is)	
		<15	15–18	24–30		Flour	<15-μm Fraction
Arthur	SRW	16.3	15.7	17.1	26	9.2	23.6
Daws	SWW	15.2	16.0	19.4	31	7.6	18.8
Hart	SRW	15.3	16.2	18.2	18	9.4	23.8
Ruler	SRW	16.8	16.5	18.6	12	8.4	22.6
Len	HRS	24.5	12.9	8.8	70	14.5	20.8
Marshall (MN)	HRS	20.4	13.1	8.0	62	12.1	21.1
Marshall (ND)	HRS	17.9	13.2	8.5	62	13.1	24.4
Wheaton	HRS	21.4	14.9	12.3	68	12.1	18.7
Centurk 78	HRW	14.4	16.9	19.8	56	9.8	21.2
Newton	HRW	13.9	16.6	17.4	44	10.9	23.2
Sage	HRW	11.0	12.2	22.4	67	12.6	26.7
Scout 66	HRW	11.9	13.9	24.0	51	10.9	21.5
Arkan	HRW	11.5	13.2	22.4	60	10.9	24.3
Brule	HRW	15.5	14.1	7.2	46	11.6	27.6

[a] Values for 18–24-μm and >30-μm fractions not reported, because no differentiation between hard and soft wheats or between hard red spring and hard red winter wheats was observed.
[b] SRW, soft red winter; SWW, soft white winter; HRS, hard red spring; HRW, hard red winter.
[c] Near-infrared reflectance spectroscopy.

wheats in percentages of <15-, 15–18-, and 24–30-μm fractions. If Brule is omitted, soft wheats also differ from hard red winter wheats in percentage of <15-μm fraction.

Protein Content of Wheat Flour and Air-Classified Flour Fractions

Protein contents of wheat flour showed that soft wheats had the lowest protein contents that separated soft wheats from hard wheats (Table VII). Flours from HRS wheats had higher protein contents than those from HRW wheats except Sage. Wheat hardness as determined by NIR was correlated with flour protein content ($r = 0.84$, $P < 0.01$). However, wheat hardness from NIR was not correlated with protein content of <15-μm fraction of air classified flours ($r = 0.056$, $P > 0.05$).

CONCLUSIONS

Various authors (Cutler and Brinson 1935, Worzella and Cutler 1939, Symes 1961, Miller et al 1982, Obuchowski and Bushuk 1980, Williams and Sobering 1986b, Yamazaki and Donelson 1983) have determined particle size indices of wheat meal by using different grinders, screens, and shaking times. Generally, only the percentage of meal passing through one screen is determined.

While such analyses are relatively easy to perform, we found that mean flour particle size calculated from a number of screened fractions is more reproducible than amounts of individually screened fractions. Therefore, mean flour particle size may measure wheat hardness more reliably than particle size index.

For this study, we chose to perform extensive milling studies on a limited number of varieties. Nevertheless, results appear consistent within some classes except for varieties known to be atypical, such as Brule. Although Brule is usually considered a hard wheat, it has both hard and soft kernels and its flour screens at times like a soft wheat. Arkan exhibits phenotypic heterogeneity, but is regarded as a high-quality HRW wheat. In our studies, it also behaved as a hard wheat, and presented no difficulty in screening studies.

Hard and soft wheats also differ in percentage of coarse residue (>30 μm) from air classification of flour, of flour further ground at 9,000 rpm, and of flour further ground at 9,000 and 14,000 rpm (Table VI). By air classification, Brule flour had a consistently lower percentage of coarse residue than other hard wheat flours, but a higher percentage than did soft wheat flours. After more passes through the air classifier, before and after further pin-milling, Brule flour resembled soft wheats more than hard wheats. It appears that percentage of coarse residue from air classification of wheat flours may differentiate hard and soft wheats better than flour screening, perhaps because basic endosperm structural differences between wheat classes are emphasized.

Even more interesting is the observation from air classification studies that HRS and HRW wheats differ in percent <15-μm fraction, and (with the exception of Brule) in percent 24–30-μm fraction. Whereas several methods (in this work and published previously) differentiate hard and soft wheats, this is one of the first observations of a true apparent difference between HRW and HRS wheats. Further studies are necessary to test this observation on a greater number of samples.

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