Wheat Hardness Determined by a Single Kernel Compression Instrument with Semiautomated Feeder

Y. POMERANZ,[1,2] C. R. MARTIN,[1] R. ROUSSER,[1] D. BRABEC,[1] and F. S. LAI[1]

ABSTRACT

Cereal Chem. 65(2):86–94

Hardness was determined in 33 samples representing varieties from six wheat classes, in 16 samples from three classes representing wheats from the grain trade, in 24 laboratory-prepared blends (eight each of three pairs of various hard red winter and soft red winter varieties), and in 22 double-blind blends of hard red winter and soft red winter wheats. Individual kernels of various sizes and moisture contents were evaluated by a compression instrument equipped with a semiautomated kernel feeder. Software was developed to automatically compute, print, and analyze the data. Single-kernel hardness tests were related to determinations of hardness of bulk wheat samples and damaged starch of flours. Estimation of the amounts of soft and hard wheats in a blend was affected, among other things, by wide heterogeneity in hardness among individual kernels in a variety or a class. The range in hardness among kernels within a variety or class may be larger than the difference between individual hard kernels of a soft wheat and soft kernels of a hard wheat. On the average, hard red spring wheat kernels were harder than those of hard red winter wheat. Distribution histograms of crushing scores were narrowest in soft winter wheats; crushing scores of soft white wheats from the midwest and east were lower than the average score for soft white wheats from the northwest.

We recently reported on an apparatus for measuring hardness of single wheat kernels (Lai et al 1985). Subsequent studies demonstrated the need to design an instrument that allows simple continuous feeding, interpretation of the results to account for effects of moisture and kernel size on hardness characteristics, and automated printout of results including distribution histograms and statistical interpretation. This report summarizes the results of investigations conducted in our laboratories to meet those needs. The objectives were to identify data output from the instrument consistent with wheat hardness and compatible to computer analysis; to determine the effect of kernel size, orientation, and moisture content on data output; and to compare the results obtained from the instrument with results obtained from hardness tests of bulk wheat samples.

MATERIALS AND METHODS

Wheat Samples

The wheats in this study included samples from three sources. The first group of samples was provided by plant breeders, and blends were prepared in the laboratory. The 33 samples from plant breeders included 10 hard red winter (HRW) (five from Kansas and five from Nebraska), four hard red spring (HRS) from North Dakota, five western soft white winter (SWW) from Washington and Idaho, five club from Washington, five soft red winter (SRW) from Ohio and Michigan, and four eastern SWW wheats from Michigan and New York.

Samples from the grain trade were provided by the Federal Grain Inspection Service (FGIS-USDA) including six HRW, five HRS, and five SRW.

Double-blind blends of HRW and SRW wheats were provided by G. Schiller, Arkansas City, KS. The blends included 22 mixtures from one commercial HRW and one commercial SRW wheat.

Analytical Methods

The wheats were cleaned on a Hart-Carter dockage tester. Whole kernels were analyzed for moisture by ASAE method S352.1 (ASAE 1986).

For determination of hardness, the samples were stored in a humidity cabinet at 26° C and 58% rh to produce a moisture content of 11.0% ± 0.4%.

Wheat hardness was measured by the time to grind 4 g of wheat with a Brabender automated microhardness tester (BMHT) (Miller et al 1981), by particle size index (PSI) (Miller et al 1982), by near-infrared reflectance at 1,680 and 2,230 nm, and by a Stenvert hardness tester (SHT, resistance to grinding, seconds) (Pomeranz et al 1985). The results from NIR reflectance data were used to compute a hardness index on a scale of 20 (very soft) to 110 (very hard). Hard wheats were lower in BMHT and PSI and higher in SHT than soft wheats.

Kernel density (an index of wheat hardness) was determined with a Quantachrom stereopycnometer using helium (Thompson and Isaacs 1967). The samples were purged three times with helium and allowed to equilibrate for 5 min before determination of density.

The wheats were milled on an Allis-Chalmers mill by the procedure of Finney and Bolte (1985) and were assigned hardness scores (on the basis of their milling performance) of 2.0 (very soft) to 8.0 (very hard). The flour yields ranged from 67.1 to 76.5% (average, 72.1%), and the decrease in protein contents from wheat to flour ranged from 0.54 to 1.17% (average, 0.94%). The ash content of the flours ranged from 0.36 to 0.46 and averaged 0.42%.

Starch damage of the experimentally milled flours was determined by AACC method 76-30A (AACC 1983) and was considered a reference method for hardness determination. Starch damage was consistently higher in hard wheats than in soft wheats.

All tests on bulk samples were made at least in duplicate and all results were averaged; hardness tests on single kernels were made on 100 kernels for pure varieties and FGIS samples and 2× 250 for blends.

Design of Instrument

The design of the instrument, basically a compression meter, is shown in Figures 1 and 2. The individual kernels are crushed between two flat surfaces. The major components of the instrument are a Daytronic model 152A-250 LVDT load cell, a Schaevit LPM-210 signal conditioner, a Bodine gear motor type NSH-33R, and a Bodine DC motor speed control, type ASH 400. The bottom crushing surface was driven by a cam designed to provide 0.03549 m/s of linear travel when driven by a shaft rotating at 24.4 rad/s. The fully open gap was 5.78 mm, and the fully closed clearance was adjusted and maintained at 0.533 mm. A second cam mounted on the shaft operated a micro switch designed to enable the computer to collect load cell data during linear travel of the crushing surface. This cam caused on and off signals from which

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[1] Research chemist, agricultural engineer, instrument maker, engineering technician, and research chemical engineer, respectively, U.S. Department of Agriculture, Agricultural Research Service, U.S. Grain Marketing Research Laboratory, Manhattan, KS 66502.

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[2] Present address: Department of Food Science and Human Nutrition, Washington State University, Pullman 99164-2032.

kernel thickness and subsequent deformation during crushing were calculated by a computer. A third cam mounted on the shaft operated another micro switch that caused the shaft to rotate one revolution after a manual start command.

The Kernel Feeder System

The feeder system, basically a semiautomated kernel orientation unit, is shown in Figures 3 and 4. Kernels were oriented to a stable position as they slid over action surfaces. The first surface was a diamond patterned rubber pad that caused the kernel to rotate about its longest axis. As the kernel passed from the pad to a smooth Plexiglas surface, rotation stopped when its center of gravity was lowest, usually with the crease down. Finally, the kernel was centered under the load cell when the feeder reached a fixed stop. A brush on the feeder handle swept the previously crushed kernel from the crushing surface before a fresh kernel was centered. The feeder was loaded manually or automatically by dropping a kernel into a receiving hole.

Data Acquisition

A Hewlett Packard 150 II PC computer equipped with an analog-to-digital converter was used for data acquisition. Data obtained included kernel thickness as a measure of kernel size, kernel deformation, and force to deform the kernel.

Hardness Reference Data from the Instrument

The kernel feeder system was not used during operations to

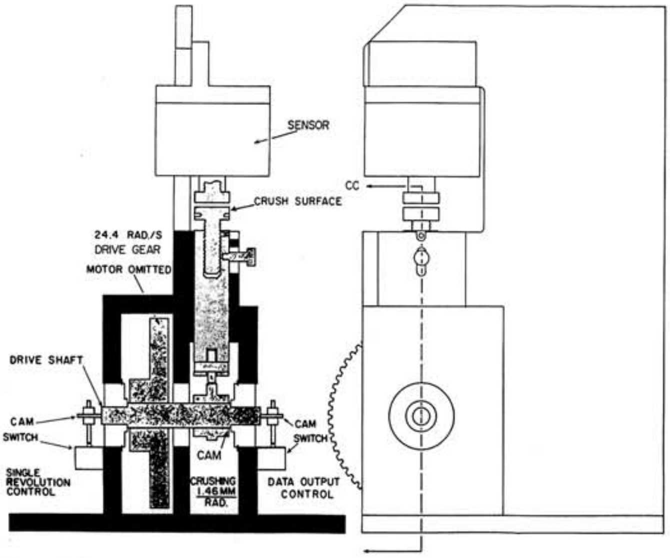

Fig. 1. Diagram of compression meter.

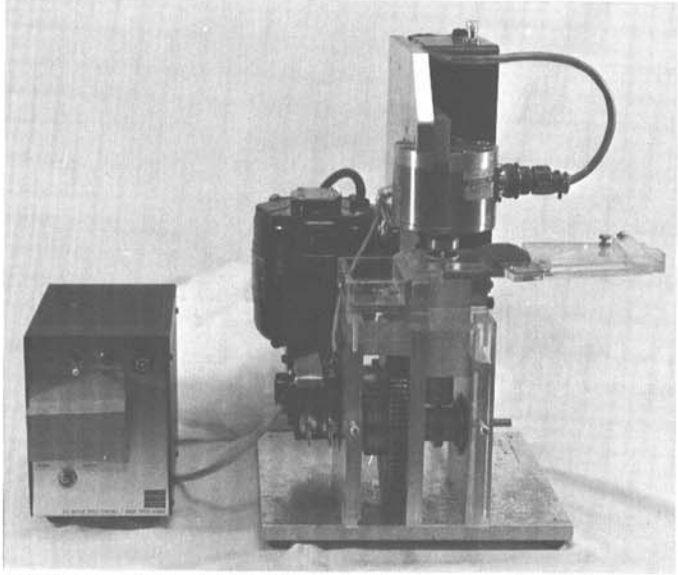

Fig. 2. Compression meter with attached feeder system (center right) and switch and speed control (bottom left).

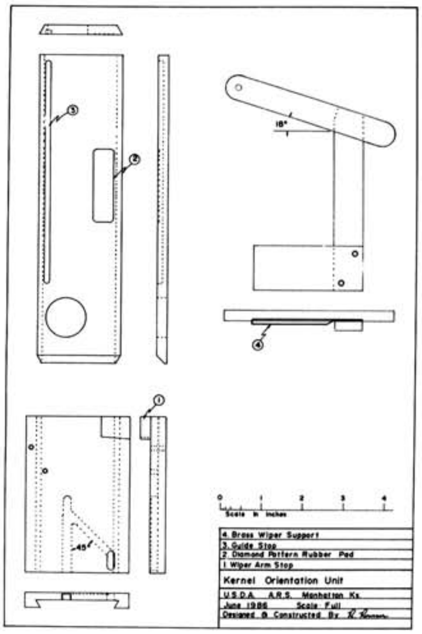

Fig. 3. Diagram of feeder system.

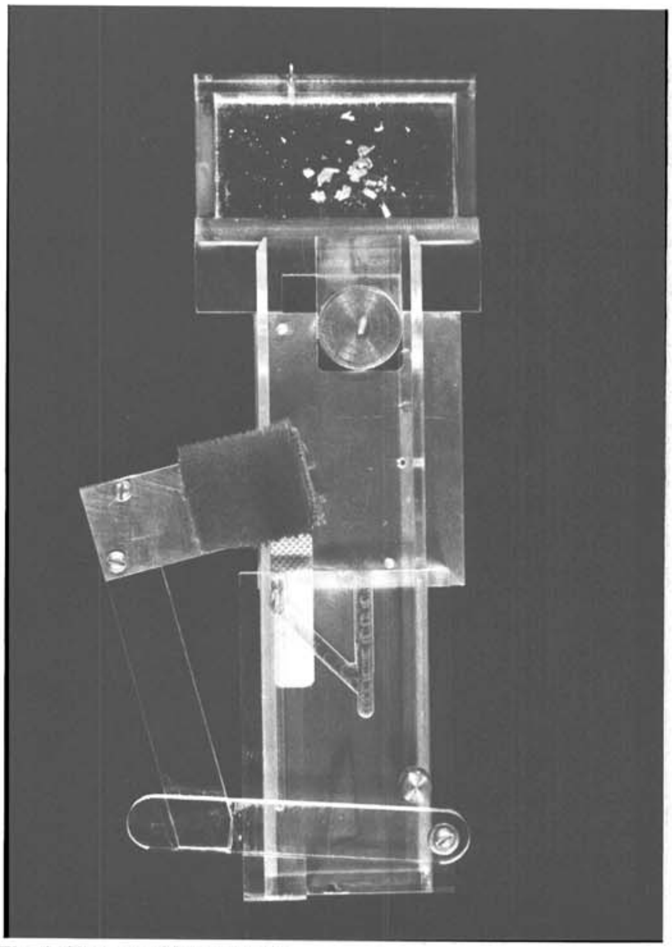

Fig. 4. Close-up of feeder system.

establish reference data. For those operations, kernels were oriented manually on the crushing surface.

Mustang and Hawk (HRW) and Caldwell and Pike (SRW) wheat cultivars were selected to obtain hardness reference data. Each cultivar was separated into three kernel size fractions by screening with Tyler nos. 7 and 8 mesh sieves. Data from 52 kernels of each size for each cultivar were used to determine effect of kernel size. One reference set was obtained for a crease-down orientation and one set for a random orientation.

The effect of moisture was determined on cultivars that had been equilibrated at constant temperature and relative humidity. Moisture contents ranged between 9.5 and 14.0% for the equilibrated samples. In this reference set 100 kernels of Hawk, Newton, and Bounty (HRW) and Caldwell, Adena, and Titan (SRW) wheats were selected because of their wide, intermediate, and narrow differences, respectively, in bulk hardness measurements.

RESULTS AND DISCUSSION

Hardness Reference Data from the Instrument

Two work parameters were selected to characterize the crushing force differences between hard and soft wheat kernels. Figure 5 illustrates the fundamental difference observed from data recorded during compression of a hard and soft kernel of the same thickness and deformation. More work was required to initially deform a hard kernel 0.2 to 0.4 mm than a soft kernel. However, the force to deform hard kernels dropped rapidly toward zero after initial deformation fractured a brittle kernel. Soft kernels were plastic and required relatively constant work to continue deformation after initial fracture. As deformation progressed to the extreme, hard kernels required more work to crush than soft kernels.

Figure 6 illustrates the difference between work per unit kernel thickness for the same kernels shown in Figure 5. This difference is consistent with the results of previous findings that used a ratio of first valley to first slope for predicting hardness (Lai et al 1985). Fracture characteristics were determined by calculating the work to induce maximum stress before fracture. Work to fracture was obtained automatically by a computer program that extracted the maximum work-per-unit-kernel-thickness value.

Figure 7 illustrates the difference between work required to crush hard and soft kernels to 60% of their thickness; the force-deformation relation of the same kernels is shown in Figure 5. Work was calculated from the summation of absolute difference between force times deformation. The 60% kernel thickness crush value was selected on the basis of crushing the thinnest kernels (1.3 mm) with a clearance setting of 0.533 mm between the crushing surfaces. Force to fracture, change in force after fracture, and force to crush are all included in the work parameter. The work parameter was extracted automatically by a computer program.

Reference Data for Kernel Size Effect

Figures 8 and 9 show a statistical plot of discrimination values versus kernel thickness for two work parameters and lines obtained by linear regression analyses of data from the two HRW (Mustang and Hawk) and two SRW (Caldwell and Pike) cultivars. Data from 52 kernels of each size were grouped to calculate the average work value and its standard deviation (SD). Discrimination values used in the linear regression analysis were the average minus 1 SD for hard cultivars and average plus 1 SD for soft cultivars. Note in Figures 8 and 9 the total separation (for average ± SD) of hard and

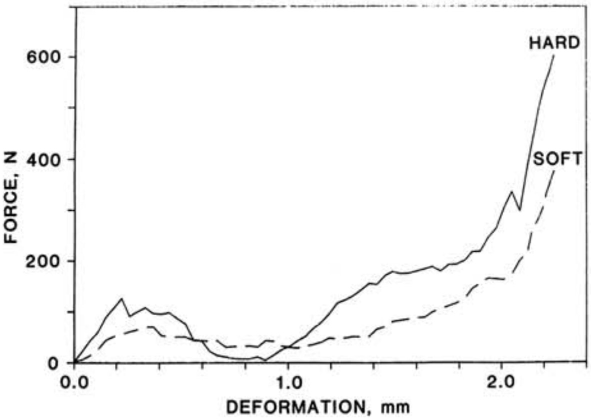

Fig. 5. Crushing curve examples of hard and soft wheat kernels.

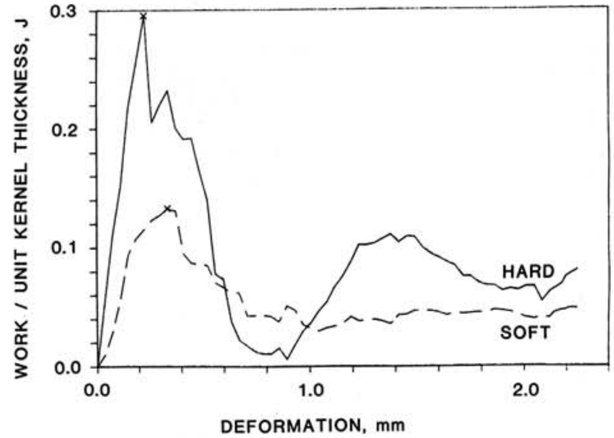

Fig. 6. Example of relation between work and deformation for typical hard and soft wheat kernels; x = work for maximum stress.

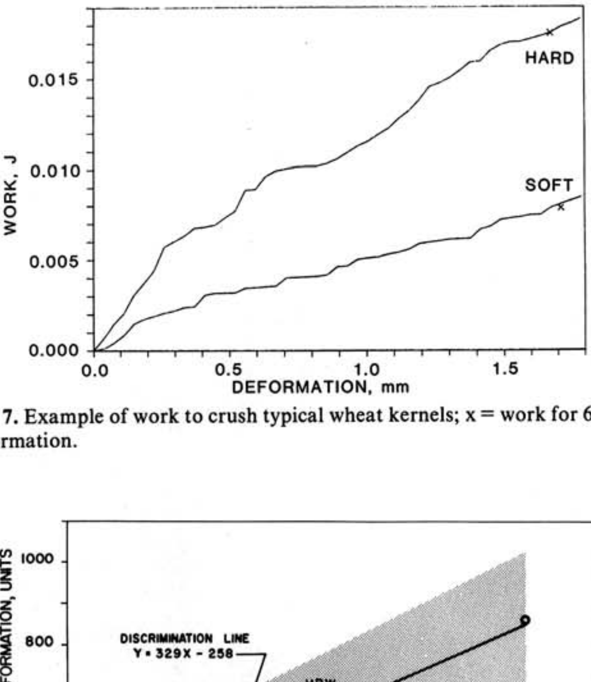

Fig. 7. Example of work to crush typical wheat kernels; x = work for 60% deformation.

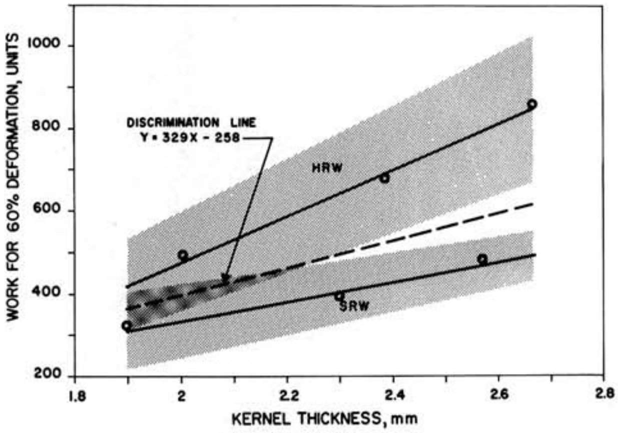

Fig. 8. Effect of kernel thickness on work required to yield a 60% deformation; $y = 329x - 258$; $r = 0.895$. The figure shows the regression lines for hard red winter (HRW) and soft red winter (SRW) kernels (solid lines), the discrimination line (broken line), and one standard deviation around the HRW and SRW lines (shaded areas).

soft values for large kernels, overlap of values for medium kernels, and reversal (hard in soft zone and vice versa) for the small kernels. This sequence of overlap and reversal is the result of a narrowing work parameter difference between small hard and soft kernels.

A hardness value for a given kernel was calculated as the difference between work value and the discrimination value for that kernel's thickness by:

$$H_1 = W_1 - (267 \times T + 374)$$

$$H_2 = W_2 - (329 \times T + 258)$$

where W_1 = maximum work per unit kernel thickness, W_2 = work to crush to 60% kernel thickness, T = kernel thickness, H_1 = hardness value for W_1, and H_2 = hardness value for W_2.

Combining the two hardness values produced a more consistent discrimination than either value produced alone. Combining the two hardness values required computation of a ratio so that the ranges for both values would be equal. Discrimination ratios were calculated by dividing work-to-crush values by work-per-unit-kernel-thickness values that were used in the discrimination regression analysis. Figure 10 shows the linear regression analysis of the discrimination ratios that were applied as follows:

$$H_t = H_2 + H_1\,(4.854 - 1.154 \times T)$$

where H_t = total hardness.

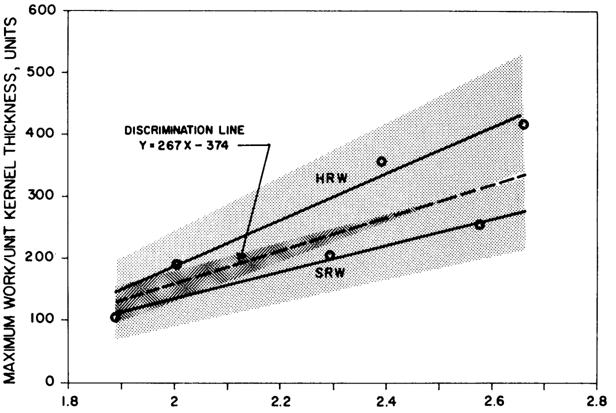

Fig. 9. Effect of kernel thickness on work per unit kernel thickness; $y = 267x - 374$; $r = 0.942$. The figure shows the regression lines for hard red winter (HRW) and soft red winter (SRW) kernels (solid lines), the discrimination line (broken line), and one standard deviation around the HRW and SRW lines (shaded areas).

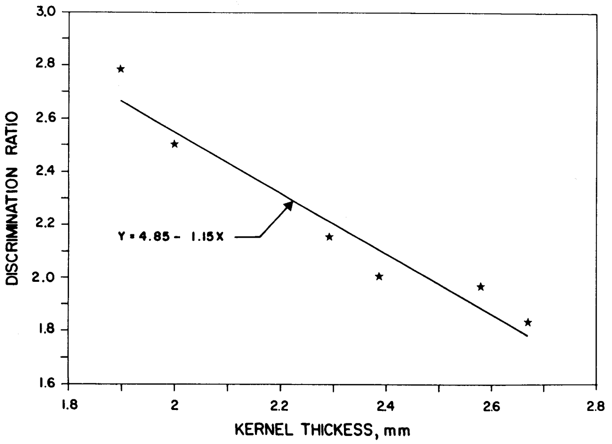

Fig. 10. Effect of kernel thickness on work discrimination ratio; $y = 4.85 - 1.15x$, $r = 0.832$.

Total hardness values were adjusted for the range of 20 (very soft) to 110 (very hard) as follows:

$$\text{if } H_t \geqslant 0, \text{ then } H_s = 50\,(1 + H_t/1{,}500)$$

$$\text{if } H_t < 0, \text{ then } H_s = 50\,(1 - H_t/1{,}000)$$

where H_s = hardness score.

For interpretation of results, both the effect of kernel orientation and moisture content must be considered.

Reference Data for Kernel Orientation Effect

The effect of orientation on crush score was determined for 52 kernels, each, for two hard wheats (Mustang and Hawk) and two soft wheats (Caldwell and Pike), equilibrated to 11.7% moisture. Random orientation of kernels lowered the score (results not shown). Still, the difference in scores between soft and hard wheats remained relatively constant.

Reference Data for Moisture Effect

To determine the effect of moisture on average crush score, kernels from six varieties were selected. All six varieties (three SRW: Adena, Caldwell, and Titan; three HRW: Bounty, Hawk, and Newton) showed a slight peak in average crush score between 10.5 and 11.0% moisture (results not shown). Soft wheats equilibrated to a slightly higher moisture than hard wheats for moisture levels above 9.5%. Generally, as moisture increased there was a decrease in crush score. There was little effect on the crush score in the 9.5–11.0% moisture range; at higher moistures it may be necessary to make a correction for moisture.

Statistical Analysis

The hardness scores (H-scores) can be presented in two modes: sequential H-scores as tested by the instrument (not shown), or histograms (sorted H-scores) of the results to illustrate the distribution of hardness in the tested sample.

A comparison of measures of variance including $\Sigma(\bar{x} - x_i)$, second moment (standard deviation), third moment, fourth moment (curtosis), and heterogeneity factor (Hf) was made for the 49 samples used in this study. Hf (arbitrary units) is defined as:

$$Hf = \frac{\Sigma \text{ absolute differences between crush scores} \times \text{range of crush scores}}{\text{percent of crush scores at max.}}$$

The higher the score, the more heterogeneous the sample. The results of variance measures yielded correlation coefficients presented in Table I. Whereas the correlation coefficients between the various moments of variance were very high (probably indicating similar information), the correlation coefficients with Hf were much lower (probably indicating different types of information). Visual examination of sorted histograms indicated that Hf was the best indicator of heterogeneity caused by a broad range of crush scores and multiple peaks in grouped data of varieties, commercial mixtures, and blends of wheats from various classes.

Summaries of the data can be printed to document the maximum, minimum, and average hardness scores, the heterogeneity factor (Hf), and the distribution of hard and soft kernels among large, medium, and small kernels (thickness below 2 mm). The emphasis on determining hardness of small kernels was prompted by the fact that the semiautomated orientation unit was much more effective in consistently placing large- and medium-

TABLE I
Correlation Coefficients for Measures of Variance

	2nd	3rd	4th
Hf[a]	0.743	0.728	0.676
2nd		0.960	0.870
3rd			0.968

[a] Hf = Heterogeneity factor.

sized kernels in the crease-down position (over 90%) than small kernels (over 70%). In addition, some of the small kernels (mainly shrunken and shriveled, rather than underdeveloped) were not characterized consistently with regard to hardness. Still, this is not likely to create difficulties in interpretation, as the percentage of shrunken and shriveled kernels permitted by U.S. grain standards is limited.

Plant Breeder and FGIS Samples

The results of hardness tests of the plant breeder and FGIS samples are summarized in Table II. Correlation coefficients of linear regression lines for hardness parameters are given for the combined red wheats (HRW + HRS + SRW) and the combined hard red wheats (HRW + HRS) (Table III). For the combined red wheats, the single kernel tests, as well as all bulk hardness tests (NIR reflectance, BMHT, PSI, and SHT), were highly correlated among themselves and with the reference hardness test (starch damage) and end-use hardness test (milling score). The required correlation coefficient for all red wheats for significance at the 0.001 level was 0.54. The required correlation coefficient for the combined hard red wheats was 0.63; only a few correlation coefficients were significant at the 0.001 level for this pooled group of samples.

Results of crush scores of 100 kernels of the red wheats (HRW, HRS, and SRW) are summarized in Table IV and of the white wheats (eastern SWW, western SWW, and club) in Table V. For each sample, average, minimum, and maximum score, heterogeneity factor, and percent of kernels with scores of at least 47.0, 57.0, and 67.0, respectively, are presented. Among the SRW wheats provided by FGIS, on the average, 14.4% had crush scores of 57.0 or above and 1.0% had crush scores of 67.0 or above. Among the SRW wheats provided by plant breeders, however, 34.4% had crush scores of 57.0 or above and 8.6% of 67.0 or above. This reflects the potentially undesirable hardness of some of the

TABLE II

Mean and Standard Deviation (SD) of Hardness Parameters for Plant Breeder and FGIS[a] Samples

Wheat Class[b] (no. of samples)	Single Kernel Hardness Score	Starch Damage (%)	Milling Score	NIR[c] Reflectance	BMHT[d] (sec)	PSI[e] (%)	SHT[f] (sec)
HRW (16)							
Mean	68.32	6.97	6.06	65.14	29.01	28.04	49.82
SD	3.59	0.54	0.85	6.60	2.49	2.24	3.51
HRS (9)							
Mean	68.94	6.92	7.22	72.64	28.36	26.77	49.36
SD	4.75	0.80	0.67	10.22	3.18	2.31	3.55
SRW (10)							
Mean	50.26	4.43	3.30	26.66	59.54	41.68	31.79
SD	4.75	0.38	0.82	4.71	13.19	2.41	1.87
Western SWW (5)							
Mean	52.58	5.34	3.20	27.52	45.26	37.70	30.16
SD	6.07	0.83	0.45	8.31	9.15	3.13	1.80
Eastern SWW (4)							
Mean	52.50	4.47	2.75	27.00	52.22	41.95	31.42
SD	5.80	0.21	0.96	4.72	8.41	3.19	1.70
Club (5)							
Mean	51.48	4.36	3.40	31.26	43.12	38.26	31.64
SD	3.66	0.52	0.89	4.22	6.31	1.91	3.61
Combined HRW + HRS (25)							
Mean	68.55	6.95	6.48	67.84	28.78	27.58	49.65
SD	3.96	0.63	0.96	8.69	2.71	2.30	3.46
Combined HRW + HRS + SRW (35)							
Mean	63.32	6.23	5.57	56.08	37.57	31.60	44.55
SD	9.34	1.28	1.72	20.38	15.81	6.85	8.74

[a] FGIS = Federal Grain Inspection Service.

[b] HRW = Hard red winter, HRS = hard red spring, SRW = soft red winter, SWW = soft white winter.

[c] Near-infrared.

[d] Brabender microhardness tester.

[e] Particle size index.

[f] Stenvert hardness test.

TABLE III

Correlation Coefficients of Linear Regression Lines for Hardess Parameters of Plant Breeder and FGIS[a] Samples

Hardness Parameter[b]	Single Kernel Hardness Score	Starch Damage (%)	Milling Score	NIR[b] Reflectance	BMHT[b] (sec)	PSI[b] (%)	SHT[b] (sec)
	Combined HRW + HRS + SRW (35)						
Single kernel		0.89	0.77	0.90	−0.89	−0.91	0.92
Starch damage	0.46		0.77	0.90	−0.88	−0.93	0.91
Milling score	0.25	0.03		0.88	−0.79	−0.80	0.78
NIR reflectance	0.41	0.46	0.56		−0.89	−0.95	0.90
BMHT	−0.24	−0.58	−0.32	−0.83		0.93	−0.88
PSI	−0.27	−0.64	−0.18	−0.74	0.88		−0.93
SHT	0.55	0.46	−0.02	0.26	−0.25	−0.40	
	Combined HRW + HRS (25)						

[a] Federal Grain Inspection Service.

[b] NIR = Near-infrared, BMHT = Brabender microhardness tester, PSI = particle size index, SHT = Stenvert hardness tester.

SRW wheat varieties and was confirmed by the bulk hardness tests.

At least 98% of the kernels in HRS wheats provided by FGIS had hardness scores of at least 47.0; among the HRS wheats provided by plant breeders, hardness scores above 47.0 ranged from 90 to 99%. A similar picture was obtained for the HRW wheats.

Histograms of crushing scores for the combined samples described in Tables IV and V are shown in Figure 11. To eliminate abrupt changes in crushing scores, the raw data were smoothed by plotting averages of three consecutive scores. The mean crushing scores of the hard wheats were much higher than those of the soft wheats. The HRS wheat kernels were on the average harder than the HRW wheat kernels. The SRW wheat kernels had the lowest

TABLE IV

Crush Scores of 100 Kernels of Hard Red Winter, Hard Red Spring, and Soft Red Winter Wheats; Plant Breeder and FGIS[a] Samples

Wheat Variety and/or Class	Average Score	Maximum Score	Minimum Score	Heterogeneity Factor	>47.0 (%)	>57.0 (%)	>67.0 (%)
Hard red winter							
Bennett	70.8	98.1	37.9	49.2	99	93	64
Bounty	63.5	107.7	30.6	72.3	85	68	40
Colt	66.2	93.4	40.4	60.5	94	79	50
Hawk	71.5	108.8	42.6	55.0	96	90	61
Lancer	61.9	103.0	31.6	47.5	96	73	24
Lindon	71.3	99.1	52.0	44.2	99	94	62
Newton	68.8	96.9	40.0	52.0	97	89	59
Probrand 830	75.8	129.6	43.5	59.3	95	92	77
TAM 105	66.7	90.6	20.5	56.0	94	84	45
TAM 105	68.7	108.3	42.6	48.0	96	92	58
FGIS-Omaha, NE	65.6	92.3	45.7	59.6	98	79	42
FGIS-Portland, OR	66.8	88.2	43.4	54.3	97	86	46
FGIS-Portland, OR	67.5	92.4	37.0	59.4	99	86	53
FGIS-Portland, OR	70.4	94.6	48.7	66.9	100	90	64
FGIS-Wichita, KS	67.1	110.7	37.5	88.1	97	81	44
FGIS-Wichita, KS	70.1	90.5	36.1	66.4	98	88	67
Hard red spring							
Len	69.5	94.9	34.0	51.3	99	88	61
Marshall	71.6	99.3	48.2	49.7	99	90	59
Oslo	61.9	92.4	37.0	56.5	90	67	31
Stoa	76.7	114.1	47.2	75.3	95	89	68
FGIS-Grd Fks, ND	63.9	84.4	44.6	51.6	99	79	32
FGIS-Grd Fks, ND	64.6	96.3	40.7	68.9	98	79	35
FGIS-Portland, OR	68.3	97.5	43.6	107.3	99	77	54
FGIS-Portland, OR	71.8	98.3	52.4	53.0	100	94	67
FGIS-Portland, OR	72.2	108.9	48.4	77.0	100	91	70
Soft red winter							
Adena	50.1	72.2	31.4	36.4	56	20	3
Caldwell	47.1	72.0	18.8	45.5	46	20	1
Caldwell	48.4	69.4	28.4	31.3	53	13	2
Hillsdale	61.7	83.1	38.5	48.9	96	76	26
Titan	55.7	74.2	32.3	36.8	79	43	11
FGIS-Indpls, IN	49.2	69.4	26.3	58.6	62	18	1
FGIS-Indpls, IN	49.6	66.6	26.4	48.6	66	15	0
FGIS-St. Louis, MO	45.7	69.3	26.7	58.9	41	9	1
FGIS-St. Louis, MO	46.8	63.9	29.3	41.4	52	8	0
FGIS-Toledo, OH	49.8	85.5	28.0	66.8	60	22	3

[a] Federal Grain Inspection Service.

TABLE V

Crush Scores of 100 Kernels of Western and Eastern Soft White Winter and Club Wheats; Plant Breeder Samples

Wheat Variety and/or Class	Average Score	Maximum Score	Minimum Score	Heterogeneity Factor	>47.0 (%)	>57.0 (%)	>67.0 (%)
Western soft white winter							
Dawes	46.6	78.2	21.5	69.8	50	8	1
Hill 81	49.6	65.7	31.2	43.3	62	17	0
Hill 81	62.5	95.4	31.4	60.4	90	66	33
Nugaines	53.5	81.3	35.1	57.5	81	35	3
Stephens	50.7	82.4	12.9	58.7	62	34	11
Eastern soft white winter							
Augusta	58.9	87.8	38.9	40.0	88	62	16
Frankenmuth	55.3	72.9	40.8	37.5	90	41	4
Houser	45.7	77.7	23.7	71.0	41	11	3
Purcell	50.1	64.7	32.2	38.0	64	16	0
Club							
Crew	54.0	101.4	36.3	58.5	82	31	6
Crew	55.5	91.3	32.6	114.1	72	41	17
Moro	48.2	93.7	25.8	78.5	55	15	3
Tres	47.1	77.3	26.3		48	15	2
Tyee	52.6	81.7	30.7	54.0	77	29	5

average score and the most narrow distribution histogram. The average crushing values in the eastern SWW and club wheat histograms were lower than in the western SWW wheat histogram, but the club wheat histogram was broader than the eastern SWW wheat histogram. As expected, the average crushing score decreased and the histogram curve broadened substantially when SRW wheat kernels were included in combination with HRW + HRS wheat kernels. Histograms were selected to reflect high and low Hf in plant breeder and FGIS samples (Fig. 12). The average Hf in plant breeder samples was much lower than in FGIS samples (Table IV). High Hf in plant breeder samples were much lower than high Hf in FGIS samples. FGIS samples can be assumed to be blends of varieties, locations, and possibly crop years (Fig. 12).

Laboratory Blends of Plant Breeder Samples

We selected, on the basis of bulk hardness tests (Table II) and data on single kernel tests (Table IV), three pairs of HRW and SRW wheats to prepare blends in the laboratory. HRW Probrand and SRW Caldwell are extremes in hardness (average kernel scores of 75.8 and 47.1); HRW Bounty and SRW Titan represent a pair with relatively similar hardness scores (63.5 and 55.7), and HRW TAM 105 and SRW Adena are intermediate (68.7 and 50.1). The results of testing the laboratory-prepared blends are summarized in Table VI.

As the percentage of hard wheat in the blend increased, the average score increased. Similarly, the percentage of kernels with scores of 47.0, 57.0, or 67.0 increased. Blending of two wheats having widely differing crush scores increased Hf, even in 1% blends. Blending of two wheats having similar crush scores and high Hf caused little change in crush scores or Hf. To determine the percentage of admixture, three criteria should be considered: the average score, the heterogeneity factor, and the percentage of kernels with scores of 67.0 or above to determine admixture of hard to soft wheat or with scores below 47.0 to determine the admixture of soft to hard wheat.

This single-kernel test, albeit, can only approximate the amount of wheat from other classes in the mixture. The factors that affect the results include spread of values (heterogeneity) among individual kernels in a pure variety, difference in overall average hardness of varieties in a class and between classes used for blending, spread of values in hardness among kernels within a class, sampling error, and large differences in kernel weights; data for single kernel hardness were evaluated on the basis of numbers and not weights.

Double-Blind Blends of HRW and SRW

Whereas there was no sampling error in testing the laboratory-prepared blends, the double-blind blends had to be subsampled and this introduced a substantial error. We therefore used 100

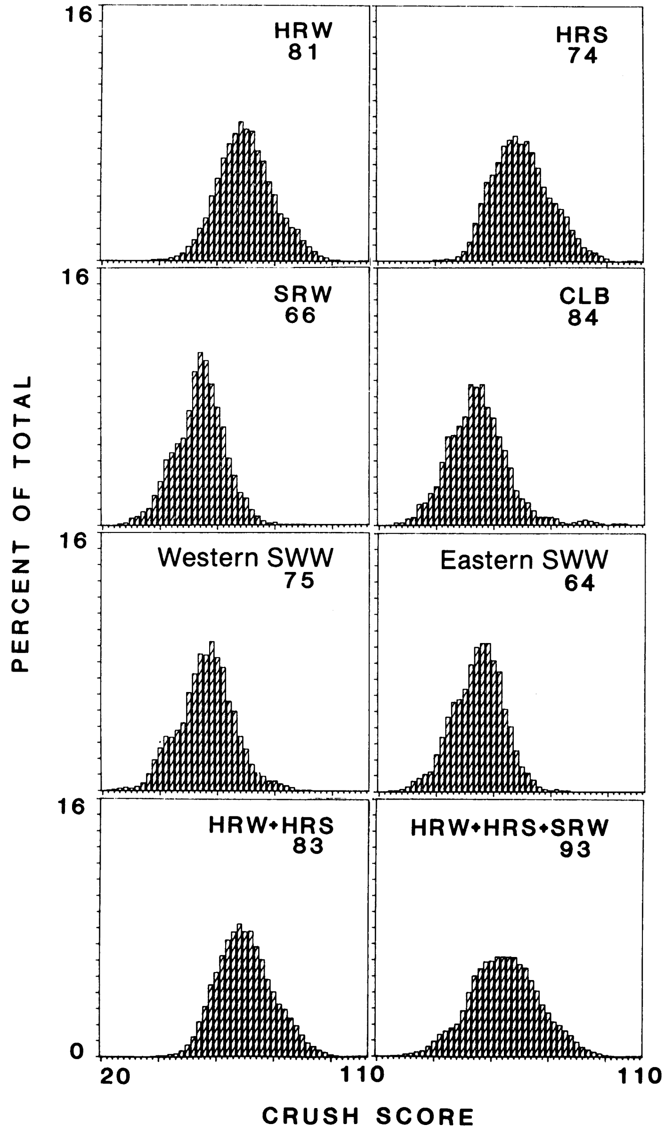

Fig. 11. Histograms of distribution (sorted according to increasing hardness) of crushing scores for hard red winter (HRW, 1,600 kernels), hard red spring (HRS, 900), soft red winter (SRW, 1,000), club (500), western soft white winter (SWW, 400), and eastern SWW (500) wheat kernels, and combinations (HRW + HRS and HRW + HRS + SRW). Figures in top right corner denote heterogeneity factors.

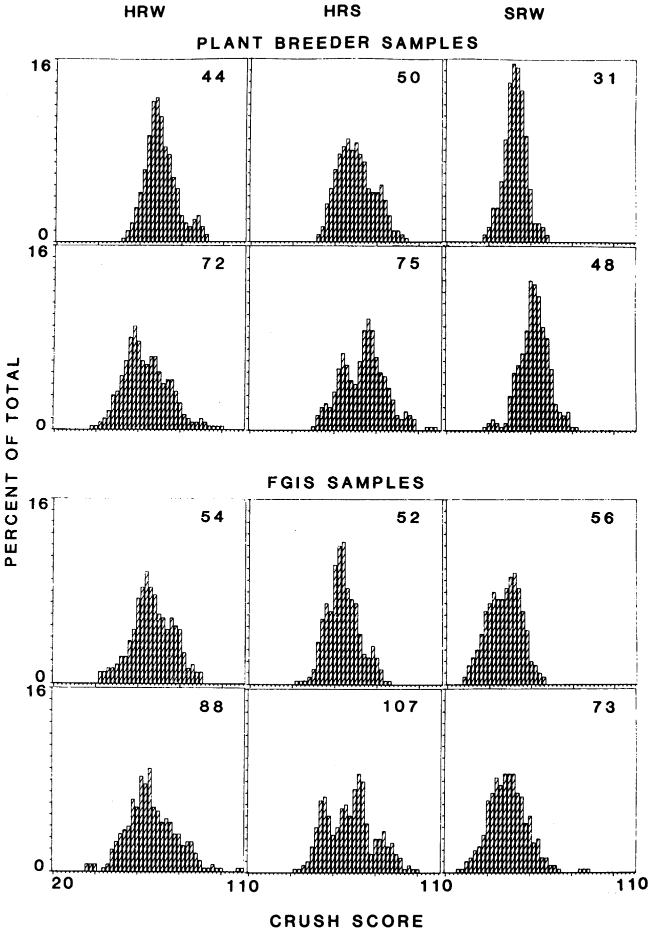

Fig. 12. Histograms of distribution (sorted according to increasing hardness) of crushing scores for 100 kernels each of hard red winter (HRW) wheats (left column), hard red spring (HRS) wheats (middle column), and soft red winter (SRW) wheats (right column), representing plant breeder samples (rows 1 and 2) and FGIS samples (rows 3 and 4). Rows 1 and 3, samples with a low heterogeneity factor (Hf); rows 2 and 4, samples with a high Hf. Figures in top right corner denote Hf values.

kernels for the laboratory and 2× 250 kernels for the double-blind blends for the single-kernel test. Still, as indicated by the results of bulk tests (Table VII), the two samples provided as 50:50 blends were not identical (at least insofar as hardness tests were concerned). As the percentage of HRW in the mixture decreased,

TABLE VI
Crush Score Analysis of 100 Kernel Samples (two replicates) of Laboratory Blends of Hard and Soft Red Winter Wheats; Plant Breeder Samples

Mixture (varieties and % of hard wheat)	Average Score	SD of Replicate Scores	Hetero-geneity Factor	>47.0 (%)	>57.0 (%)	>67.0 (%)
Bounty-Titan						
0	55.7	1.6	57.3	88.5	42.0	5.5
5	55.5	0.1	45.7	89.0	39.0	4.0
10	57.0	0.1	54.0	94.0	43.0	7.5
20	56.6	1.0	64.5	89.5	43.5	8.0
80	61.8	0.3	79.2	94.0	66.5	26.0
90	64.8	1.0	89.2	93.5	74.5	39.5
95	62.8	0.3	70.0	94.5	64.0	30.0
100	63.5	0.9	77.1	96.0	71.0	33.0
Probrand-Caldwell						
0	47.1	0.4	50.3	50.0	10.5	0.5
5	49.0	0.6	63.3	55.5	10.0	4.0
10	49.8	0.5	85.8	50.0	14.5	8.0
20	51.9	0.7	95.1	59.5	21.5	15.0
80	71.0	0.7	103.1	93.0	78.0	63.5
90	72.3	0.8	106.8	94.5	90.0	71.0
95	74.9	0.7	89.6	98.0	94.0	75.0
100	75.8	2.2	73.1	100.0	95.5	78.0
TAM 105-Adena						
0	50.1	0.6	49.0	70.0	13.5	1.5
5	50.9	0.5	69.2	70.0	19.0	5.5
10	52.7	0.2	60.1	75.5	25.5	8.5
20	54.7	0.1	69.5	77.0	32.5	12.0
80	65.4	0.3	77.6	93.0	76.0	43.5
90	67.4	0.0	82.5	96.5	83.5	49.0
95	68.6	0.3	70.0	99.0	84.5	54.5
100	68.7	0.1	79.3	99.0	89.0	52.5

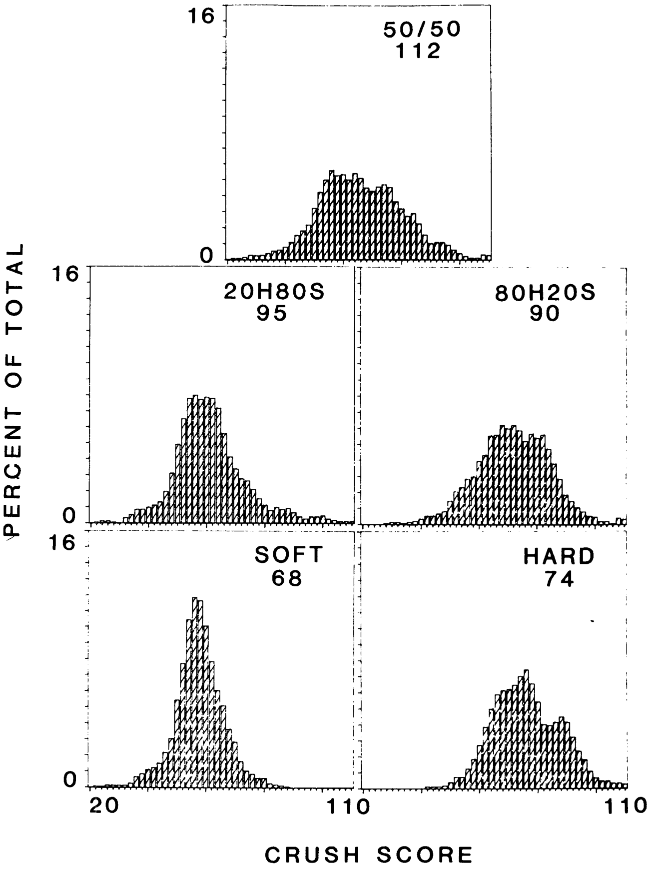

Fig. 13. Histograms of distribution (sorted according to increasing hardness) of crushing scores for 2× 250 kernels, each, of a 50:50 mixture of hard red winter (HRW) and soft red winter (SRW) wheat, a mixture of 20% HRW and 80% SRW wheat, a mixture of 80% HRW and 20% SRW wheat, SRW wheat, and HRW wheat. Figures in top right corner denote heterogeneity factors.

TABLE VII
Determination of Hardness in Double-Blind Blends of Hard Red Winter and Soft Red Winter Wheats

Hard Red Winter Wheat (% in blend)	Hardness Parameters: Single Kernel Hardness Score: Average	Single Kernel Hardness Score: Heterogeneity Factor	NIR[a] Reflectance	Stenvert Hardness Tester (sec)	BMHT[b] (sec)	PSI[c] (%)	Density
100	76.2	73.7	73.4	53.0	29.3	27.7	1.452
99	71.7	81.0	80.2	53.6	29.8	27.6	1.449
98	73.1	89.9	77.6	52.5	30.4	27.0	1.451
97	74.1	75.1	77.8	55.5	29.4	26.6	1.451
96	73.9	83.8	74.9	53.0	30.3	27.3	1.452
95	74.0	72.0	73.1	53.5	30.8	28.1	1.458
90	75.1	80.1	72.8	51.2	31.9	28.9	1.448
80	71.9	89.9	65.8	49.9	32.7	29.7	1.444
70	71.4	91.9	58.8	45.7	35.4	31.5	1.449
60	70.0	101.0	55.6	41.9	37.9	32.6	1.440
50	65.8	120.0	42.5	36.7	46.5	38.6	1.425
40	64.0	94.3	46.0	38.4	47.5	38.1	1.437
30	59.2	87.4	41.7	36.5	54.3	38.9	1.431
20	61.3	94.9	39.1	37.4	62.8	41.0	1.428
10	59.4	101.5	36.7	34.4	61.4	40.6	1.436
5	57.7	74.3	34.7	32.6	70.3	44.0	1.429
4	56.8	72.2	31.3	33.0	62.4	43.1	1.436
3	57.7	78.8	30.3	34.4	67.9	42.1	1.434
2	58.3	81.0	32.2	34.2	69.0	41.7	1.433
1	57.7	61.7	36.2	34.5	71.2	41.9	1.433
0	57.7	67.8	36.7	32.9	69.2	45.1	1.431
50	66.8	118.0	50.1	39.7	41.2	36.4	1.440

[a] Near-infrared.
[b] Brabender microhardness tester.
[c] Particle size index.

TABLE VIII
Significant (0.001 level) Correlation Coefficients Between Percentage of Hard Red Winter (HRW) Wheat in a Blend and Hardness Parameters

Parameter[a]	Av. Single Kernel Score	NIR	SHT	BMHT	PSI	Density
Percentage of HRW wheat in blend	0.98	0.98	0.97	−0.98	−0.98	0.86
Av. kernel score		0.96	0.95	−0.97	−0.97	0.86
NIR reflectance			0.99	−0.94	−0.98	0.90
SHT				−0.93	−0.98	0.92
BMHT					0.97	−0.84
PSI						−0.90

[a] NIR = near-infrared, SHT = Stenvert hardness tester, BMHT = Brabender microhardness tester, PSI = particle size index.

the single-kernel hardness score, SHT, and density values decreased, and BMHT and PSI values increased. The heterogeneity factor for the single-kernel hardness test increased as the percentage of SRW in HRW or HRW in SRW increased (Tables VI and VII).

Histograms and Correlations

Histograms of crushing scores of 2× 250 kernels, each of HRW, SRW, and their blends (50:50, 20:80, and 80:20) are shown in Figure 13. The 50:50 curve is much wider than the 80:20 or 20:80 curves. The 100% HRW curve was much wider than the 100% SRW curve. This indicated larger variability in kernel hardness among HRW than among SRW kernels. The difference may result from any one (or a combination) of three factors: the use of algorithms and mode of calculation of crushing scores, differences related to the instrumental method used to crush the kernels, or real differences in kernel hardness. The use of algorithms and mode of calculation are not likely to present a distorted histogram of crushing scores, as raw data (work) gave similar histograms. In addition, the data in Figures 8 and 9 point to a much wider range in hardness for individual HRW kernels than for SRW wheat kernels. Instrumental effects are probably small but cannot be excluded. Thus, for instance, the crushing method gives erratic results for durum wheats because of the splintering and loss of some vitreous kernel pieces. Those limitations notwithstanding, it is assumed that the differences in the shape of the HRW and SRW histograms in Figure 13 are caused mainly by real differences in hardness of individual kernels of wheats from the two classes.

There were excellent correlations between the percentages of HRW in the mixture and the average single kernel hardness score or bulk hardness tests (Table VIII). These highly significant correlations reflect to a large extent the fact that only two commercial wheats (one HRW and one SRW) were used to prepare blends (Table VII). In practice, commercial lots may contain several varieties from a single class. The range in hardness among those varieties may be greater than the difference between the hardness of some SRW cultivars and the softness of some HRW wheat cultivars. This poses the most challenging problem in discrimination between HRW and SRW wheats, especially in light of some recent crosses between varieties from the two classes, wide heterogeneity and nonuniformity among kernels from certified pure varieties, and narrowing of the average difference in hardness between some SRW and HRW wheats.

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[Received October 6, 1986. Accepted October 15, 1987.]