Measuring Wheat Hardness by Revolutions per Minute Reduction[1]

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ABSTRACT

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Two methods are described for modifying the Udy cyclone grinder for direct assessment of hardness in wheat. The first method was based on the energy developed during grinding, expressed as watts per square meter (W/m^2). The second was based on the reduction in revolutions per minute (rpm) incurred by grinding samples of wheat of different hardness. The rpm reduction (Δrpm) method was superior and represents a fast (20-sec) method for screening wheats on the basis of hardness. The Δrpm data were highly correlated to flour properties classically associated with hardness, such as starch damage, gassing power, and water absorption. Kernel size had a small effect in reducing Δrpm. Moisture content had a significant effect, and all types of wheat tested showed an increase in Δrpm (apparent increase in hardness) as the moisture content increased. This phenomenon was also apparent in the standard particle size index grinding-sieving test, wherein the influence of moisture was generally lower but different types of wheats showed marked differences in their reaction to increasing moisture content.

Hardness in wheat is strongly and simply controlled by genetics and can easily be transferred into or from a genotype (Symes 1965, 1969). A method for expressing hardness numerically was first described by Cobb (1897) and subsequently by many workers including Jelinek (1929), Cutler and Brinson (1935), Kramer and Albrecht (1948), Kosmolak (1978), Chung and co-workers (1977), Miller and co-workers (1982), Sauer (1978), Williams and Sobering (1986), and Wetzel (1984), all of whom introduced different approaches. Methods for measuring hardness include measurement of the weight required to crush the kernels (Cobb, Jelinek, and others), resistance to pearling (Kramer and Albrecht, Beard and Poehlman 1954, Chung and co-workers, and others), granulation by grinding and sieving (Cutler and Brinson, Symes 1961, and others), time taken to grind a set weight of grain (Kosmolak), energy required to grind a set weight of wheat (Miller and co-workers, and others), and most recently, near-infrared analysis (Saurer 1978, Williams 1979, Wetzel 1984). Meppelink (1974), Simmonds (1974), and more recently Yamazaki and Donelson (1983) have compiled reviews of the subject of wheat kernel hardness and its measurement. Grinding is in most cases an essential prerequisite to analysis of wheat, and a hardness measurement incorporated into the grinding process itself would be a logical choice of methods. The grinding-time test introduced by Kosmolak (1978) and the methods of Chung and co-workers (1977) and Miller and co-workers (1982) represent attempts to achieve this objective. Both of these groups recorded the energy involved in grinding grain.

The Udy cyclone impeller mill has become widely adopted for sample preparation in North America in connection with near-infrared analysis of cereal grains. The present study illustrates two methods for the adaptation of a Udy grinder to assess directly the hardness of wheat.

MATERIALS AND METHODS

Recording Grinding Energy as Torque

A cyclone sample mill (Udy Analyzer Co., Boulder, CO) was modified by replacing the existing 0.5-hp motor with a 1.0-hp motor. The heavier motor provided excess power and increased rotational inertia, which minimized speed variations incurred by the grinding process. To eliminate slippage in the V-belt drive system, all belts and pulleys were replaced with notched timing belt components. Impeller speed was monitored by an electromagnetic sensor connected to a frequency counter. This showed that during operation of the modified mill, impeller speed was 12,770 rpm, and the maximum speed reduction observed during grinding was about 1%. The motor and grinding head were mounted in a floor stand (Fig. 1).

A torque transducer, D in Figure 2, (model 1102-1K, Lebow Associates Inc., Troy, MI) was placed in the belt-drive system between the motor and impeller to detect the impeller torque generated during the grinding operation (Voisey 1971). The transducer was connected via an amplifier to an electronic digital

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integrator to record the grinding energy. This recording system was calibrated by attaching a pulley (Fig. 1; P, Fig. 2), impeller shaft (E), and applying a selected force at a known radius using a cord (O), and weight (M). By integration for a selected time, the integrator readings were then converted to energy based on the rotation speed of the impeller (Voisey 1971). A strip-chart recorder connected in parallel with the integrator also gave a record of torque versus time and permitted observation of the effect of seed feed rate.

Seeds were fed into the grinder by a vibrating tray (G, Fig. 2), where the vibration amplitude was adjusted to control feed rate. Preliminary trials indicated that 25 g of seed would pass through the grinder in less than 40 sec.

In operation, the recording system was first calibrated by applying the weight and adjusting the zero and sensitivity of the amplifier so that the integrator and recorder read in rational units. The calibration pulley was removed and the grinder cover replaced (Fig. 1). The motor was then switched on and the zero setting readjusted to compensate for inertia and wind resistance. Preliminary tests using a high-frequency recorder showed that the maximum torque required to overcome the impeller inertia and accelerate it to speed was half the 6 newtons/meter (N/m) capacity of the transducer, so it was considered that the frequent starting torques could not damage the transducer. The full-scale torque found suitable for recording the test data was 0.25 N/m. The weighed sample was fed into the grinder by the vibrator, and the total energy used in 40 sec was recorded.

Recording Reduction in Revolutions per Minute (rpm)

Results of testing wheat samples with a wide range of hardness based on the particle size index (PSI) method showed that fluctuations in rpm of the torque-recording grinder were slightly more closely related to the PSI data than were the energy or torque values. Consequently, a second Udy grinder was modified by replacing the original motor and belt drive with a 0.5-hp direct-drive motor. Grinding wheat with a direct-drive grinder has the

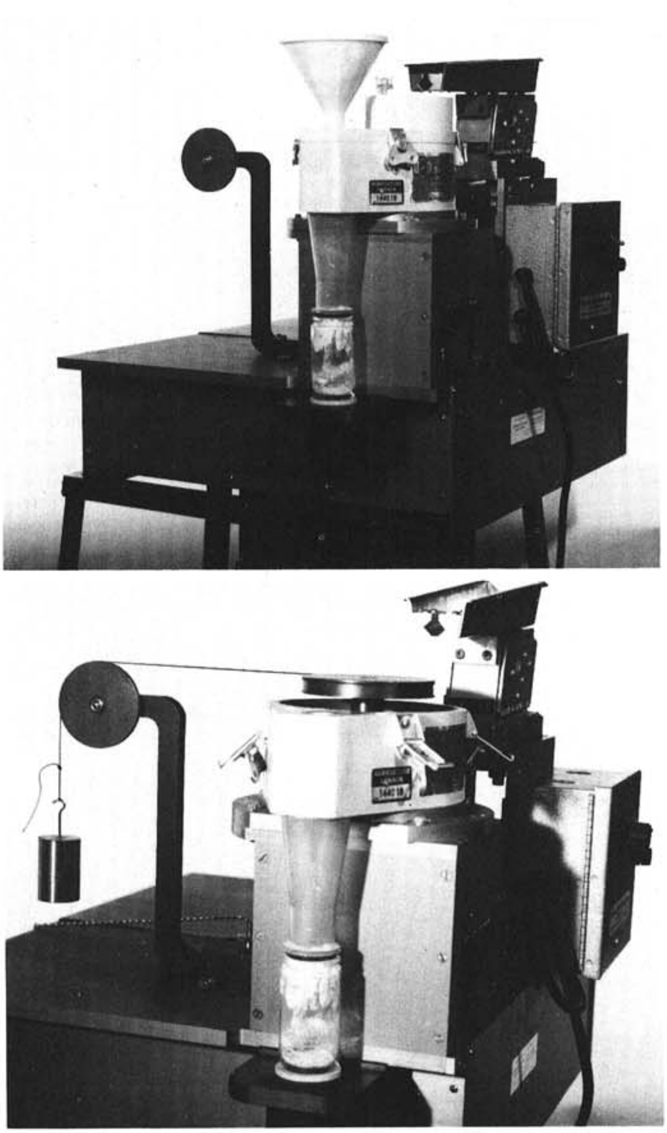

Fig. 1. Top, The original torque-recording grinder. **Bottom,** The torque-recording grinder set up for calibration.

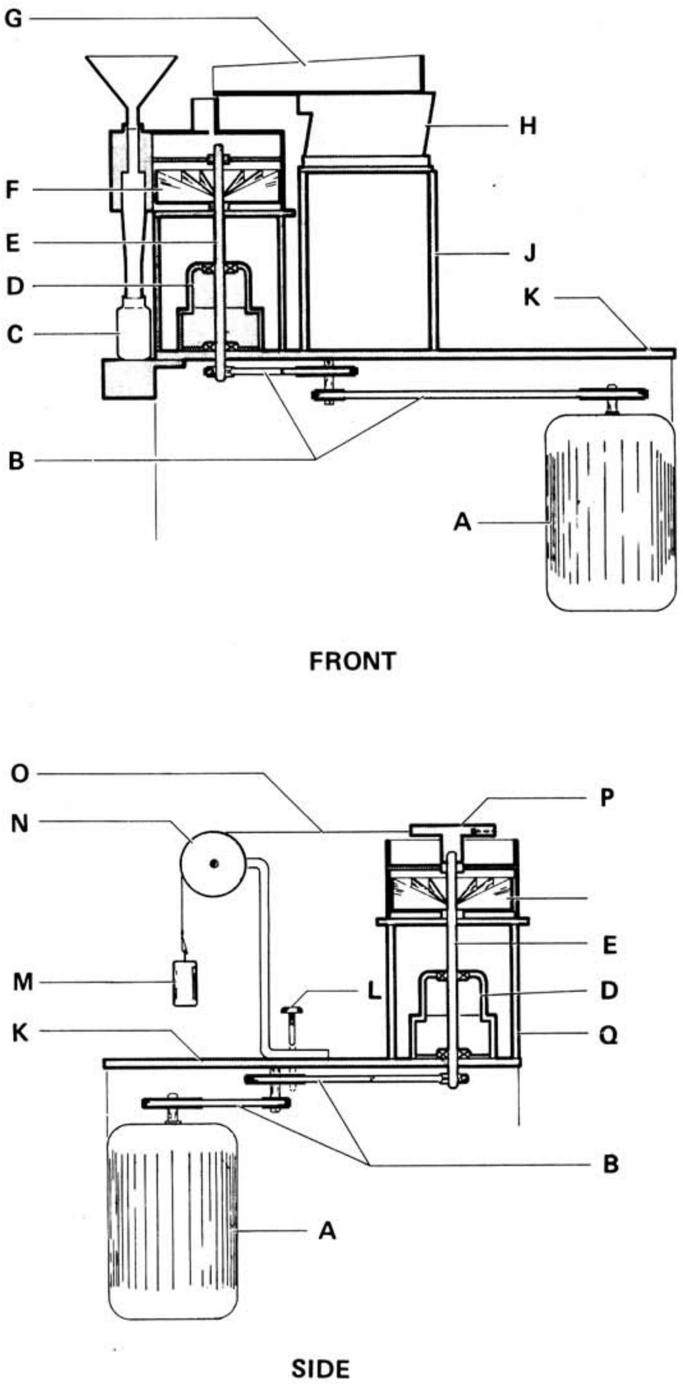

Fig. 2. Torque-recording grinder schematic. **A,** motor; **B,** v-belt drives; **C,** sample jar; **D,** torque transducer; **E,** impeller shaft; **F,** impeller; **G,** vibrating feeder; **H,** vibrating feeder drive; **J,** vibrating feeder support; **K,** base plate; **L,** removable screw for attaching secondary calibration pulley; **M,** calibration weight; **N,** secondary calibration pulley; **O,** string for calibration; **P,** primary calibration pulley; **Q,** grinder casing.

effect of maximizing sensitivity to work input, with the result that differences in the rpm reduction on grinding wheats of different hardness are maximized. The torque transducer was replaced by an rpm counter, which was interfaced to a minimum rpm recording device. An rpm reading was taken every half second. When the grinder was energized, rpm was continuously recorded. Grain was added at maximum rate via the vibrating feeding device. As the grain was added, rpm fell rapidly to a minimum, then rose to the original level. The meter retained the lowest rpm reached until the motor was switched off, or the meter reset. The operator recorded the starting rpm, which was stable after the grinder had been operating for a few seconds. No other "calibration" was needed. The minimum rpm was also recorded, and the difference between minimum and starting rpm, called the delta rpm, or Δrpm, was directly related to the hardness of the grain. The modified version is illustrated in Figure 3 and the circuitry in Figure 4. The grinder was noisy and housed in a sound cabinet for routine operation.

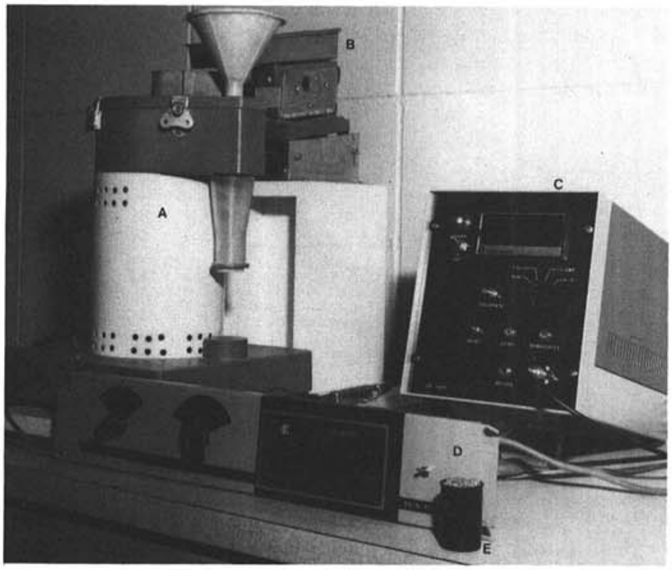

Fig. 3. The rpm reduction grinder. **A,** grinder; **B,** vibrating grain feeder; **C,** minimum rpm detector; **D,** rpm counter; **E,** sampling cup.

Determination of hardness by the PSI system was made by grinding the wheat in a Falling Number KT30 burr mill set at its finest setting and fitted with no. 2 "fine" burrs. PSI was also determined after grinding on a Udy cyclone grinder (1.0-mm screen). Duplicate 10-g samples were sieved for 10 min over a U.S. standard no. 200 mesh (74 μm) sieve using a Ro-tap sieve shaker. The weight of throughs, multiplied by 10, was recorded as the PSI. About 50 g of whole wheat kernels was added with the wholemeal to the sieve to minimize blocking of the sieve. Moisture was determined by AACC methods 44-15A and 44-19 (AACC 1983), respectively, the two-stage and single-stage air-oven methods. Grinding time was determined using a Brabender Schrot mill, as proposed by Kosmolak (1978). Wheats were milled into flour using the Grain Research Laboratory (GRL) Allis-Chalmers mill (Black et al 1980). Flour starch damage was determined by the Farrand method (1964), gassing power by AACC method 22-11 (AACC 1983), and water absorption by means of a Brabender Farinograph, using a 50-g bowl and the constant flour weight method.

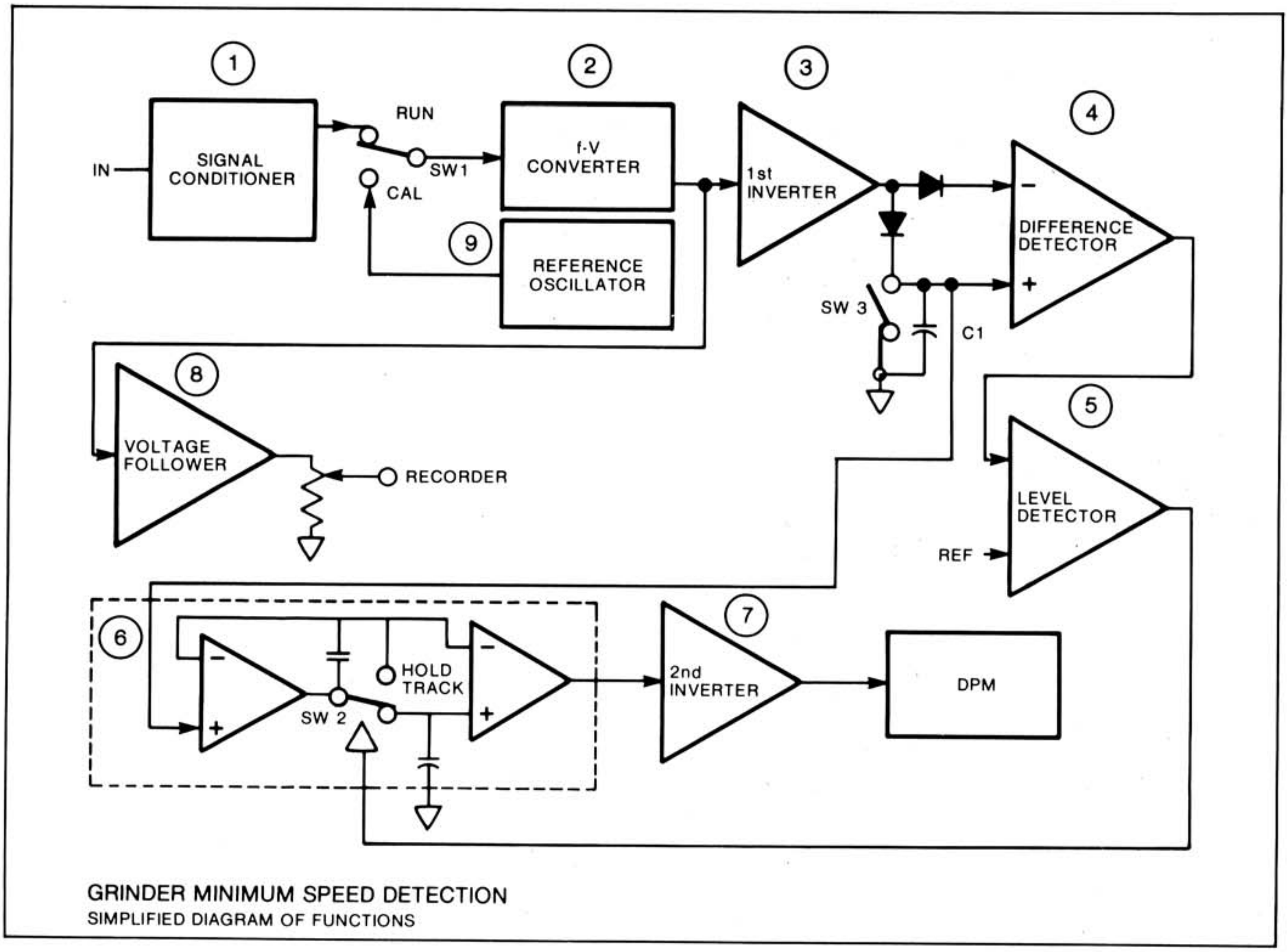

Fig. 4. Circuitry for rpm reduction grinder.

RESULTS

Measurement of Hardness by Torque Development

Using the original equipment, preliminary tests were conducted at the Engineering and Statistics Research Institute, Ottawa, with six wheat varieties and one rye variety. These samples had been in storage for 18 months and were at a similar moisture content. Ten subsamples of each variety were tested.

Torque built up rapidly as the impeller became loaded with seed. Overall, the torque-time curves reached a maximum and then decayed as the seed remaining in the impeller was ground and discharged. However, there were large and small torque fluctuations within the overall bell shape, caused by the random arrival of the seed at the impeller. The results (Table I) indicated that the total energy readings were more reliable than those of maximum torque. This reflected the random effects of the quantity of seed being ground at the time of maximum torque compared to the unformity of the integrated total value (energy) required to grind the whole sample. Maximum torque readings were therefore discarded as a hardness index. Energy readings within varieties were remarkably consistent, having a maximum coefficient of variation of less than 5%. The mean energy values ranked the varieties in order, placing the hardest (durum) at the highest level of hardness.

The precision (reproducibility) of both tests was determined simultaneously on the same sample of hard red spring (HRS) wheat, which was tested every 15 min. The energy values, representing the power consumed while grinding the same weight (20 g) of sample, fell from an initial high level early in each day to a level as low as 48% of the highest value, recorded for the first test of the day. The trend for the Δrpm tests recorded simultaneously was in the same direction, but the difference between the highest and lowest Δrpm values was only 10.5% of the highest value. The respective precision figures are given in Table II. The Δrpm values were nearly three times as precise as the torque (N/m) values.

The temperature of ground grain usually rises to a maximum after grinding about 20 samples (Williams et al 1982). Thereafter, the small time intervals between testing individual samples serve to stabilize the temperature of the grinder. In this study, there was no evidence that variance in rpm reduction was related to temperature fluctuations. Precision of the starting rpm was excellent.

Further tests were carried out on the original equipment at the GRL using 50 samples of North American wheat in which the PSI varied from 6.6 (extra hard, durum type) to 34.0 (very soft). The results are summarized in Table III. The higher correlation of Δrpm to PSI was considered to have originated in the superior precision of Δrpm relative to N/m. In view of the results of these preliminary studies, work with the torque-recording grinder was discontinued and all further studies were devoted to developing and evaluating an rpm reduction grinder.

Measurement of Hardness by rpm Reduction

The same 50 samples of wheat were tested for hardness by the rpm reduction grinder. The precision was tested by grinding check samples of durum, HRS, and soft white spring (SWS) wheats. Table IV illustrates both the principle and the precision of Δrpm hardness testing.

The Δrpm test was more precise than the PSI test itself. To test the relationship between the Δrpm method of hardness and flour parameters, 67 wheats consisting of U.S., Canadian, Australian, European, Middle Eastern, and Latin American varieties were milled into flour using the GRL Allis-Chalmers mill. All eight types of common wheat were included and also some durum wheats. The results are summarized in Table V, and include for comparison data for PSI determined after grinding on either the cyclone or KT-30 grinders, and grinding time determined as described by Kosmolak (1978).

Hardness expressed as Δrpm was highly correlated to flour starch damage, gassing power (which is affected by both starch damage and the inherent α-amylase activity of the flour), and water absorption. The respective coefficients of correlation were higher than the corresponding statistics obtained by measuring hardness by grinding time and comparable to PSI statistics. Table VI presents the coefficients of correlation between the four hardness measurements and the flour parameters.

Variables Affecting Δrpm Hardness Measurement

Variables studied included a comparison of testing Δrpm by

TABLE I
Grain Hardness Tests:
Samples Ranked According to Total Energy Absorbed

	Total Energy Absorbed (W/m^2)[a]		Maximum Torque (N/m)[b]	
Sample[c]	Mean[d]	C.V.%	Mean	C.V.%
USDA (A)	2,194	2.2	0.093	15.6
Frederick	2,432	4.3	0.100	15.5
Puma Rye	2,521	2.4	0.108	7.0
USDA (B)	2,586	4.4	0.095	10.2
Guelph S.W.	2,728	4.7	0.107	12.6
Glenlea	2,996	2.4	0.113	10.9
Durum	3,441	2.7	0.158	4.8

[a] Total energy absorbed during 40 sec of grinding in watts per square meter (W/m^2). (Maximum change of speed during grinding was 1%. Mean speed was 12,700.)

[b] Newtons/meter.

[c] USDA (A) and USDA (B) were two different samples supplied by the USDA; Guelph S.W. was a sample of medium hard wheat supplied by the University of Guelph.

[d] Mean of 10 reps.

TABLE II
Relative Precision of Energy (W/m^2)
and Δrpm Test Parameters and Particle Size Index (PSI)[a]

Statistic	W/m^2	Δrpm	Starting rpm[b]	PSI
Mean	409,599	473	12,768	15.9
Standard deviation	67,360	28	22	0.54
C.V.	16.4	5.9	0.2	3.4
n	27	27	27	27

[a] PSI after grinding in KT-30 burr mill.

[b] Starting rpm of grinder before carrying out each test.

TABLE III
Relationship Between Energy (W/m^2), Δrpm, and Particle Size Index (PSI)

Parameter	A W/m^2	B Δrpm	C PSI[a]
Mean	447,138	468	20.4
C.V.[b]	15.2	20.6	52.5
High	605,279	738	34.0
Low	288,266	327	6.6
Comparison	A:C	B:C	A:B
r^2	0.54	0.67	0.56

[a] PSI after grinding in KT-30 burr mill.

[b] Coefficient of variation.

TABLE IV
Relative Precision of Δrpm Parameters
and Particle Size Index (PSI[a]) ($n = 24$)

	Initial rpm		Final rpm		Δrpm $\times 10^{-2}$		PSI	
Wheat type	Mean	C.V.[b]	Mean	C.V.	Mean	C.V.	Mean	C.V.
Durum	15,289	0.7	9,280	1.3	60.1[c]	2.0	7.4	3.8
HRS[d]	15,203	0.8	9,559	1.2	56.4	0.9	15.7	3.2
SWS	15,219	0.6	10,808	1.1	44.1	1.7	27.6	4.2

[a] PSI after grinding in KT-30 burr mill.

[b] Coefficient of variation.

[c] True Δrpm = 15,289 − 9,280 = 6,009; results are multiplied by 10^{-2} to simplify reporting and statistical analysis.

[d] HRS = hard red spring. SWS = soft white spring wheats.

TABLE V
Interrelationships Between Wheat Hardness and Flour Parameters ($n = 67$)

	PSI[a] KT30	PSI Cyclone	Grinding Time	Δrpm	Starch Damage	Gassing Power
PSI cyclone	0.94	...				
Grinding time	0.79	0.69	...			
Δrpm	−0.86	−0.89	−0.71	...		
Starch damage	−0.86	−0.95	−0.60	0.84	...	
Gassing power	−0.73	−0.76	−0.62	0.79	0.80	...
Water absorption	−0.84	−0.90	−0.61	0.79	0.92	0.70

[a] Particle size index after grinding in KT-30 burr mill.

TABLE VI
Coefficients of Correlation Between Wheat Hardness Test Methods and Flour Parameters[a]

		Correlation Coefficient (r)		
Hardness Test Method	Mean r	Starch Damage	Gassing Power	Water Absorption[b]
PSI KT-30	−0.81	−0.86	−0.73	−0.84
PSI cyclone	−0.87	−0.95	−0.76	−0.90
Grinding time	−0.61	−0.60	−0.62	−0.61
Δrpm	−0.81	−0.84	−0.79	−0.79

[a] PSI = Particle size index.
[b] Farinograph.

TABLE VII
Seed Size (1,000-kernel weights) of Large, Medium, and Small Kernels of Three Wheats, Separated by Sieving

	Sieve Size		
Type[a]	Over 10/64 in. (4 mm)	10–7/64 in.	Through 7/64 in. (2.8 mm)
HRS	36.6	28.9	19.3
Durum	51.9	39.2	25.4
SWS	45.4	33.3	21.5

[a] HRS = Hard red spring; SWS = soft white spring.

constant volume and constant weight, sample size, kernel size, and moisture content.

Influence of kernel size (weight/1,000 kernels). Three samples each of HRS, SWS, and durum wheats were separated into large, medium, and small kernel size ranges by sieving through 10/64-in. (4-mm) and 7/64-in. (2.8-mm) sieves. The mean kernel sizes are given in Table VII.

Each sample was ground in duplicate. The first series was ground on the basis of constant weight of 20 g. The second series was ground on the basis of a constant volume of grain. A small container holding 23 ± 0.2 ml was used for the constant volume study. The use of a constant volume would be preferable to constant weight, because no balance would be necessary, and the additional operation of weighing would be eliminated. The results are summarized in Table VIII.

There was a small but statistically significant effect of kernel size on Δrpm as measured by both constant weight or constant volume methods. The smallest kernels, which were approximately one half the size of the largest kernels, were associated with an average reduction of less than 2% in rpm reduction, and for all practical purposes, kernel size may not be considered an important factor in hardness measurement by rpm reduction.

Influence of Δrpm hardness testing by constant weight or constant volume. This was evaluated by determining the reproducibility of Δrpm measurement by the two methods. The Δrpm of a sample of HRS wheat was determined 21 times during a day. Reproducibility of Δrpm by the constant weight method was 0.68 (C.V. 1.2%), whereas reproducibility by the constant volume method was 1.05 (C.V. 1.8%). Accordingly, although the constant weight method involves slightly more time per test (due to weighing), all further studies, including the accumulation of the data in Table V, were carried out by the constant weight method.

Influence of sample size. When different weights of wheat were ground, the Δrpm values increased directly with the sample weight, up to 35 g, which is the maximum weight of ground wheat that will fit into the sample collecting jar of the grinder. Results are illustrated in Table IX.

The coefficient of variation increased from 13.8% for a 5-g sample to 16.7% at 35 g. On the basis of these data, the degree of differentiation was not so clear at low sample weights. The coefficient of variation was 16.4% for a sample size of 20 g, which was used in subsequent studies. A smaller sample weight could be used if necessary, for example, in a breeding program.

Influence of moisture content. Moisture content at the time of grinding is a very critical aspect of hardness measurement. Yamazaki and Donelson (1983) showed that the slopes of moisture content on hardness measured by the particle size index (PSI) method differed between wheat types. The influence of moisture on hardness measurement by Δrpm was studied using durum, HRS, and SWS wheats. A range of moisture contents (determined by the two-stage air-oven method) from less than 6 to over 19% was achieved by tempering or gentle drying with warm (30° C) air (Williams and Thompson 1978). The samples were allowed to stand for four days after moisture content adjustment before testing for moisture by the two-stage air-oven method. Each sample was then ground in duplicate on the Δrpm grinder and the KT-30 burr mill for hardness measurement, respectively, by Δrpm or PSI. Table X illustrates the influence of moisture on the hardness of wheat as measured by PSI or Δrpm. Two features are apparent from the table: 1) that all three wheat types apparently became harder at higher moisture contents when hardness was measured by Δrpm, but only very hard, durum types became harder as moisture content rose when tested by PSI. The other two wheat types became softer at higher moisture contents. 2) The Δrpm test was much more sensitive to moisture than the PSI test. Wheat is normally tested for hardness at moisture levels ranging from 10 to 13%, regarded as "normal" levels of moisture at which the wheat is received. The 15–16% moisture range is theoretically more critical, because this is the level at which the wheat is to be milled. Hardness tests are carried out at the lower moisture levels to indicate the optimum moisture level for tempering in preparation for milling. In practice, all correlations reported between various hardness tests and flour parameters such as starch damage and water absorption involved hardness tests performed at the lower 10–13% moisture range, but these data were correlated to flours milled at optimum (15–16.5%) moisture levels for the respective wheats, so that the correlation data between hardness and flour parameters remain valid.

CONCLUSION

In summary, a direct grinding method has been developed for determination of the hardness of wheat. The method is very rapid and precise, capable of differentiating clearly between wheats of different hardness, and is considered suitable for use in wheat-breeding programs. Data based on the reduction in rpm were more useful than those based on total energy required for grinding. The results were influenced to a minor degree by kernel size but to a more significant degree by moisture content. The slopes of the influence of initial moisture content on the hardness results changed at about 11% moisture by both PSI and Δrpm methods.

TABLE VIII
Influence of Grain Size (Kernel Weight) on Δrpm Using Constant Weight or Constant Volume

Sieve size	Constant Weight				Constant Volume			
	HRS[a]	Durum	SWS[b]	Overall	HRS	Durum	SWS	Overall
Over 10/64 in.	57.6[c]	63.1	45.1	55.3	55.5	60.5	43.5	53.2
10–7/64 in.	57.1	63.3	46.3	55.6	55.2	61.1	44.6	53.6
Through 7/64 in.	55.7	62.6	44.6	54.3	53.3	61.2	43.4	52.6

[a] Hard red spring.
[b] Soft white spring.
[c] Δrpm × 10^{-2}.

TABLE IX
Effect of Sample Size on Δrpm

Sample Weight (g)	Δrpm × 10^{-2}		
	Durum	HRS[a]	SWS[b]
5	47.9	43.6	36.3
10	51.2	47.7	38.9
15	55.4	50.9	40.6
20	60.6	56.1	43.7
25	63.2	57.0	45.3
30	65.3	58.6	46.7
35	68.8	61.1	49.0

[a] Hard red spring.
[b] Soft white spring.

TABLE X
Influence of Moisture Content on Particle Size Index (PSI) and Δrpm

PSI Range (%)	PSI			Δrpm		
	Durum	HRS[a]	SWS[b]	Durum	HRS	SWS
Moisture						
7	9.1	15.9	23.1	49.2	44.9	38.8
9	8.7	16.2	23.5	52.8	46.9	41.1
11	8.3	16.5	24.0	56.5	48.9	43.5
13	7.9	16.9	24.4	60.1	50.9	45.8
15	7.5	17.2	24.8	63.8	53.0	48.1
17	7.1	17.5	25.3	67.4	55.0	50.4
Overall change	−22.0	10.1	9.5	37.0	22.5	30.0

[a] Hard red spring.
[b] Soft white spring.

Durum wheats appeared to become progressively harder at higher moisture levels when tested by either method. Other wheats tested became progressively softer at higher moisture levels when tested by the PSI method but appeared to become progressively harder at higher moisture levels when tested by the Δrpm method. Durum wheats in this study were the most sensitive to moisture level, whether tested by PSI or Δrpm methods. It is essential that the initial moisture content of the wheat be considered when data are reported for wheat hardness, no matter what method is used for hardness determination.

LITERATURE CITED

AMERICAN ASSOCIATION OF CEREAL CHEMISTS. 1983. Approved Methods of the AACC. Method 22-11, approved April 1961; Method 44-15A, approved October 1975; and Method 44-19, revised October 1975. The Association: St. Paul, MN.

BEARD, B. H., and POEHLMAN, J. M. 1954. A study of quality as measured by the pearling test, in crosses between hard and soft wheats. Agron. J. 46:220.

BLACK, H. C., HSIEH, F.-H., TIPPLES, K. H., and IRVINE, G. N. 1980. The GRL sifter for laboratory flour-milling. Cereal Foods World 25:757.

CHUNG, C.-J., CLARK, S. J., LINDHOLM, C., McGINTY, R. J., and WATSON, C. A. 1977. The Pearlograph technique for measuring wheat hardness. Trans. ASAE 18:185.

COBB, N. A. 1897. The hardness of the grain in the principal varieties of wheat. Agric. Gaz. N.S.W. 7:279.

CUTLER, G. H., and BRINSON, G. A. 1935. The granulation of wholemeal and a method of expressing it numerically. Cereal Chem. 12:120.

FARRAND, E. A. 1964. Flour properties in relation to the modern bread processes in the United Kingdom, with special reference to alpha-amylase and starch damage. Cereal Chem. 41:98.

JELINEK, J. 1929. Apparatus for the determination of the hardness of the kernel. Proc. Int. Congr. Bread Wheat Flour, 1st, Prague.

KOSMOLAK, F. G. 1978. Grinding time—A screening test for kernel hardness in wheat. Can. J. Plant Sci. 58:415.

KRAMER, H. H., and ALBRECHT, H. R. 1948. The adaptation to small samples of the pearling test for kernel hardness in wheat. Cereal Chem. 20:422.

MEPPELINK, E. K. 1974. Untersuchungen uber die Methodik der Kornhartbestimmung bei Weizen. Getreide Mehl Brot. 28:142.

MILLER, B. S., AFEWORK, S., POMERANZ, Y., BRUINSMA, B. L., and BOOTH, G. D. 1982. Measuring hardness in wheat. Cereal Foods World 27:61.

SAURER, W. 1978. Verwendung von Infrarot-Refleximsmessung cfor die Bestimmung von Protein und Wassergehalt sowie der Komhart in Weizen. Getreide Mehl Brot 32:272.

SIMMONDS, D. H. 1974. Chemical basis of hardness and vitreousity in the wheat kernel. Bakers Dig. 48(5):16.

SYMES, K. J. 1961. Classification of Australian wheat varieties based on the granularity of their wholemeal. Aust. J. Exp. Agric. Amin. Husb. 1:18.

SYMES, K. J. 1965. The inheritance of grain hardness in wheat as measured by the particle size index. Aust. J. Agric. Res. 16:113.

SYMES, K. J. 1969. Influence of a gene causing hardness on milling and baking quality of two wheats. Ibid 20:971.

VOISEY, P. W. 1971. Modernization of texture instrumentation. J. Texture Stud. 2:129.

WETZEL, D. L. 1984. Physical sample characterization by granulation sorting from diffuse reflectance constants in the near-infrared. Proc. Int. Users Conf. NIR Researchers, 3rd. Pacific Scientific: Rockville, MD.

WILLIAMS, P. C. 1979. Screening wheat for protein and hardness by near-infrared reflectance spectroscopy. Cereal Chem., 56:169.

WILLIAMS, P. C., and SOBERING, D. C. 1986. Attempts at standarization of hardness testing of wheat. II. The near-infrared reflectance method. Cereal Foods World 31:417.

WILLIAMS, P. C., and THOMPSON, B. N. 1978. Influence of wholemeal granularity on analysis of HRS wheat for protein and moisture by near-infrared reflectance spectroscopy. Cereal Chem. 55:1014.

WILLIAMS, P. C., NORRIS, K. H., and ZAROWSKI, W. S. 1982. Influence of temperature on estimation of protein and moisture in wheat by near-infrared reflectance. Cereal Chem. 59:473.

YAMAZAKI, W. T., and DONELSON, J. R. 1983. Kernel hardness of some U.S. wheats. Cereal Chem. 60:344.

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