DEVELOPMENT OF A SINGLE-KERNEL WHEAT CHARACTERIZATION SYSTEM

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Development of a Single-kernel Wheat Characterization System

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Abstract. *A single-kernel wheat crushing device was developed to determine crush force, moisture, and size characteristics at a rate of approximately 180 kernels/min. A procedure for determining hardness of single kernels was developed with corrections for the effects of kernel moisture and size on the crush force profile. Single-kernel moisture measurement comparisons with bulk oven moisture measurements were satisfactory. Average kernel size measurements were highly correlated with average kernel weight, although a random machine interaction with single kernel size measurement was noted. Six prototypes of the rotor-crescent system were assembled for further evaluation. Tests to determine the system's potential for wheat classification and inclusion in the official grain inspection process are under way.* ***Keywords.** Hardness, Moisture, Size, Classification.*

Single-kernel hardness measurements may be obtained from force-deformation curves created by crushing a wheat kernel between two surfaces that move closer together over time. Force can be represented by a voltage signal, while kernel deformation is represented by time. Characteristics of the force-deformation curve that are representative of hardness include slope values or force change as a result of a specific change in kernel deformation (time), specific peak force values that occur at intervals during deformation, and areas under the curve between specific deformation values. Single-kernel hardness studies at the U.S. Grain Marketing Research Laboratory (Lai et al., 1985) showed that ratios of front slope to back slope about the first peak were good indicators of hardness. In single-kernel compression instrument measurements (Pomeranz et al., 1988), two hardness parameters were used. One was based on a first peak force, the other on a specific area determination from a summation of the absolute slope values over a specified time interval. In the first version of a rotor-crescent device (Martin et al., 1987), the slope values were shown to be better indicators of hardness than peak values.

A prototype rotor-crescent crushing device (fig. 1) was fabricated to determine hardness and other characteristics of single wheat kernels. The determinations include crush forces, moisture, and size characteristics at a rate of approximately 180 kernels/min. Single wheat kernels were crushed as they passed through a wedge-shaped cavity between a smooth crescent surface and a coarse-toothed rotor. The crescent was a lever supported by a load cell that measured a force vector from the crushing action. The rotor was electrically insulated so that conductivity data could be obtained during kernel contact between the rotor and crescent. The conductivity data were used to determine kernel moisture. Kernel size was measured using the time that a kernel exerts force on the crescent. Data acquisition was automatic and controlled by computer software that responded to the force and conductance data from an analog to digital (A/D) converter. The software collected data from a prescribed number of kernels, processed the data, and stored machine summary parameters for each kernel. The single-kernel summary parameters required further processing for conversion to hardness, moisture, and size characteristics. Sample throughput time ranged between 2.0 and 2.5 min for a 300-kernel sample (about 10 g).

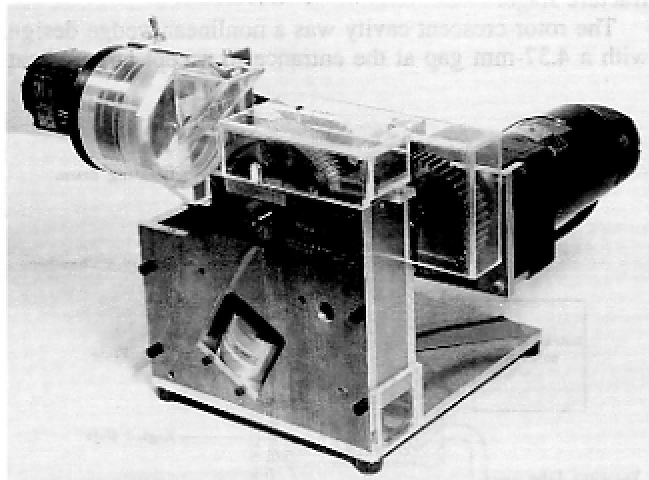

Figure 1–Rapid single-kernel crushing device with single-kernel feeder.

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Objective

The objective of this article is to describe a single-kernel wheat characterization system developed for use in a national wheat hardness study. The prototype components, measurements, and procedures used to calibrate the system to determine single-kernel wheat hardness are described.

Design Description

Single-kernel Feeder

A precision kernel feeder (fig. 2) was designed to deliver individual kernels from a bulk sample contained in a rotating horizontal drum (8.5 cm in diameter × 5 cm long at 30 rpm). Individual kernels were oriented and conveyed toward a face plate as they moved and tumbled in and along a spiral groove inside the drum. A U-shaped groove intercepted a kernel by holding it in the groove with vacuum from one of six small pickup holes in the bottom of the groove. The intercepted kernel was elevated by the drum while other kernels fell or slipped downward inside the drum. The face plate had an intercepting groove inside the drum which formed an enclosed chamber. The elevated kernel was carried into the chamber where it was dropped by vacuum release with a consistent lengthwise orientation. The falling kernel was guided by the chamber into an angled hole that led into the rotor-crescent cavity.

Crushing Device

A brass rotor with a coarse-toothed surface (fig. 3) was driven by a 186-W direct-current gear motor equipped with an electronic speed controller. The stainless steel crescent was supported by a linear variable differential transformer load cell (Daytronic 152A-100, 100-lb rated load range) connected to an electronic excitation and signal conditioner (Schaevitz, LPM-210). The calibration setting for the load cell was 108.3 N per volt, which translates to an A/D converter (12 bit, 10 v F.S.) output of 0.2644 N per A/D count.

The crescent was a lever design with a 2:1 mechanical advantage between the point of most frequent kernel contact and the point of kernel exit. This crescent design mechanically amplified initial contact force to enhance signal detection and increase sensitivity at the initial fracture stage.

The rotor-crescent cavity was a nonlinear wedge design with a 4.37-mm gap at the entrance to accept large wheat kernels. The gap decreased through a 93° crescent arc to 0.508-mm tooth tip to crescent at the exit. With the rotor operating at 120 rpm, kernels were deformed at an approximate rate of 30 mm/s, nearly the same as used in a previous single-kernel hardness study (Pomeranz et al., 1988).

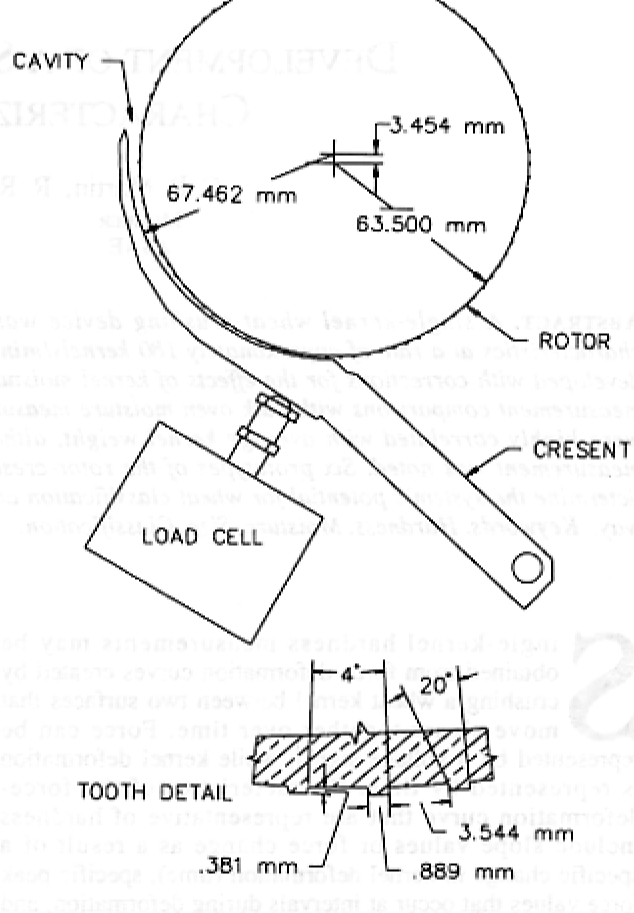

Figure 3–Schematic of the crushing device.

The by-products generated during kernel crushing, heat from friction on the crescent and dust from crushed kernels, were controlled by air movement. A fan (60 cfm) was used to cool the crescent and also control air-borne dust particles.

Data Acquisition

A multifunction high-speed A/D I/O expansion board (MetraByte Dash-16) mounted in an expansion slot of an IBM PC/AT-compatible personal computer (286, 12 MHz) was used for data acquisition. The data acquisition cycle began with the A/D system monitoring the force signal to detect kernel entry. Upon kernel detection, the system initiated rapid acquisition of conductance and force data at 0.25-ms intervals and stored the data in computer memory. Data acquisition continued for 125 ms with actual crushing time ranging between 50 and 100 ms. At a kernel throughput rate of three per second, 208 ms of CPU time was available for data processing, storing, and initializing of the system for the next kernel.

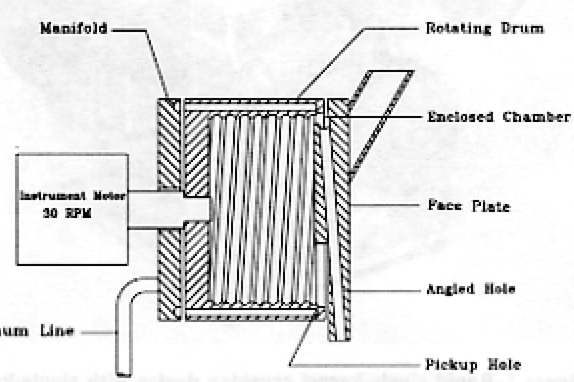

Figure 2–Schematic of the single-kernel feeder.

Machine Data Summary Parameters

The single-kernel crushing system generated approximately 1,000 conductance and force measurements for each kernel processed. Storing all machine data points for each kernel was incompatible with the initial PC computer capacities. Consequently, a method for condensing individual kernel measurements to a small number of summary parameters was developed. An initial data set (300 kernels each variety) was collected using samples of soft and hard wheat varieties at about 12.5% moisture content. Crush force slope values (DY), measured in A/D counts across each 0.25-ms time interval, were determined from the A/D data representing the force-time profile. A frequency distribution of the DY values was made to determine the relationship between sample hardness and the measured DY values. The machine data summary parameters (table 1) were selected after the analysis of the initial data set.

Moisture

The force and conductance measurements (fig. 4) were used to determine the moisture of a single wheat kernel. A regulated –90 V D.C. source (Analog Modules, model 521, Longwood, FL) was connected to the rotor through a 1-MΩ resistor. Conductance ranged between 0.002 and 2.0 µS for single kernel moisture between 10 and 17% w.b., respectively. The conductance signal was coupled through a 0.05-µF capacitor to a log ratio amplifier which provided an output signal proportional to log (conductance) - log (force) or log (conductance/force). The output signal, 1.5 to 8.5 V, was connected to the A/D converter.

A moisture calibration was obtained using three varieties each of hard red spring (HRS), hard red winter (HRW), and soft red winter (SRW) wheats at five different moisture levels in the range between 10 and 17% w.b. Moisture determinations for all wheats at each moisture level were made by the oven method for ground wheat using a Wiley mill and a No. 20 mesh screen. Moisture calibration data were also used to determine the effect of moisture on hardness parameters and to establish moisture correction constants. Moisture determinations allowed

Table 1. Machine data summary parameters

No.	Definition	Projected Relationship
1	Moisture signal, A/D count	A parameter related to moisture; logarithm of the conductance to force ratio.
2	Peak force, A/D count	Used to select the data points for determining moisture measurement.
3	Number of DY > 0	A parameter related to size based on the time a kernel exerts force on the crescent.
4	Sum of 1/DY, for all DY > 0, (A/D count)$^{-1}$	A parameter that is proportional to hardness. Soft wheat kernels produce a large value, hard kernels produce a small value.
5	Number of DY > 8	A parameter that is proportional to hardness.
6	Sum of DY for all DY > 0, A/D count.	A parameter that is related to the work required to crush a kernel.

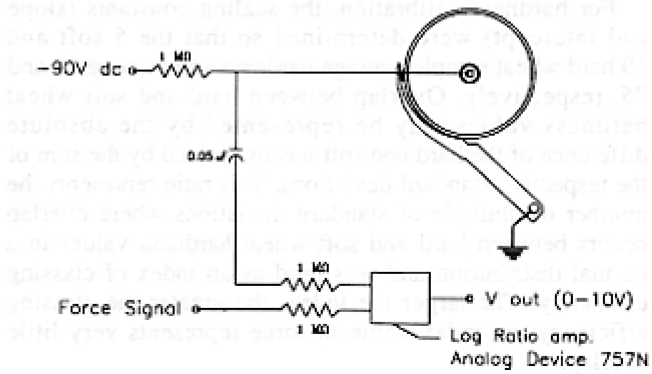

Figure 4–Schematic of the conductance circuit.

hardness measurements to be corrected to a constant moisture basis.

Size

The diameter of a kernel determined the point in the cavity (fig. 3) where initial contact occurred between the crescent, kernel, and rotor. Large kernels made contact sooner and passed through a greater contact arc than small kernels. For constant rotor speed and zero slip, the contact arc was proportional to contact time, which was used to estimate the rotor-crescent gap at initial contact and hence kernel size.

A kernel weight prediction algorithm was developed from the time intervals that a kernel exerts force on the crescent (positive DY values only). The statistical kernel weight prediction calibration was based on 253 samples representing the five major wheat classes (McGaughey et al., 1989). Each 300-kernel sample was segregated into three different size groups by sieving. Mean kernel weight was determined by weighing each sieved fraction before crushing and counting the number of kernels processed. If the sieved fraction was less than 16 kernels, the fraction was omitted from the weight calibration. Kernel weight prediction was used for hardness measurement corrections relating to kernel size.

Hardness

Hardness was determined from the force profile stored in computer memory by the A/D converter. At the end of data acquisition from a kernel, summations of the slope values (DY) were determined from successive A/D converts (0.25 ms) and stored in memory as summary parameters. After all kernels in a sample were crushed, the summary parameters were further processed to determine hardness values corrected for moisture and size for each kernel.

A national wheat hardness standard (NWHS) set, supplied by the Federal Grain Inspection Service (FGIS) for instrument calibrations in a national wheat-hardness study (Wishna, 1989), was used to calibrate the crushing device for hardness and optimize size and moisture correction coefficients. The NWHS set included 17 samples from the five major wheat classes, HRW, HRS, SRW, white wheat (WW), and durum. The NWHS set was run three times with the samples equilibrated to a different moisture content for each run. The first run was in March, the second in May, and the third in July of 1988.

For hardness calibration, the scaling constants (slope and intercept) were determined so that the 5 soft and 10 hard wheat sample average hardness values were 25 and 75, respectively. Overlap between hard and soft wheat hardness values may be represented by the absolute difference of the hard and soft means divided by the sum of the respective standard deviations. This ratio represents the number or multiple of standard deviations where overlap occurs between hard and soft wheat hardness values in a normal distribution and was used as an index of classing efficiency. The larger the index, the greater the classing efficiency; an index value of three represents very little overlap.

Optimum size correction constants were determined by selecting the values that produced the greatest classing efficiency (least overlap) between soft and hard wheat varieties in the NWHS set. Selection was made after several iterative trials starting with no size correction and increasing the size correction until a maximum classing efficiency was observed.

A method which improved both the classing efficiency and stability of crushing method measurements was developed using two hardness functions in a strategy to reduce kernel-to-kernel variability. The mean hardness value from both functions over all the kernels in a sample was calculated. Then for each kernel, the hardness value closest to this mean was used as the final score. Because each hardness algorithm differentiated hard and soft wheat independently and equally, the distinction between hard and soft wheat was retained.

Results and Discussion

Crush Force Profiles

Soft wheats (fig. 5) produced smooth, low, crush-force profiles with "flowing" or mild slopes as kernels disintegrated into a multitude of small particles. Hard wheats (fig. 6) produced jagged crush-force profiles with multiple peaks and sharper slopes as kernels fractured into smaller and smaller particles. The insets in figures 5 and 6

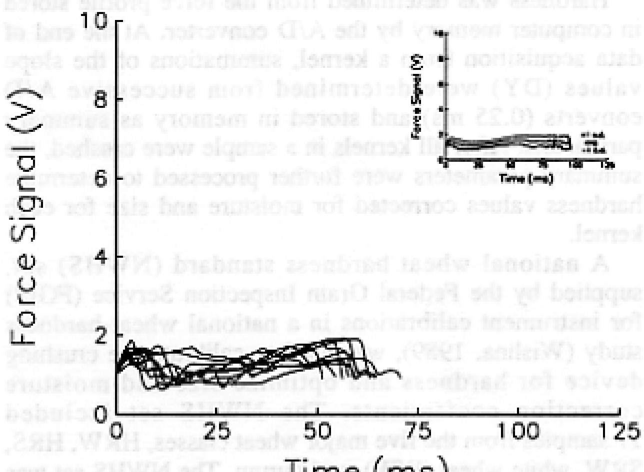

Figure 5–Force profiles of soft red winter wheat from the rotor-crescent system. Inset shows the average profile and the profile ±1 s.d. for 320 kernels.

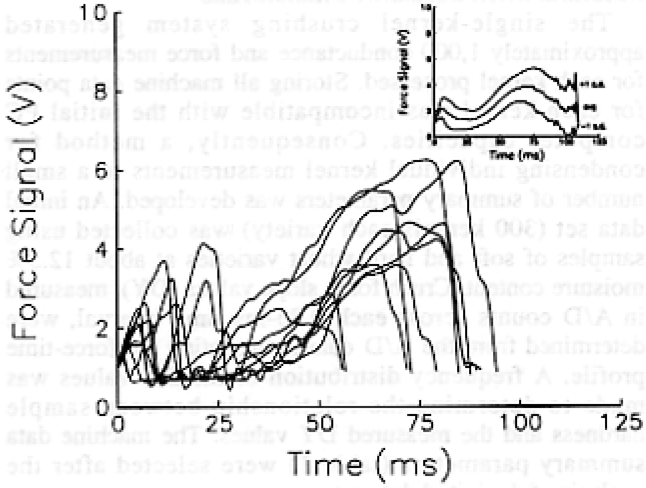

Figure 6–Force profiles of hard red spring wheat from the rotor-crescent system. Inset shows the average profile and the profile ±1 s.d. for 320 kernels.

show the average profile and the profile ± 1 s.d. for 320 kernels of the same variety or class.

The frequency distribution of the crush force slope values (DY) showed that soft kernels had more DY values between 1 and 8 than hard kernels, while hard kernels had more DY values greater than 8 than soft kernels.

Since soft wheats mill into a larger number of smaller particles than hard wheats (Neel and Hoseney, 1984), the number of the positive slopes across the digitized interval in a force profile may be proportional to the number of particles, and the slope value may be proportional to the size of particles created by crushing. This suggestion permitted the development of a hardness measurement based on the positive slope values from the digitized force-time profile. From the initial study, 13 machine data summary parameters were selected as a data base for kernels processed by the rotor-crescent system. After hardness calibration and further analysis for moisture and size corrections, the machine data summary parameters were reduced to six (table 1).

Moisture

Conductance was related to moisture, contact area, and force of the kernel as it was deformed and crushed between the rotor and crescent. Contact area and force change continuously during the kernel deformation process. As a result, the conductance signal also changed during the deformation process even though the kernel may have been uniform in moisture content. Differences in kernel size, shape, orientation, and hardness also influenced the force on the crescent. However, the ratio of conductance to load cell force was nearly constant when crushing equilibrated kernels.

From kernel to kernel, the most consistent moisture measurements (fig. 7) were near the end of the conductance profile and corresponded to the region near the maximum force value. All moisture determinations from the rotor-crescent method were calculated from the logarithm (conductivity/force) signal at or near the maximum force value.

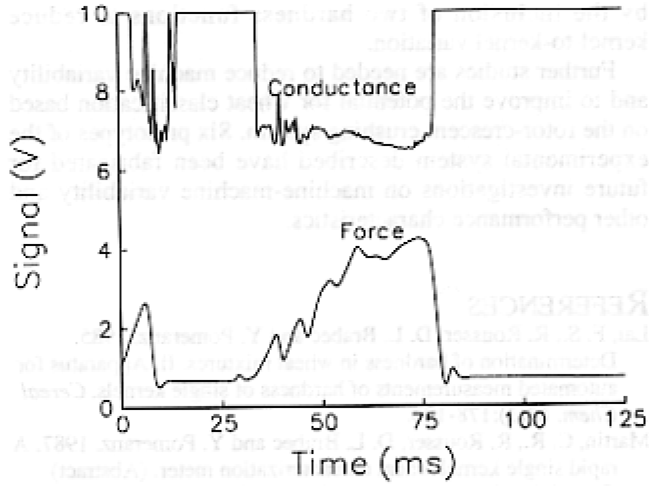

Figure 7–Force and conductance profile of a wheat kernel from the rotor-crescent system. Conductance signal is the logarithm of conductance/force ratio.

The results of the moisture calibration (fig. 8) showed that one calibration was satisfactory for hard red winter, hard red spring, and soft red winter wheat classes. This calibration was also adequate to cover the moisture range found in the 1988 national wheat hardness study which also included classes of white and club wheat but not durum.

Size

The contact time (fig. 5) for smaller kernels was less than the contact time for larger kernels (fig. 6). The initial kernel contact may occur at rotor tooth tip, or at the base of a rotor tooth (land), which represents a dimensional difference of 0.38 mm. As deformation progresses, the kernel may slip off the tooth into the land or split into two pieces with each piece separated by a tooth. When splitting or slipping occurred, the force exerted by the kernel on the crescent was momentarily reduced which frequently produced negative DY values. Splitting and slipping introduce a random machine reaction to the size measurement using rotor-crescent contact time. Hard kernels were observed to require a slightly longer time to pass through the instrument than soft kernels of the same

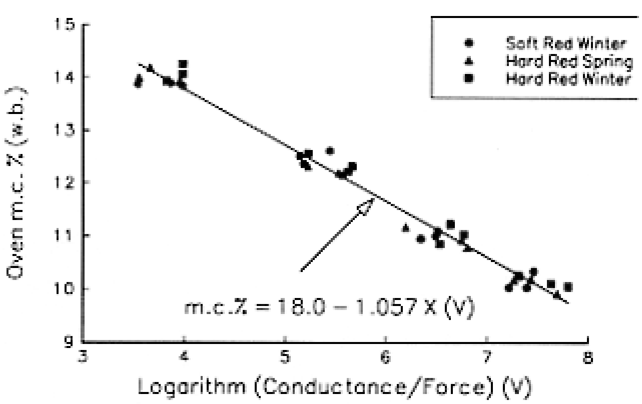

Figure 8–March 1988 moisture calibration for the rotor-crescent system.

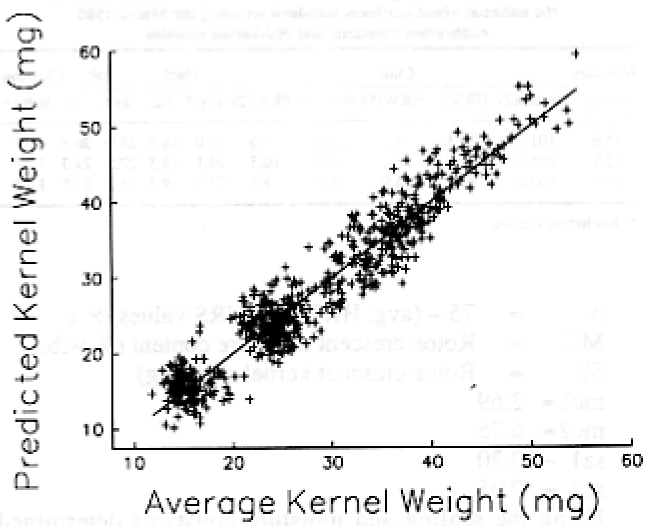

Figure 9–Results of the size calibration for the rotor-crescent system showing predicted kernel weight vs. average kernel weight.

weight. This may be the result of two effects: 1) that more slip occurred and/or 2) more rotational slowing occurred during the crushing of hard kernels compared to crushing of soft kernels.

Rotor-crescent size measurements (fig. 9) for the sieved size groups were highly correlated with average kernel weight ($r^2 = 0.916$, N = 754). However, the hardness interaction on the size measurement was apparent in that most of the points below the regression line were hard wheats, while most points above the line were soft wheats.

Hardness

Rotor-crescent hardness measurements were based on the summary parameter sum 1/DY and a combination of the summary parameters #DY > 0 and #DY > 8 (table 1). The sample averages of the two hardness functions were highly correlated ($r^2 = 0.97$, N = 253) across samples of the five major wheat classes. The high correlation suggested that the two hardness algorithms measure similar kernel properties. Hardness values based on the sum 1/DY parameter were corrected to a reference 12% w.b. moisture content and rotor-crescent kernel size value of 35 mg as follows:

$$H1 = b1 + a1 \times [\text{sum } 1/DY > 0 + (12 - MC) \times mc1 + (35 - SZ) \times sz1] \quad (1)$$

Hardness values based on #DY > 0 and #DY > 8 were corrected for moisture and size as follows:

$$H2 = b2 + a2 \times [100 \times \#DY > 8/(\#DY > 0 \times SZ^{0.5}) + (12 - MC) \times mc2 + (35 - SZ) \times sz2] \quad (2)$$

where

a = 50/(avg. HRW and HRS values – avg. SRW and WW values)

Table 2. Average crushing device hardness values and classing index for the national wheat hardness standard set using the March 1988 calibration constants and 300-kernel samples

Moisture % w.b.	Class Durum(2)	HRS(5)	HRW(5)	WW(3)	SRW(2)	Hard avg.*	Hard s.d.	Soft avg.	Soft s.d.	Classing Index*
11.6	101.2	76.3	73.7	36.4	8.0	75.0	18.7	25.0	20.5	1.27
12.3	105.7	82.1	76.1	39.0	10.3	79.1	19.3	27.5	21.3	1.27
13.3	107.0	80.9	74.9	36.8	7.7	77.9	19.5	25.2	21.5	1.29

* Excluding durum.

b = 75 – (avg. HRW and HRS values) × a
MC = Rotor-crescent moisture content (% w.b.)
SZ = Rotor-crescent kernel size (mg)
mc1 = 2.69
mc2 = 6.75
sz1 = 0.30
sz2 = 0.05

Using the scaling and moisture constants determined from the March calibration, single-kernel hardness values were calculated for each sample in the NWHS set when the average moisture content of the set was 11.6, 12.3, and 13.3% w.b. in March, May, and July, respectively. A summary shows that the rotor-crescent average hardness values (table 2) for HRS were larger than those for HRW, that WW were between the HRW and SRW, and that the SRW were lower than the WW wheats. This order of hardness for these major wheat classes also was observed among the 1,200 samples evaluated in the 1987 national wheat hardness study (Wishna, 1989). For the NWHS set, the classing index increased from about 0.95 to about 1.27 by the inclusion of two hardness functions to reduce kernel-to-kernel variation.

Further studies are needed to reduce machine variability and to improve the potential for wheat classification based on the rotor-crescent crushing system. Six prototypes of the experimental system described have been fabricated for future investigations on machine-machine variability and other performance characteristics.

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