Kernel Hardness of Some U.S. Wheats[1]

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ABSTRACT

Pure variety wheat samples grown over a 21-year period at locations in the eastern United States generally showed no significant correlation between particle size index (PSI) and protein content. Grain moisture content was found to exert a considerable effect on PSI. In a given wheat sample, higher moisture content was associated with greater softness as determined by our PSI test procedure. In making comparisons of hardness, an adjustment to a uniform moisture content may be made by reference to a fan-shaped family of regression lines developed under specific conditions prevailing for PSI determinations. Particle size index values appear to have greater value when they can be associated with a milling characteristic such as break flour yield rather than standing alone. PSI values obtained by grinding the wheat samples through a properly calibrated burr-type grinder correlated significantly with break-flour yield from Allis-Chalmers laboratory millings, whereas PSI data using a comminution grinder were not correlated with milling data.

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Kernel hardness or apparent hardness in wheat has been measured for decades. Early researchers had an appreciation of the relationship between grain texture and quality (Aamodt et al 1935, Biffin 1905, Roberts 1910). Lacking a sophisticated means for evaluating kernel hardness, Biffin (1905) employed a visual method. He realized, however, that translucency or vitreosity was not necessarily related to bread quality. He saw that some soft wheats were translucent, questioned whether such wheats were intrinsically valuable for breadbaking, and declared (Biffin 1908) that the only true test of quality was to bake bread. He was also an early cereal chemist, suggesting that wheat be tested for hardness by crushing grain on an iron plate, stating "weak grain...breaks to fine powder while strong grain crushes to angular fragments or to a gritty powder." Following this principle, Cutler and Brinson (1935) developed a procedure for obtaining a particle size index (PSI) value for wheat.

Since these early efforts, a large body of literature has been developed that bears on procedures to conduct a kernel hardness test, on the genetic aspects of hardness, and on the relation of hardness to variety and to grain moisture content. Procedures used to determine kernel hardness have been briefly reviewed by Kosmolak (1978) and by Simmonds (1974). Australian workers have used kernel hardness as a test for differentiating cultivars in their breeding programs (Symes 1961, 1965; Wrigley and Moss 1968). More recently, grinding time was used to differentiate between hard and soft wheats (Kosmolak 1978). Still more recently, a near-infrared apparatus was suggested as a means of

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measuring kernel hardness in wheat (Bruinsma and Rubenthaler 1978, Williams 1979). An engineering approach to the study of wheat kernel hardness was made by Chung et al (1977), who defined a "grindability index."

Heritability of Kernel Hardness

There is overwhelming evidence to indicate that kernel hardness is a heritable trait. Its heritability has been studied and discussed by a number of workers (Aamodt and Torrie 1935; Aamodt et al 1935; Baker 1977; Benjamin and Poehlman 1954; Berg 1947; Briggle et al 1968; Bryan and Pressley 1920; Harrington 1922; Howard and Howard 1912; Kellenbarger and Swenson 1948; Symes 1961, 1965, 1969; Trupp 1976; Worzella 1942; Wrigley 1972; Wrigley and Moss 1968). All agreed that kernel hardness is inherited simply and directly, with one or perhaps two major genes and one or more minor genes involved in the process.

Influence of Protein Content on Vitreosity and Hardness

Kernel texture has often been intimately related to grain protein content, and many researchers now support the idea that the higher the protein content is, the more likely the wheat is to be vitreous and the kernel texture to be harder. The relation of kernel hardness to protein content has been discussed by several workers (Aamodt and Torrie 1935), but it seems likely that the "hardness" often referred to in earlier works actually may have been meant to be "vitreosity." Simmonds (1974) explained the distinction between the two attributes. Vitreosity is the degree of translucency shown by wheat kernels, and its measurement is essentially subjective, although efforts toward objectivity have been made. Hardness in a wheat kernel is frequently measured as the resistance of the grain to fracture when subjected to forces intended to reduce its particle size. Within a wheat sample, vitreous kernels are higher in protein content and in density than mealy or starchy kernels (Sharp 1927). Wheat protein is lower in density than wheat starch, and, when density alone is considered, kernels having lower protein content would be expected to have higher density than those with higher protein content. The lower density of such kernels, however, is attributed to the presence of air pockets (Sharp 1927) that may also cause light refraction and hence impart an opaque appearance to the kernels. Yamazaki and Briggle (1969) noted the increase in density with progressive grinding, which exposed air pockets, and calculated the percentage of air spaces in kernels of differing densities.

Barmore and Bequette (1968) discussed some of the difficulties they encountered in attempting to distinguish between hard and soft wheats from the standpoint of grain standards. They also noted the lack of parallel between the terms "hardness" and "flour strength."

The relationship between kernel hardness and protein content within a cultivar was studied by Symes (1965), who found that for some cultivars, particle size index (PSI) increased with protein content, whereas for others PSI decreased with protein content. For still others, protein content appeared to have no effect on texture. Trupp (1976) stated that kernel hardness as determined by a PSI test and protein content do not have common genetic causes.

Influence of Moisture Content on Hardness Measurements

There is general agreement that grain moisture content affects measurements of kernel hardness. Using a penetrometer method, Grosh and Milner (1959) found wheat hardness to decrease with increasing moisture content. Using a barley pearler, McCluggage (1943) stated that moisture, added artificially to wheat, had little effect, but Kramer and Albrecht (1948) found pearling resistance to increase (indicating greater hardness) with increasing moisture. The effect was noted to a greater extent for soft wheat than for hard. Using a similar procedure, Chesterfield (1971) found that the moisture effect was variable, but in general had little direct effect on pearling index. Orth (1977) found that soft wheat showed increasing softness at higher moisture, but that hard wheats showed little response. Kosmolak (1978) obtained similar results using a type of burr grinder. In general, some confusion seems to exist regarding the effects of both moisture and protein contents on kernel hardness.

We have been conducting hardness tests for 40 years on soft (and a few hard) wheat samples submitted to our laboratory for quality evaluation. Test results have yielded a wider range in kernel hardness among soft wheat cultivars than among hard wheats. This diversity in softness, and susceptibility of hardness characteristics to grain moisture content, imply a relationship between kernel hardness and milling, perhaps to a greater extent than among hard wheats.

In more recent efforts, we have attempted to associate kernel hardness data with a milling characteristic, because it appeared that the value of a kernel hardness test would be enhanced if it could be related directly to a milling characteristic rather than standing alone as a kernel property without any relevance to processing quality. This report represents an effort to clarify the apparently confused picture of kernel hardness testing and of factors affecting endosperm granularity, mostly as it applies to soft wheat grown in the eastern United States.

MATERIALS AND METHODS

Particle Size Index Tests Used at the Laboratory

Several procedures have been used to determine kernel hardness of wheat at our laboratory. All of our PSI determinations have involved a grinding and sifting procedure, but the apparatus and techniques for conducting the determination have changed.

A Hobart coffee grinder (Finney and Yamazaki 1946), properly calibrated, was first used to prepare a meal. Grinding was followed by sieving on a Tyler Ro-Tap sifting apparatus having a screen with an opening of 105 μm. A Labconco Heavy Duty grinder with special burrs and provision for adjusting burr distance was later substituted for the Hobart grinder. The special burrs (7.2-cm diameter) have both the rotor and the stator milled to present a flat surface about 2 cm inward from the periphery. Sieving was changed from the Ro-Tap apparatus to the Allen Bradley Sonic-Sifter, with a screen of the same mesh opening as that used previously (Yamazaki 1972). Still later, sieving was performed on a round 20-cm screen with large openings (425-μm) mounted on a rotary sifter. The change to the screen with the coarse opening was made for several reasons. First, PSI is one of three tests used in our early-generation soft wheat quality-evaluation program (Yamazaki and J. R. Donelson 1972), and the sifted meal is recovered for further testing. Second, sieving is less affected by partial blinding with a coarser screen than with a finer one.

Present Particle Size Index Test

In the PSI test used at our laboratory, the Labconco Heavy Duty mill, equipped with special burrs, is calibrated. Grain (20 g) is ground by passing through the grinder at a predetermined setting by first turning on the grinder, then feeding the machine as fast as it will grind. The meal is collected, keeping loss minimal, the grinder chamber is cleaned, and the fine residue is added to the meal, which is mixed and blended thoroughly. Meal (15.00 g) is weighed on a round 20-cm 425-μm-opening metal screen over a pan and sifted 30 sec on a rotary sifter (190 rpm, 10 cm throw). The assembly is then tapped lightly, and the thrus are weighed. PSI is calculated as the percent of meal passing through the screen. Moisture content of grain is determined by using the Motomco or another official procedure.

The grinder is calibrated by determining the PSI of three wheats (a hard red winter, a soft red winter, and a soft white winter wheat) of known PSI by the above procedure. The sum of the indexes should fall within prescribed limits; otherwise, the grinder setting should be adjusted.

The Pearling Index Test

The apparatus and procedure used for this test closely followed those described by McCluggage (1943). In later trials, the test was modified by attaching a baffled extension to the feed hopper, and pearling only 5.0 g wheat (instead of 20 g) for only 42.5 sec (instead of 1 min) to obtain pearling index values comparable to those obtained with the larger sample.

Milling for Break Flour Yield

Cleaned and conditioned (usually to moisture content of 15.3%) wheats were milled on a modified Allis-Chalmers laboratory mill according to Yamazaki and Andrews (1982), using a six-break variable-reduction system. Break flour yield was computed as percent recovery on an as-is moisture basis.

Several experiments, each with different sets of wheat samples, are reported in this paper. In order to minimize confusion, we describe the samples and procedures together with the results obtained.

RESULTS AND DISCUSSION

Effect of Grain Moisture Content on Kernel Hardness Tests

Preliminary PSI data for wheats of various classes obtained by using the above procedure showed that at a grain moisture content of 11%, the PSI range for hard and durum wheats was 20–30%. Durum wheats were in the low 20s, and hard red spring and winter wheats fell in the range of about 24–30%. Soft wheats were found to range from 30 to almost 60%, with most in the 35–45% range. The Eastern soft whites were mostly about 33–38%, and some of the current Southern soft red cultivars were as high as 55–60%.

Ten wheats covering the spectrum in kernel hardness in soft wheats were dried over concentrated sulfuric acid or moistened by adding distilled water to give a range in moisture content from about 7.5 to about 15.0%. The samples were sealed and permitted to reach moisture equilibrium for at least a week. Duplicate determinations were made of PSI (Labconco grinder, Ro-Tap sieving through 105-μm screen), pearling index (McCluggage 1943), and moisture content (AACC 44-19) modified by first breaking kernels by passing them through Tag-Heppenstall rolls and then heating at 140°C for 2 hr. These three tests were run simultaneously immediately upon breaking the seal in order to minimize grain moisture change.

Particle Size Index. Within a cultivar, the correlation coefficient (r-value) between moisture content and PSI was highly significant (Table I) and denoted that within a cultivar, increasing moisture content increased PSI value.

TABLE I
Grain Moisture Content vs Particle Size Index (PSI) at 11 Moisture Levels for 10 Cultivars[a]

Cultivar	Wheat Class	Moisture Content Range (%)	PSI Range (%)	r	Regression Coefficient (% PSI/% moisture)	Adjusted PSI at 11% Moisture (%)
Purkof	SH	7.59–14.67	8.60–12.10	0.994	0.490	10.18
Comanche	HRW	7.45–14.74	8.53–13.15	0.986	0.588	10.62
Kawvale	SH	7.85–14.80	10.38–16.43	0.983	0.937	13.39
Clarkan	SRW	7.92–15.41	10.73–18.45	0.996	1.054	14.01
Blackhawk	SRW	8.07–14.90	12.50–19.05	0.990	0.914	15.28
Avon	SWW	8.20–14.90	12.60–19.45	0.987	1.113	15.42
Am. Banner	SWW	8.01–14.86	12.90–18.80	0.986	0.901	15.57
Trumbull	SRW	8.05–15.10	13.58–24.90	0.993	1.472	18.25
Thorne	SRW	8.02–15.22	13.65–24.83	0.991	1.527	18.41
Fairfield	SRW	8.16–15.10	15.23–25.75	0.994	1.425	19.30

[a] Using Labconco grinder and sieving on a screen having a 105-μm opening.

TABLE II
Moisture Content vs Particle Size Index (PSI) at Five Moisture Levels for Four Wheats[a]

Entry	Wheat Type	Moisture Content Range (%)	PSI Range (%)	r	Regression Coefficient (% PSI/% moisture)	Adjusted PSI at 11% Moisture (%)
HRW Blend	HRW	10.14–13.54	26.1–30.8	0.998	1.392	27.36
Comanche	HRW	10.81–13.94	32.2–40.2	0.989	2.685	32.94
Thorne	SRW	10.64–13.79	35.5–45.2	0.984	3.016	37.42
Frederick	SWW	10.37–13.70	36.4–47.0	0.983	3.191	38.99

[a] Using Labconco grinder and sieving on a screen having a 425-μm opening.

TABLE III
Moisture Content vs Pearling Index at 11 Moisture Levels for 10 Cultivars

Cultivar	Wheat Type	Moisture Content Range (%)	Pearling Range (%)	r	Regression Coefficient (% PI/% moisture)	Adjusted PI[a] at 11% Moisture (%)
Purkof	SH	7.59–14.67	33.25–29.10	−0.958	−0.612	30.73
Comanche	HRW	7.45–14.74	36.00–29.70	−0.965	−0.836	32.60
Clarkan	SRW	7.92–15.41	38.70–33.40	−0.960	−0.699	35.71
Kawvale	SH	7.85–14.80	43.55–35.48	−0.966	−1.155	39.73
Blackhawk	SRW	8.07–14.90	46.45–38.05	−0.983	−1.319	42.50
Fairfield	SRW	8.16–15.10	48.33–39.80	−0.974	−1.183	44.56
Trumbull	SRW	8.05–15.10	49.43–39.88	−0.995	−1.420	45.09
Am. Banner	SWW	8.01–14.86	49.33–41.25	−0.986	−1.233	45.11
Thorne	SRW	8.02–15.22	51.25–40.18	−0.996	−1.630	46.55
Avon	SWW	8.20–14.90	51.88–41.93	−0.996	−1.531	47.52

[a] PI = pearling index.

The cultivar PSI adjusted to 11.0% moisture content correlated significantly ($r = 0.95$, $df = 8$) with the sample regression coefficient; the softer the texture was, the greater was the effect of moisture content on PSI. This suggested a family of regression lines with slopes increasing with softness that could be used to adjust PSI to a uniform moisture content. In the experiment, the standard deviation for moisture content was 0.09% and for PSI it was 0.44%. Data from a recent experiment using the present PSI test procedure confirmed the nature of the relationship between moisture content and kernel hardness (Table II).

Pearling Index. Pearling, the attritional abrasion of wheat kernels by a carborundum wheel, is a treatment also used to differentiate hardness among wheats (McCluggage 1943). Hardness data obtained by this procedure is significantly correlated with those obtained by a PSI test (Bode 1954). Yamazaki (1972) has stated, however, that the PSI test appears to be preferable as a hardness test since the entire kernel is involved, whereas the bran appears to play a disproportionate role in determining pearling index.

A high order of association existed within a cultivar between moisture content and pearling index as indicated by the respective correlation coefficients (Table III). And, as previously found for PSI, a fan-shaped family of lines representing the relation between the two was visualized because the r-value for adjusting varietal pearling value and cultivar regression coefficient was −0.93. For pearling, the sign of the r-value pointed to an apparent increase in kernel hardness with increasing moisture content, while PSI results indicated the opposite.

In milling, increasing the wheat temper is believed to soften the endosperm and toughen the bran so that the bran is more resistant to the cutting action of the rolls. In a kernel hardness test such as PSI, increasing grain moisture content results in higher PSI as evidence of increasing endosperm softness. The opposite effect of moisture on pearling appears to indicate that pearling is measuring the bran toughening effect of water, whereas PSI is measuring the influence of water on endosperm friability or hardness. If kernel hardness is to be related to a grain milling property (primarily the friability of the endosperm), it would appear that a test that parallels grain response to milling would be preferable to one that did not.

Effect of Grain Protein Content Within a Cultivar on Kernel Hardness

Wheat cultivars selected to represent the range in soft wheat quality (called Variety Protein Series) had been grown for more than 25 years in Indiana, Illinois, Ohio, Kentucky, and New York and had been milled and analyzed to determine the intracultivar effects of protein content on quality tests. Some cultivars had been replaced by others during the program, but PSI data, obtained by the Labconco-Ro-Tap procedure, and break flour yield data (from Allis millings using a four-break technique), as well as grain protein content, were available for 12 cultivars, which included Comanche and Kharkof, hard red winters; Kawvale and Purkof, red wheats intermediate between hard and soft; Blackhawk, Clarkan, Fairfield, Thorne, Trumbull, and Wabash, soft red winters; and American Banner and Avon, Eastern soft white winters. For all but two cultivars, the correlation between protein content and PSI was not significant (Table IV). These data indicated a general independence of varietal PSI and grain protein content and tended to confirm that kernal hardness is a varietal trait.

Relation Between Particle Size Index and Break Flour Yield

The belief has been widely held that kernel texture is related to break flour yield, but few citations document this. Stenvert (1972) referred to a correlation of 0.50 between PSI and break flour yield, the latter data obtained with a Buhler laboratory mill.

The relationships between PSI and break flour yield from a four-break Allis milling for 861 entries of the 12 cultivars grown over the period 1950–1970 are given in Table IV. Highly significant r-values for varietal PSI vs break flour yield were found for all cultivars tested. The r-value for pooled data was also a highly significant 0.83, indicating that kernel hardness was influencing this milling characteristic regardless of crop year and/or varietal source of the wheat among those tested.

It was also found that, except for one cultivar (Kharkof), there was a general lack of significant correlation between grain protein content and break flour yield within a cultivar (Table IV). Such results would be expected based on similar nonsignificance for varietal PSI vs protein content.

Later PSI data by the Labconco-coarse (425-μm) screen procedure on one hand and six-break Allis milling break flour yield for 614 samples of soft wheat cultivars and breeders' lines on the other gave a correlation coefficient of 0.76 (Table V), a highly significant value made more so because no hard or intermediate wheats were included among these samples, thus limiting the range in PSI values. This value was comparable to those obtained for entries in the individual crop years 1978, 1979, 1980, and indicated an interseasonal consistency in the association. Similar results were obtained for samples tested over the period 1950–1970 for which procedures in both kernel hardness test and break flour milling differed somewhat. The difference in r-value for PSI vs break flour yield among the 1950–1970 entries and that for 1978–1980 may be attributed to the inclusion in the former series of hard wheat entries that extended the ranges in both PSI and break flour yield. Increasing the range in data of a given dispersion usually improves the r-value. We assume that the dispersion in both PSI and break flour yield data are comparable for the two sets.

TABLE IV
Correlation Coefficients Among Protein Content, Particle Size Index (PSI), and Break Flour Yield for 12 Cultivars[a]

Cultivar	Wheat Class	Number of Entries	Protein Content Range (%)	Correlation Coefficient[b]: Protein vs PSI	PSI vs Break Flour	Protein vs Break Flour
Comanche	HRW	45	9.8–15.4	0.131 NS	0.545**	−0.045 NS
Kharkof	HRW	43	8.5–15.2	−0.458**	0.647**	−0.646**
Kawvale	SH	89	8.2–15.6	−0.015 NS	0.848**	−0.121 NS
Purkof	SH	83	8.4–15.5	0.275*	0.387**	−0.057 NS
Blackhawk	SRW	89	8.4–15.8	0.183 NS	0.665**	0.124 NS
Clarkan	SRW	89	8.5–14.6	−0.032 NS	0.820**	0.023 NS
Fairfield	SRW	89	7.6–14.9	−0.184 NS	0.773**	−0.172 NS
Thorne	SRW	89	8.1–15.9	−0.089 NS	0.800**	−0.149 NS
Trumbull	SRW	89	8.7–15.8	−0.136 NS	0.677**	−0.002 NS
Wabash	SRW	44	8.3–14.1	−0.130 NS	0.714**	−0.217 NS
Am. Banner	SWW	89	8.1–14.7	0.138 NS	0.717**	−0.059 NS
Avon	SWW	23	8.7–13.5	0.209 NS	0.716**	0.174 NS
Pooled	...	861	...	...	0.825**	...

[a]Grown at seven locations in Ohio, Illinois, Kentucky, Michigan, and New York, 1950–1970.
[b]* = Significant at $P = 0.05$. ** = Significant at $P = 0.01$. NS = not significant.

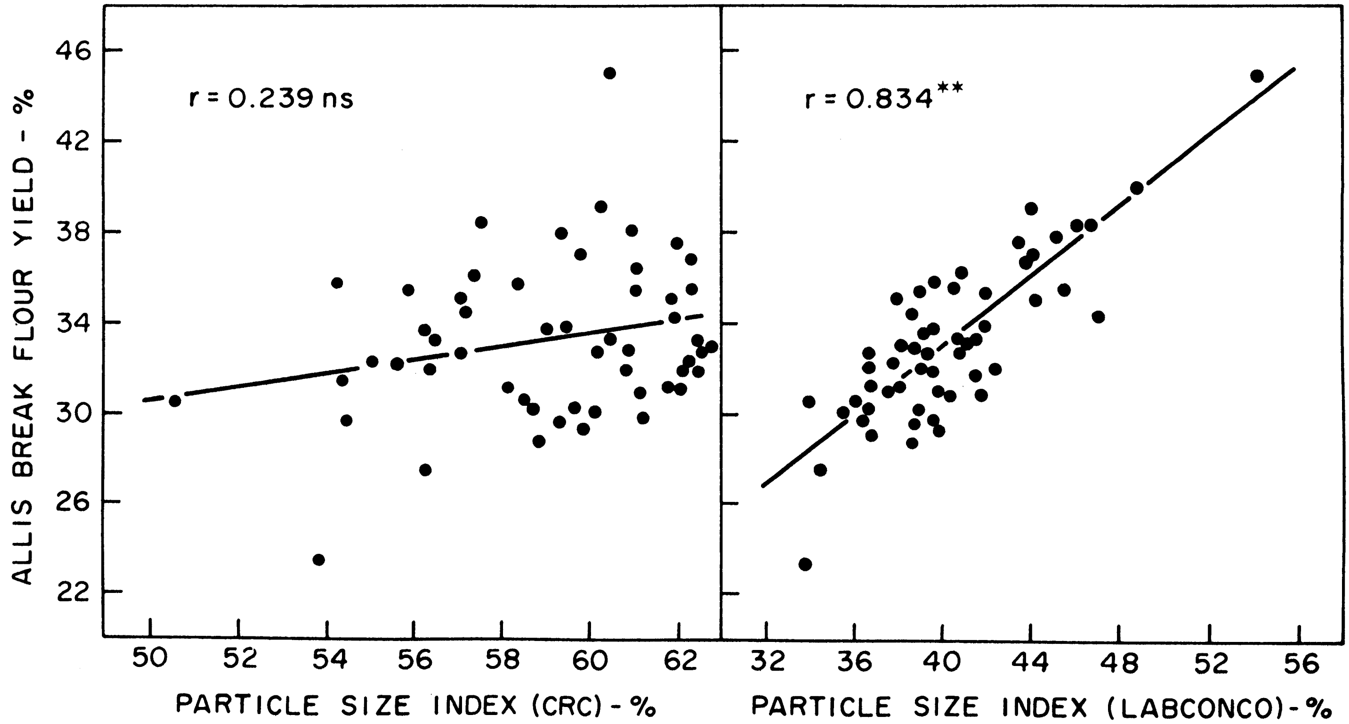

Fig. 1. Scattergrams for particle size index vs break flour yield using the comminution grinder in the particle size index (left) and single-pass burr grinder (right) for 55 soft wheat entries, 1977 crop.

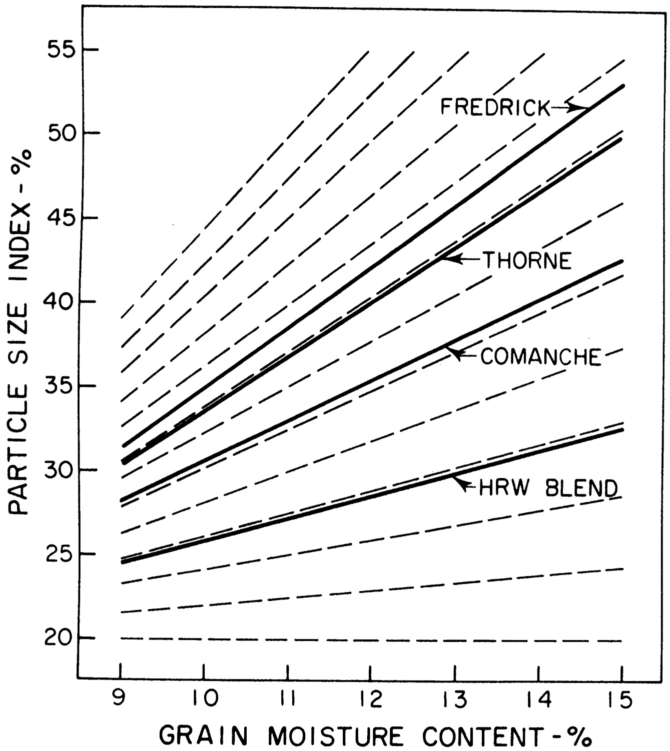

Fig. 2. Idealized fan-shaped family of regression lines for particle size index vs moisture content, and regression lines for four wheats.

TABLE V
Particle Size Index and Break Flour Yield Ranges and Correlation Coefficients for Wheats Grown in Breeders' Nurseries in 1978, 1979, 1980, and in 1950–1970

Crop Year	No. of Entries	Particle Size Index Range (%)	Break Flour Yield Range (%)	Correlation Coefficient
1978	170[a]	31.5–53.2[b]	23.1–44.9[c]	0.817**
1979	221[a]	30.7–57.7[b]	23.9–38.1[c]	0.741**
1980	223[a]	33.2–48.5[b]	25.4–37.7[c]	0.751**
1978–1980	614[a]	30.7–57.7[b]	23.1–44.9[c]	0.759**
1950–1970	861[d]	7.2–35.7[e]	12.8–33.6[f]	0.825**

[a]Soft wheats only.
[b]Labconco grinder, meal thru 425-μm screen.
[c]Allis-Chalmers milling, six-break system.
[d]Includes hard red, semihard, soft red, and white winter wheats.
[e]Labconco grinder, meal thru 105-μm screen.
[f]Allis-Chalmers milling, four-break system.

Effect of Grinder on the Relation Between Particle Size Index and Break Flour Yield

Two grinders, the Labconco unit used in our present PSI test and a type of small propeller-type closed chamber grinder (CRC) in which a wheat sample could be reduced to a meal, the extent of reduction dependent on grinding time, were used to prepare meal for the PSI test. In the latter grinder the wheat was ground for 28 sec at a rotational speed of 19,000 rpm. After each grinder was calibrated, 55 wheat samples were analyzed in duplicate for kernel hardness, and the data were plotted against break flour yield (Fig. 1).

PSI data obtained with (Labconco) burr-type grinder provided superior association with milling break flour yield than those from the comminution grinder. Because milling is a series of short-contact single-pass grindings with intervening screening to make the succeeding grindings more selective, it appears that the action of a burr grinder more closely resembles milling action than does a comminution reduction. Particle size index determined by the single-pass procedure seems to measure milling properties related to endosperm fracturing properties and break flour yield.

Particle Size Index Adjustment for Moisture Content

It has been reported previously that PSI is influenced by moisture content. It follows that the extent of association between PSI and break flour yield depended on the moisture content of the grain when the PSI determination was made, since our break flour yield data were obtained by milling wheat at a uniform temper level of 15.3%, whereas PSI data were obtained for grain varying in moisture content. Therefore, samples for which PSI were

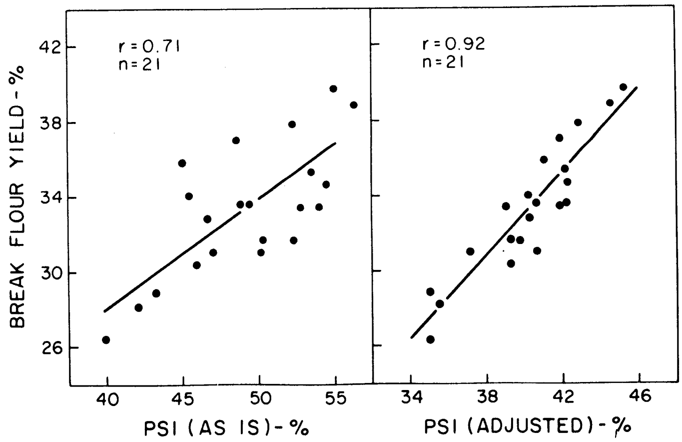

Fig. 3. Scattergrams for particle size index unadjusted for moisture (left) and for particle size index adjusted to 11% moisture (right) vs break flour yield for 21 high-moisture (12.2–15.3%) wheats milled on an Allis-Chalmers mill at a uniform temper of 15.3%.

determined at differing moisture contents could have such data adjusted to a uniform moisture content as in Table II before relating to break flour yield. Such adjustments may be based on an idealized fan-shaped family of regression lines based on an equation determined under our set of conditions:

$$A = X + k(Y - 11.0)(X - 20)$$

where A = PSI at moisture content Y, X = PSI at 11.0% moisture content, and k = constant. Under our PSI test apparatus and operating conditions, k = 0.184 obtained from data in Table II. Figure 2 presents such a family of lines, with regressions for the four entries in Table II superimposed thereon. According to Fig. 2 and results in Table II, the effect of moisture increases with increasing kernel softness, and for a (hard) wheat with PSI value of 20% or lower, moisture content would be presumed to have no effect (Orth 1977).

Figure 3 presents scattergrams exemplifying the improvement in PSI vs break flour yield when moisture adjustments were made as above for PSI values. The moisture contents for the 21 samples ranged from 12.2 to 15.3%. The data suggested that good correlation between PSI and break flour yield may be attained provided the PSI test is conducted under proper conditions and moisture adjustment is made in the data.

SUMMARY

In spite of apparent visual differences in vitreosity among grain of a given cultivar attributable to differences in protein content, extensive tests indicated no significant relationship between protein content and PSI within a cultivar. The varietal nature of kernel hardness was thus further confirmed.

Particle size index for soft wheat was significantly associated with break flour yield obtained in milling the wheat, provided the PSI grinding was done in an appropriate manner. This association could be improved if PSI values were adjusted to a uniform moisture content and the millings were done at a given temper moisture.

Particle size index data may be influenced by grain moisture content, and measurements should be made at similar grain moisture content or the data should be adjusted to a uniform moisture basis to obtain comparable results. Such adjustments may be made by reference to a fan-shaped family of regression lines for PSI vs moisture content or by utilizing an adjustment formula developed to conform to the particular set of conditions used in carrying out the test.

Particle size index had previously been associated with varietal cake quality potential (Yamazaki and D. H. Donelson 1972), and this relationship has been utilized in an early-generation soft wheat quality screening program (Yamazaki and J. R. Donelson 1972). Although PSI may not in itself be the prime factor in cake quality (Chaudhary et al 1981), factors contributing to endosperm friability and to cake volume may arise from the same source.

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LITERATURE CITED

AAMODT, O. S., and TORRIE, J. H. 1935. Studies on the inheritance of and the relation between kernel texture and protein content in several spring wheat crosses. Can. J. Res. Sect. C 13:202.

AAMODT, O. S., TORRIE, J. H., and WILSON, A. 1935. Studies of the inheritance of and the relationship between kernel texture, grain yield, and tiller-survival in crosses between Reward and Milturum spring wheats. J. Am. Soc. Agron. 27:456.

AMERICAN ASSOCIATION OF CEREAL CHEMISTS. 1979. Approved Methods of the AACC. The Association, St. Paul, MN.

BAKER, R. J. 1977. Inheritance of kernel hardness in spring wheat. Crop Sci. 17:960.

BARMORE, M. A., and BEQUETTE, R. K. 1968. Kernel color and shape as guides to potential flour performance in wheat marketing. Agron. J. 60:223.

BENJAMIN, 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.

BERG, S. O. 1947. Is the degree of grittiness of wheat flour mainly a varietal character? Cereal Chem. 24:274.

BIFFIN, R. H. 1905. Mendel's laws of inheritance and wheat breeding. J. Agric. Sci. England 1:4.

BIFFIN, R. H. 1908. On the inheritance of strength in wheat. J. Agric. Sci. 3:86.

BODE, C. E. 1954. Research at the soft wheat quality laboratory. Part I. Trans. Am. Assoc. Cereal Chem. 12:108.

BRIGGLE, L. W., YAMAZAKI, W. T., and HANSON, W. D. 1968. Heritability of three soft wheat quality characters in the F2 and F3 generations. Crop Sci. 8:283.

BRUINSMA, B. L., and RUBENTHALER, G. L. 1978. Estimation of lysine and texture in cereals by NIR. Proc. 8th Technicon Intl. Congr., Tech. Inst. Co., Ltd., Basingstoke, U.K., p. X-BR-1.

BRYAN, W. E., and PRESSLEY, E. H. 1920. Plant breeding. Ariz. Exp. Stn. 31st Annu. Rep. p. 480.

CHAUDHARY, V. K., YAMAZAKI, W. T., and GOULD, W. A. 1981. Relation of cultivar and flour particle size distribution to cake volume. Cereal Chem. 58:314.

CHESTERFIELD, R. S. 1971. A modified barley pearler for measuring hardness of Australian wheat. J. Aust. Inst. Agric. Sci. 37:148.

CHUNG, C. J., CLARK, S. J., LINDHOLM, J. C., McGINTY, R. J., and WATSON, C. A. 1977. Comminution parameters for wheat hardness measurement. Trans. Am. Soc. Agric. Eng.:375.

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

FINNEY, K. F., and YAMAZAKI, W. T. 1946. A micro-milling technique using the Hobart grinder. Cereal Chem. 23:484.

GROSH, G. M., and MILNER, M. 1959. Water penetration and internal cracking in tempered wheat grain. Cereal Chem. 36:260.

HARRINGTON, J. B. 1922. The mode of inheritance of certain characters in wheat. Sci. Agric. 2:319.

HOWARD, A., and HOWARD, G. L. C. 1912. On the inheritance of some characters in wheat. I. Mem. Dept. Agric. India. Bot. Ser. 5:1.

KELLENBARGER, S., and SWENSON, S. P. 1948. Pearling index and wheat meal fermentation time in two winter wheat crosses. J. Am. Soc. Agron. 40:929.

KOSMOLAK, F. G. 1978. Grinding time—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. J. Am. Soc. Agron. 40:422.

McCLUGGAGE, M. E. 1943. Factors influencing the pearling test for kernel hardness in wheat. Cereal Chem. 20:686.

ORTH, R. A. 1977. Determination of kernel hardness of Australian wheats by a rapid grinding procedure. Aust. J. Exp. Agric. Anim. Husb. 17:462.

ROBERTS, H. F. 1910. A quantitative method for the determination of

hardness in wheat. Kansas A.E.S. Bull. 167, pp. 371.
SHARP, P. F. 1927. Wheat and flour studies. IX. Density of wheat as influenced by freezing, stage of development, and moisture content. Cereal Chem. 4:14.
SIMMONDS, D. H. 1974. Chemical basis for hardness and vitreosity in the wheat kernel. Bakers Dig. 48(5):16.
STENVERT, N. L. 1972. The measurement of wheat hardness and its effect on milling characteristics. Aust. J. Exp. Agric. Anim. Husb. 12:159.
SYMES, K. J. 1961. Classification of Australian wheat varieties based on the granularity of their wholemeal. Aust. J. Exp. Agric. Anim. 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. Aust. J. Agric. Res. 20:971.
TRUPP, C. R. 1976. Particle size index-breeding behavior and association with protein percentage in wheat. Crop Sci. 16:618.
WILLIAMS, P. C. 1979. Screening wheat for protein and hardness by near infrared reflectance spectroscopy. Cereal Chem. 56:169.
WORZELLA, W. W. 1942. Inheritance and interrelationship of components of quality, cold resistance, and morphological characters in wheat hybrids. J. Agric. Res. 65:501.
WRIGLEY, C. W. 1972. The biochemistry of the wheat protein complex and its genetic control. Cereal Sci. Today 17(12):370.
WRIGLEY, C. W., and MOSS, H. J. 1968. Selection for grain quality in wheat breeding. Proc. 3rd Int. Wheat Genetic Symp., K. W. Finlay and K. W. Shepherd, eds. Aust. Acad. Sci., Canberra.
YAMAZAKI, W. T. 1972. A modified particle-size index test for kernel texture in soft wheat. Crop Sci. 12:116.
YAMAZAKI, W. T., and ANDREWS, L. C. 1982. Experimental milling of soft wheat cultivars and breeding lines. Cereal Chem. 59:41.
YAMAZAKI, W. T., and BRIGGLE, L. W. 1969. Components of test weight in soft wheat. Crop Sci. 9:457.
YAMAZAKI, W. T., and DONELSON, D. H. 1972. The relationship between flour particle size and cake-volume potential among Eastern soft wheats. Cereal Chem. 49:649.
YAMAZAKI, W. T., and DONELSON, J. R. 1972. Evaluating soft wheat quality of early generation progenies. Crop Sci. 12:374.

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