Measurement of Wheat Hardness by Seed Scarifier and Barley Pearler and Comparison with Single-Kernel Characterization System

KeShun Liu1,2

A new procedure based on a seed scarifier (SS) for measuring wheat hardness was described and investigated along with methods using a barley pearler (BP) and the single kernel characterization system (SKCS). Hardness measured by SS and BP is expressed as a percentage of kernel weight remaining after abrading and defined as abrasion resistance index (ARI). For a given sample weight, increased abrading time decreased ARI but improved the ability to differentiate variation among samples. The effect of sample moisture was also statistically significant. For improved performance of SS and BP, based on distinct patterns of relationships between surface removal rates and surface removal levels among soft and hard wheats, a combination of parameters that produces ARI values in the range of 80–20, and a run for a set of reference material are recommended. Differences in measured hardness values from SS, BP, and SKCS existed within a wheat group, but they were very much method-dependent. Nevertheless, all methods were able to differentiate variations between soft and hard wheat groups. Because of low cost, durability, simplicity, repeatability, and aforementioned ability, SS and BP, although limited by lack of standardization and calibration procedures, can still be useful for grain hardness measurement, particularly when and where instruments for contemporary popular methods such as SKCS and near-infrared reflectance (NIR) spectroscopy are not readily available.

Hardness or texture of wheat is the single most important trait that determines milling properties and end-uses. It is common to differentiate soft and hard wheat in the world trade. Soft wheat is more friable, requires less energy to mill, and produces flours and meals with finer particles and lower starch damage, which are suitable for cake and biscuit production. Hard wheat meals are coarser, have more broken and damaged starch granules, but flow and bolt more easily and are thus suitable for breadmaking. The term wheat hardness also refers to the quantitative variation within and across these qualitative classes.

Yet wheat hardness has to be empirically measured and thus is largely related to how the trait is measured. There are many reported methods for measuring hardness of wheat and some other cereal grains, often based on different principles. Hardness of individual kernels can be measured by penetrometers and defined as the force required for cracking the kernels. The single kernel characterization system (SKCS) is an advanced technique based on this principle (Martin et al. 1993; Osborne and Anderssen 2003). The magnitude of interkernel variation can be decreased to some extent by measuring bulk grain samples. Methods of this category measure either resistance to grinding, milling, or abrading (Obuchowski and Bushuk 1980) or the nature of the ground products including particle size index, its derivative property (near-infrared reflectance [NIR] spectroscopy), and amount of damaged starch (AACC International 2000).

Abrasive milling is one of several common bulk sample methods for determining kernel hardness. It is based on measurement of abrasion resistance. The method was first developed by Taylor et al. (1939), who used a Strong-Scott barley pearler (BP) to abratively mill wheat. Essentially the method consists of placing a weighed amount of wheat in the pearler and calculating percentages of outer layer removal (defined as the pearling index) after a given time of pearling. It was found that the harder the cereal kernel, the less the amount of material removed by abrasion. Since then, because of simplicity and low cost, the BP and its modifications were widely used for measuring kernel hardness of many cereal grains such as wheat, corn, sorghum, and barley (Kramer and Albrecht 1948; Kuhlman et al. 1979; Tran et al. 1981; Kirleis and Crosby 1982; Glennie-Holmes 1990). A procedure for measuring grain hardness by a tangential abrasive dehulling device (TADD), another type of abrasive milling device, was also reported (Reichert et al. 1986).

In recent years, newer methods such as SKCS and NIR are gaining popularity for measuring wheat hardness even though they require relatively expensive instruments. Apparently, it has something to do with concerns of inadequacies in the methods based on abrasion. Some reasons for this include 1) the range of pearling indexes from the hardest to the softest wheat is relatively narrow; 2) pearling index data does not clearly distinguish the hardness classes; and 3) results vary within a laboratory and greatly among laboratories (Kuhlman et al. 1979).

There is another low-cost abrasive milling device known as a seed scarifier (SS). SS has been used to break dormancy and improve germination rate by mechanically scarifying certain types of seeds that have a thick endocarp (Jensen and Boe 1991) and to detect and enumerate microbial infection in certain grains (Alderman et al. 2003). Most recently, SS has been investigated for removing surface materials from grains layer by layer (Liu 2007). However, a literature search revealed that unlike BP there is no report on using the machine for grain hardness measurement. The objective for abrading grains and collecting abraded fractions is to have less kernel breakage and uniformity of abrading, while the objective for hardness measurement is to find a hardness index that can differentiate textural differences among grain samples. Because the requirements and parameters considered for the two types of uses are rather different, this study was conducted to pursue the latter objective and at the same time to provide some practical information for using an abrasive method based on SS or BP for measuring hardness of wheat. More specific objectives included 1) describing a new procedure for measuring wheat hardness based on SS; 2) comparing the new procedure with other methods based on BP and SKCS procedures; and 3) investigating factors affecting hardness measurement and taking steps to minimize some inadequacies commonly associated with abrasive hardness measurement methods based on SS or BP.
MATERIALS AND METHODS

Wheat Grain Materials

Two sets of wheat samples were used. The first set was reference wheat material (RM 8441a) purchased from National Institute of Standards & Technology (Gaithersburg, MD). One unit of RM 8441a consisted of 50 pouches, five pouches each of five hard wheats and five soft wheats. Each pouch contains 20 g of material. Mean reference values for hardness based on both the NIR instrument and the SKCS 4100 instrument were given by the provider. Samples were stored at a refrigerated temperature and allowed to warm to room temperature immediately before use.

The second set of samples consisted of six soft wheats and 11 hard wheats. All were grown in Idaho and harvested in 2006, except for Nick and the two repeated cultivars (designated as “B” lots), which were grown at different locations in Idaho and harvested in 2005. All samples were stored at room temperature until textural measurement. Before hardness measurement, seed samples were cleaned but not sized. All treatments or measurements were duplicated.

Hardness Measurement by SS

A laboratory electrical seed scarifier (Forsberg, Thief River Falls, MN) described in Liu (2007) was used. It consisted of a metal drum with an inner surface mounted with 40-grit sandpaper and a horizontal rotating steel propeller mounted at the center of a metal cylinder. The propeller was driven by a 1/3 hp motor at a standard speed of 1725 rpm. The cylinder was fastened to the main frame of the scarifier. The diameter of the drum was small enough to slide into the cylinder.

For a typical hardness measurement by SS, a 20-g seed sample was put into the drum. The drum was horizontally aligned into the cylinder with the propeller fixed at the center. The motor was started running at a fixed and full speed. The motor was stopped after scarifying for 40 sec. Abraded kernels, mixed with surface layer fractions, were removed from the chamber and brushed into a container. The mixture was sifted over a screen (U.S. Standard, 18 mesh size, 1.00 mm opening) with the outer layer fractions passing through the screen. The abraded kernels remained on the screen and were weighed. The hardness value of wheat samples was expressed as weight % of kernels remaining after abrasion, and defined as the abrasion resistance index (ARI).

Hardness Measurement by BP

A Strong-Scott barley pearler (Seedburo Equipment, Chicago, IL) fitted with a 30-grit carborundum stone, a 10-mesh screen (10 slots per inch [25.3807 mm]) made of 0.041 in. wire (1.0408 mm) in diameter, and a 1/4 hp motor at a fixed standard speed of 1,725 rpm was used.

The general procedure for wheat hardness measurement followed the recommendation made by McCluggage (1943) with modification. It consisted of placing 20 g of cleaned, unsized wheat sample in the machine, starting the motor to run at its full speed, opening the slide outlet after 60 sec, and stopping the motor after 20 sec more. The abraded sample was sifted over the 18-mesh size screen to remove dust and powdered material. The weight of the material remaining on the screen was recorded as the weight of pearled wheat. Hardness values obtained by BP were expressed as ARI instead of pearling index (PI). PI was defined by Taylor et al (1939) and calculated as percent of surface (continued on facing page)

<table>
<thead>
<tr>
<th>TABLE I</th>
</tr>
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<tbody>
<tr>
<td>Moisture, Kernel Diameter and Weight, and Hardness Values of Reference Wheat Material (8441a) Measured by Different Methodsa</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
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<tr>
<td>Attributes</td>
</tr>
<tr>
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<tr>
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<td>Soft 2</td>
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<tr>
<td>Sample range</td>
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<tr>
<td>Rel sample range (%)</td>
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<tr>
<td>SD</td>
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<tr>
<td>Rel SD (%)</td>
</tr>
<tr>
<td>Hard wheat group</td>
</tr>
<tr>
<td>Hard 1</td>
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<tr>
<td>Hard 2</td>
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<tr>
<td>Hard 3</td>
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<td>Hard 4</td>
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<td>SD</td>
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<td>Rel SD (%)</td>
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<td>Hard min-Soft max</td>
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<td>Rel difference (%)</td>
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<tr>
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<td>Method reproducibility</td>
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<tr>
<td>Avg SD of duplicate tests</td>
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<tr>
<td>Avg rel SD method (%)</td>
</tr>
</tbody>
</table>

a Mean of duplicate measurements ± standard deviation. Values in the same column with different letters are significant at P < 0.05. SD, standard deviation; NIR, near-infrared reflectance spectrometer; SKCS, single kernel characterization system; SS40, seed scarifier, 40-sec run; BP60, barley pearler, 60-sec run; HI, hardness index; ARI, abrasion resistance index, expressed as % of remaining sample weight after abrading.

b Data and reference material provided by National Institute of Standard & Technology.
removal (or % of wheat pearled off). By definition, the two units are convertible based on the formula, \( \text{ARI} = 100 - \text{PI} \).

**Hardness Measurement by SKCS**

A Single Kernel Characterization System (SKCS) instrument, (model 4100, Pertem Instruments, Reno, NV) was used for assessment of single wheat kernel hardness, moisture, and kernel volume and weight. Duplicates of each sample were submitted to the SKCS under normal operating parameters and conditions, with a selection of 300 seeds per measurement. During operation, the instrument isolated individual wheat kernels, measured, weighed, and crushed them in a progressively narrower gap formed by a toothed rotor and a crescent. The crushing force and electrical conductivity between the rotor and electrically isolated crescent were recorded. Those data were then processed by the integrated computer software to provide the means and standard deviations for weight, size, moisture, and hardness index (HI).

**Effects of Abridging Time**

To study the effects of abrading time on hardness values and ability of BP and SS machines to differentiate variations within and across the wheat categories, varying abrading times were used for the second set of seed samples. Because each machine showed a different removal rate (% removal/see) for a given wheat sample, the time increment varied with the machine. For BP, time increments of 30, 60, 90, and 120 sec were selected. For SS, time increments of 20, 40, 60, and 80 sec were selected.

**Effect of Surface Removal Levels**

In this experiment, the relationship between surface removal rate (% removal/sec) and surface removal levels (% removal) was determined by operating BP and SS in a continuous mode, using one soft wheat (Nick) and one hard wheat (Lochsa). During operation, 20 g of sample was abraded continuously until a targeted percentage of removal was reached. In each of subsequent runs, an operation time longer than its previous run was used to reach a higher level of surface removal. Surface removal rate (SRR) was calculated by dividing % of surface removal with the time (sec) required for a particular abrading run.

**Effects of Sample Moisture**

The second set of seed samples, which had been stored in paper bags at an ambient condition until analysis, had initial moisture contents of 10–11%. To study the effects of sample moisture levels on hardness values and ability of SS, BP, and SKCS machines to differentiate variations within and between soft and hard wheat groups, all the samples in the second set were tempered to have moisture contents of 13–14%. For tempering, each sample was put into a freezer bag, and a calculated, weighed amount of water, based on the difference in the targeted moisture level and the original moisture content, was sprayed on. The bag was sealed and put into a refrigerator for five days to equilibrate. All tempered samples were measured for hardness by SKCS, SS, and BP, with varying abrading times for the latter two instruments. Moisture levels were measured by SKCS concurrently during hardness measurement.

**Data Treatments and Statistical Analysis**

Data were treated with JMP software (v.5, JMP, a business unit of SAS, Cary, NC) for analysis of variance to determine the effect of cultivar, moisture, and their interaction. The Tukey’s honestly significant difference (HSD) test was also conducted for pair

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**TABLE I (continued from facing page)**

<table>
<thead>
<tr>
<th>Attributes</th>
<th>SKCS b</th>
<th>SKCS</th>
<th>SKCS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HI</td>
<td>Rank</td>
<td>Moisture (%)</td>
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<tr>
<td>Soft wheat group</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soft 1</td>
<td>24.37 ± 0.85f</td>
<td>1</td>
<td>12.62 ± 0.02a</td>
</tr>
<tr>
<td>Soft 2</td>
<td>26.68 ± 1.99f</td>
<td>2</td>
<td>12.49 ± 0.03a</td>
</tr>
<tr>
<td>Soft 3</td>
<td>33.26 ± 0.33e</td>
<td>4</td>
<td>10.98 ± 0.03c</td>
</tr>
<tr>
<td>Soft 4</td>
<td>32.91 ± 1.36e</td>
<td>3</td>
<td>10.72 ± 0.03d</td>
</tr>
<tr>
<td>Soft 5</td>
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<td>12.47 ± 0.12a</td>
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<td>46.62</td>
</tr>
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<td></td>
<td>2.36</td>
</tr>
<tr>
<td>Rel SD (%)</td>
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<td></td>
<td>18.67</td>
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<tr>
<td>Hard wheat group</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>10.90 ± 0.09c</td>
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<tr>
<td>Hard 2</td>
<td>65.83 ± 2.79cd</td>
<td>2</td>
<td>12.08 ± 0.01b</td>
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<td>Hard 3</td>
<td>68.88 ± 0.75c</td>
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<td>12.62 ± 0.02a</td>
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<td>Hard 4</td>
<td>61.26 ± 1.92d</td>
<td>1</td>
<td>8.47 ± 0.04f</td>
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<td>Hard 5</td>
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<td>5</td>
<td>12.11 ± 0.04b</td>
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<tr>
<td>Mean</td>
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<td></td>
<td>11.07</td>
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<td>Sample range</td>
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<td>4.15</td>
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<td>37.48</td>
</tr>
<tr>
<td>SD</td>
<td>10.19</td>
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<td>1.75</td>
</tr>
<tr>
<td>Rel SD (%)</td>
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<td></td>
<td>15.79</td>
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<td>Between soft and hard groups</td>
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<td>Grand mean</td>
<td>51.38</td>
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<td>11.87</td>
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<tr>
<td>Hard min-Soft max</td>
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<td>-8.15</td>
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<tr>
<td>Rel difference (%)</td>
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<td>-68.69</td>
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<td>Hard mean-Soft mean</td>
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<tr>
<td>Relative difference (%)</td>
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<td></td>
<td>-13.33</td>
</tr>
<tr>
<td>Method reproducibility</td>
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<tr>
<td>Avg SD of duplicate tests</td>
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<td></td>
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<tr>
<td>Avg rel SD method (%)</td>
<td>2.70</td>
<td></td>
<td>0.35</td>
</tr>
</tbody>
</table>

* a Mean of duplicate measurements ± standard deviation. Values in the same column with different letters are significant at \( P < 0.05 \). SD, standard deviation; NIR, near-infrared reflectance spectrometer; SKCS, single kernel characterization system; SS40, seed scarifier, 40-sec run; BP60, barley pearler, 60-sec run; HI, hardness index; ARI, abrasion resistance index, expressed as % of remaining sample weight after abrading.

b Data and reference material provided by National Institute of Standard & Technology.
comparison among all soft and hard wheat samples measured by a single combination of machine and abrading time.

RESULTS AND DISCUSSION

Expression of Hardness

Different methods express hardness in different ways. To make the matter more complex, even for the same method using the same equipment, different reports used different expressions to define hardness values. Thus, it is important to understand the subject, clarify some units that have been used in the literature, and define a new unit for this study. For SKCS, kernel hardness was defined as hardness index and determined from formulas developed by Martin et al. (1993) using various instrument parameters along with kernel moisture and diameter, and calibrated by the reference material (RM 8441a). NIR hardness score was calibrated by the same reference material. For hardness values obtained by BP and other abrasive-action-based equipment (such as TADD), several expressions were used including 1) pearling index (PI) or % of kernel weight pearled off (Taylor et al. 1939); 2) pearling resistance index (PRI), defined as the weight of pearled grains (Obuchowski and Bushuk 1980); 3) rate constant, defined as % milling loss/min (Lawton and Faubion 1989); and 4) abrasive hardness index (AHI), defined as time (sec) required to pearl 1% off (Reichert et al. 1981). In this study, hardness values measured by SS and BP are expressed as % of remaining kernel weight after a given time of abrading and defined as abrasion resistance index (ARI). Unlike pearling index, which has been frequently used in literature for BP-based methods, ARI values correlate positively with grain hardness: the harder the texture, the higher the ARI value. It also takes into consideration the sample charge weight, which was reported to affect pearling efficiency significantly (Liu 2007).

Hardness Profile of Reference Wheat Material

Hardness profiles of reference material (RM 8441a) measured by several methods, and the ranking orders within each soft and hard group, are shown in Table I. Within each wheat group, mean, sample range (difference in maximum-minimum values), relative sample range, standard deviation, and relative standard deviation (also known as coefficient of variance) were calculated and tabulated. These calculated values indicate the ability of a particular method to differentiate textural variation within each group. To determine ability of a particular method to differentiate textural variation between the two wheat groups, the difference between the minimum value of the hard wheat group and the maximum value of the soft wheat group, the difference between means of hard and soft wheat groups, and relative differences of the two attributes against the grand mean are also provided in Table I.

The hardness data in the two left columns of Table I were provided by National Institute of Standards & Technology (NIST), from which the RM 8441a sample was purchased. These samples were prepared and analyzed by the Federal Grain Inspection Service program, Grain Inspection Packers and Stockyards Administration of the U.S. Dept. of Agriculture, based on two methods: bulk NIR hardness measurement (Approved Method 39-70A; AACC International 2000) and single kernel SKCS 4100 (Petern Instrument) measurement. Because only the mean value for each sample was given by the provider, no statistical treatment on pair comparison could be made on these data. However, the computational procedure for NIR and SKCS 4100 standardization using RM 8441a can be found in the Report of Investigation by NIST (2004).

Data in the right columns of Table I were obtained by another SKCS instrument, performed in the author’s laboratory. Not surprising, the method gave hardness values similar to the SKCS data provided by NIST. The reason is that the instrument used the same reference material for calibration and the same operation procedure as the one used by NIST. During operation of this instrument, moisture, kernel diameter, and kernel weight were also measured and are recorded in Table I. There were variations among individual samples in these attributes, but difference between the two groups was not clearly distinguished as shown by the negative value in difference between hard minimum and soft maximum values. This indicates that, although moisture, kernel diameter and weight affected wheat hardness, the effect was not as great as the genetic background of wheat cultivars.

The differences in measured values of individual samples by a particular method within a wheat group existed and, in some cases, were statistically significant (Table I). However, as these differences changed with methods, so did the ranking order based on them. In other words, although SS and BP both operated by abrasive dehulling action, they gave different values for the individual reference wheats as well as the ranking order within each of soft and hard wheat group. These differences can be attributed to the difference in mechanical features during abrasion between the two machines. The ranking order by either SS or BP also differed from those by NIR and SKCS. More importantly, even by the official methods on the same reference materials, the bulk (NIR) and single kernel (SKCS) methods also gave different values for the individual reference wheats as well as the ranking order within the soft and hard wheat groups. An explanation was that two very different techniques were used to determine wheat hardness. The NIR instruments were responding to differences in the particle size of the ground material, while the SKCS instrument depended on crushing force, moisture content, mass, and size per kernel. Another reason for the observations of all the methods was that for some samples in the same group, hardness values measured were rather close to each other.

Because measured hardness values for individual samples, as well as the ranking order within a wheat group, were found to change with methods (including the two official methods NIR and SKCS), any attempt to match hardness values of individual samples measured by SS to those by NIR, SKCS, or BP, or any pair comparison among them through means of correlation could be misleading. Instead, one should look at ability of a particular method to differentiate variation within and across wheat groups. Based on data in Table I, BP and SS gave acceptable performance with regard to the ability to differentiate variation within the soft and hard groups. For BP, relative sample range for the soft and hard wheat groups were 9.57 and 14.60%, respectively; for SS, the relative differences for soft and hard wheat groups were 7.45 and 10.68%, respectively. More importantly, the two instruments were also able to differentiate variations between the soft and hard wheat groups, as indicated by the positive values for the differences between the hard minimum and soft maximum values of ARI (6.30% for SS and 13.22% for BP).

All three methods, SKCS, BP, and SS, performed at our laboratory, had acceptable reproducibility, as indicated by the average relative standard deviation (<3%) of the duplicate measurements for each of 10 samples (Table I). Among the three methods, SS had the highest reproducibility, with a mean relative standard deviation of <0.5%.

It should be pointed out that, although the relative difference between hard-minimum and soft-maximum values and relative differences between hard mean and soft mean values for SS and BP were much less than those of SKCS and NIR, this does not diminish usefulness of the two abrasive instruments to measure hardness of grains. The key reason is that both NIR and SKCS instruments were calibrated based on the reference material, where means of soft and hard wheat groups were arbitrarily set (31.2 and 72.6, respectively, for SKCS; 30.5 and 76.7, respectively, for NIR), whereas the values obtained by the SS and BP methods reflected true resistance of samples to abrasion under a given procedure. No calibration was made for the SS and BP instruments.
Furthermore, with the given sample set, SS of 40 sec run on a 20-g sample showed less ability (narrower difference between hard minimum and soft maximum) to distinguish soft and hard wheats than BP of 60 sec run on the same amount of sample. However, the former produced more reproducible results (lower standard deviation for duplicate results). As shown below, this ability can be improved by increasing abrading time.

**Hardness Profile of 17 Selected Wheat Samples and Effects of Abrading Time**

In measuring hardness of the reference material, SS ran for 40 sec on a 20-g sample size, while BP ran for 60 sec on the same sample size. The reason for choosing different times was that for a given weight of samples, a 40-sec run by SS gave similar ARI values to a 60-sec run by BP. To see the effects of abrading time on ability can be improved by increasing abrading time. However, these differences changed with methods, as did the ranking order within a wheat group based on them. Again, one major reason was that for some samples in the same group, there was little variation in measured textural values. The other reason is that the mechanical action and principles to express hardness values differ among methods. Yet the important finding here is that, with increasing abrading time, the ability of both BP and SS machines to differentiate hardness within and across classes increased. With the longer running time, the relative sample ranges within a wheat group, as well as relative differences between hard mean and soft mean for both BP and SS approached those of SKCS. For example, with SKCS, the relative sample ranges for soft and hard wheat groups were 55.94 and 30.83%, respectively. The relative difference between the minimum value of the soft wheat group and the maximum value of the soft wheat group was 53.84%. The relative mean difference across the groups was 89.11%. With SS, as abrading time increased from 20 to 80 sec, the relative sample range increased from 12.07 to 25.77% for the soft wheat group, and 6.37 to 22.87% for the hard wheat group. At the same time, the relative difference between the minimum values of the hard wheat group and the maximum value of the soft wheat group increased from 3.00 to 26.47%, and the relative difference between means of the two groups increased from 13.14 to 52.96%. With BP, these values were closer to those of SKCS, as running time increased from 30 to 120 sec.

### TABLE II

<table>
<thead>
<tr>
<th>Samples</th>
<th>SKCS HI</th>
<th>BP30 ARI</th>
<th>BP60 ARI</th>
<th>BP90 ARI</th>
<th>BP120 ARI</th>
<th>SS20 ARI</th>
<th>SS40 ARI</th>
<th>SS60 ARI</th>
<th>SS80 ARI</th>
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</thead>
<tbody>
<tr>
<td>Alturas</td>
<td>16.06i</td>
<td>67.95kl</td>
<td>40.30k</td>
<td>18.85j</td>
<td>6.68j</td>
<td>67.63k</td>
<td>47.23l</td>
<td>43.53l</td>
<td>26.35j</td>
</tr>
<tr>
<td>Nick</td>
<td>18.30hi</td>
<td>67.68l</td>
<td>38.28l</td>
<td>15.15k</td>
<td>4.30k</td>
<td>68.70j</td>
<td>48.43k</td>
<td>35.65k</td>
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<tr>
<td>Penewawa</td>
<td>20.05hi</td>
<td>73.83i</td>
<td>50.03i</td>
<td>30.08h</td>
<td>15.15h</td>
<td>73.65i</td>
<td>55.08i</td>
<td>42.58i</td>
<td>33.83g</td>
</tr>
<tr>
<td>Pett</td>
<td>21.79h</td>
<td>70.60j</td>
<td>39.65k</td>
<td>16.85jk</td>
<td>5.53jk</td>
<td>73.20h</td>
<td>51.18h</td>
<td>36.75j</td>
<td>27.25j</td>
</tr>
<tr>
<td>White Bird</td>
<td>27.53g</td>
<td>76.13h</td>
<td>49.00h</td>
<td>25.70a</td>
<td>12.15i</td>
<td>76.28g</td>
<td>55.55i</td>
<td>40.10i</td>
<td>30.55h</td>
</tr>
<tr>
<td>Mean</td>
<td>20.50</td>
<td>70.93</td>
<td>43.65</td>
<td>22.00</td>
<td>9.12</td>
<td>71.69</td>
<td>51.52</td>
<td>38.14</td>
<td>29.24</td>
</tr>
<tr>
<td>Sample range</td>
<td>11.47</td>
<td>8.45</td>
<td>11.75</td>
<td>14.93</td>
<td>10.85</td>
<td>8.65</td>
<td>8.33</td>
<td>8.05</td>
<td>7.48</td>
</tr>
<tr>
<td>Rel sample range (%)</td>
<td>55.94</td>
<td>11.91</td>
<td>26.92</td>
<td>67.84</td>
<td>11.96</td>
<td>12.07</td>
<td>16.16</td>
<td>21.11</td>
<td>25.57</td>
</tr>
<tr>
<td>SD</td>
<td>3.93</td>
<td>3.39</td>
<td>5.03</td>
<td>5.89</td>
<td>4.26</td>
<td>3.28</td>
<td>3.38</td>
<td>3.03</td>
<td>2.87</td>
</tr>
<tr>
<td>Rel SD (%)</td>
<td>4.19</td>
<td>4.77</td>
<td>11.52</td>
<td>26.79</td>
<td>46.76</td>
<td>4.57</td>
<td>6.56</td>
<td>7.69</td>
<td>9.81</td>
</tr>
</tbody>
</table>

#### Hard wheat group

- **Classic**: 53.59f
- **Jerome B**: 56.83ef
- **Jerome**: 57.00ef
- **Lochsa B**: 59.47de
- **Jefferson**: 61.65de
- **Ivy**: 63.52cd
- **Lohr**: 67.30bc
- **Boudry**: 67.45bc
- **Darwin**: 68.45acc
- **Jumpr**: 71.36ab
- **Declo**: 73.21a
- **Mean**: 63.63
- **Sample range**: 19.62
- **Rel sample range (%)**: 30.83
- **SD**: 6.45
- **Rel SD (%)**: 10.14

#### Soft wheat group

- **Alturas**: 16.06i
- **Nick**: 18.30hi
- **Cataldo**: 19.25hi
- **Penewawa**: 20.05hi
- **Pet**: 21.79h
- **White Bird**: 27.53g
- **Mean**: 20.50
- **Sample range**: 11.47
- **Rel sample range (%)**: 55.94
- **SD**: 3.93
- **Rel SD (%)**: 4.19

<table>
<thead>
<tr>
<th>Methods reproducibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg SD of duplicate tests</td>
</tr>
<tr>
<td>Avg rel SD of method (%)</td>
</tr>
</tbody>
</table>

| Average of duplicate measurements. Values in the same column with different letters are significant at \( P < 0.05 \). HI, hardness index; ARI, abrasion resistance index; SKCS, single kernel characterization system; BP, barley pearler; SS, seed scarifier; Numbers after BP or SS are runtime (sec). ||  |
Again, all the three methods (SKCS, BP, and SS) showed very
good reproducibility, with a mean relative standard deviation of
duplicate measurement for each of 17 samples in the range of
0.27–2.01%. SS also had the best reproducibility index; the mean
relative standard deviation was <0.5% for all four runs of varying
times.

**Surface Removal Rate (SRR) as a Function of Surface Level Removal**

To understand the effect of abrading time on the ability of SS or
BP to differentiate variation in hardness within and between
wheat classes, an experiment was conducted to investigate the the
relationship between the surface removal rate and levels of surface
removal. In abrading Lochsa (representative of a hard white
wheat cultivar), the SRR by SS showed a noticeable decrease as the
level of surface removal increased, except for a very small hump at the seed surface area (Fig. 1). This indicates that from
surface to endosperm area, the resistance to abrasion (or hard-
ness) generally increased. In contrast, in abrading Nick (representa-
tive of a soft white wheat cultivar) at the surface area, the SRR
had a value not far from that of Lochsa, indicating that resistance
to abrading was somehow similar for both types of wheat at the
surface area. But what set the two types of wheat apart was that
for soft wheat, there was a sudden increase in SRR, that is, a sud-
den drop in resistance to abrade in the bran area. After that, there
was a continuous increase in resistance to abrasion as abrading
action entered the center area. This indicates that for soft wheat,
the resistance to abrasion (or hardness) increased from the inner
bran area to the endosperm area, rather than from the surface area.

The relationship between SRR with surface removal level under
operation of BP (Fig. 2) showed patterns similar to those of SS. However, for BP, the overall value of SRR was smaller than those
under SS. This explains why the 60-sec run under BP gave ARI
values similar to the 40-sec run under SS. Furthermore, the scale
of decreases in SRR with the levels of surface removal, particu-
larly for Nick, was much less than that by SS (Fig. 2A vs. Fig. 1).
Careful examination of the difference in operation between BP
and SS revealed the reason for the difference in changing patterns
between BP and SS. SS did not have a built-in screen. Only after
operation could the two fractions, surface layers scarified and
abraded kernels, be separated by passing through a screen. The
BP had a built-in screen. During operation, small particles such as
removed outer layers, broken kernels, and intact small seeds,
passed through the screen and were separated from abraded ker-
nels. This situation aggregated when the size of pearled kernel
was reduced and some kernels were broken as the level of surface
removal increased. After the weight of these passing-through ma-
terials was corrected in calculating removal rates (by subtracting
it from the total surface removal), the changing patterns of SRR
by BP were similar to those by SS on Nick and Lochsa (Fig. 2B
vs. Fig. 1).

Because hardness of wheat, expressed as % of kernel weight
remained after a given time of abrasion (ARI) is closely related to
surface removal rate, examining the changing pattern of the re-
moval rate with increasing surface removal levels as well as the
difference in values and patterns among cultivars is of practical
importance for textural measurement by both BP and SS. Within a

![Figure 1](image1.png)

*Fig. 1. Relationship between surface removal rates (SRR) and levels of
surface removal by the seed scarifier on Nick (soft wheat) and Lochsa (hard
wheat). Surface removal levels were calculated as % of surface removal after
abrading for a given time period, while SRR was expressed as % of sur-
face removal/sec. Sample charge size was 20 g.*

![Figure 2](image2.png)

*Fig. 2. Relationship between surface removal rates (SRR) and levels of
surface removal by the barley pearler on Nick (soft wheat) and Lochsa
(hard wheat) without (A) and with (B) correction for fine materials lost
through the built-in screen. Surface removal levels were calculated as %
of surface removal after abrading for a given time period, while SRR was
expressed as % of surface removal/sec. Sample charge size was 20 g.*
given level of surface removal, the larger the difference between
or among samples, the better the abrasive method could differenti-
te individual samples in hardness values. From Fig. 1, the dif-
fERENCE in SRR by SS between Nick and Lochsa was smallest at
the seed surface area, increased to a highest level at 4% surface
removal level, and then decreased to noticeable levels when sur-
face removal reached 5%. This indicates that at 4% surface
removal levels (i.e., values between 80 and 20 ARI), the SS method
was at an optimum in differentiating variation in hardness among
samples. Because for a given wheat sample, surface removal is
affected by many factors including machine type, sample charge
size, and abrading time (Liu 2007 and this study) for improved
performance of a particular SS procedure under development, a
combination of parameters that produce ARI values of 80–20 is
recommended. In this study, for a 20-g sample charge size in the
SS instrument, a running time within 40–80 sec is recommended.
For BP, due to loss of small and broken pieces into a built-in
screen, the difference in removal rate between the two samples
did not show a decrease at higher surface removal levels (Fig. 2).
However, targeting ARI values of all samples within 80–20 is also
recommended.

**Effect of Seed Moisture**

From the same lot of selected soft and hard wheats, samples
with two moisture ranges (10–11% and 13–14%) were measured
for hardness by three instruments: SS, BP, and SKCS. Analysis of
variance shows that both cultivar and moisture had a significant
effect (P < 0.05) on hardness values measured by all three instru-
ments. There was also a strong interaction effect between cultivar
and moisture. In general, based on mean hardness values of soft
and hard wheat groups and, overall, an increase in moisture levels
from 10–11% to 13–14% ranges caused significant increases in
ARI by all three methods, with varying operation times for both
BP and SS, for both soft wheat and hard wheats. However, com-
parably, the increase for hard wheat group was less than for soft
wheat group.

Controversy exists in literature regarding the moisture effect
on pearling index of wheat samples by BP, indicating that the effect
of moisture on hardness measurement is complex and needs to be
interpreted with caution. McCluggage (1943) studied the effect of
moisture content on pearling index using six hard red winter
wheats with moisture levels of 7–15% and found little or no in-
fluence. However, Kramer and Albrecht (1948) showed that pear-
ling index decreased (in other words, ARI increased) as moisture
content increased. They also noticed that soft wheats were af-
fected more by moisture content than were hard wheats. Obuch-
owski and Bushuk (1980) reported that hardness values by BP,
expressed as weight of surface removal, increased slightly with
moisture for all classes of wheat except for the hard red class,
where it decreased slightly at higher moisture levels. Singh and
Bakshi (1991) reported that the effect of moisture levels on pear-
ing index of wheat was statistically significant when pearling time
was 45 sec (20-g sample charge size), but the effect was not sig-
ificant when pearling time was 60 sec. They also found no obvi-
ous changing patterns in pearling index with increasing moisture
levels. Results of the present study agreed with the findings of
Kramer and Albrecht (1948).

Furthermore, based on data in Table III, the moisture level had
some effect on ability of methods to differentiate variation within
and between soft and hard wheat groups. At the higher moisture
range (13–14%), the ability of the BP and SS methods to differenti-
te variation between the two wheat groups apparently dimin-
ished, as shown by negative or reduced values in relative differ-
ence between the average of the hard wheat group and the max-
imum of the soft wheat group. However, the negative value was
limited only to the BP 30-sec run and the SS-S 20-sec run, ARI
values, as observed above (Figs. 1 and 2), which were not in the
recommended range of 80–20. Again, at both ranges of moisture
levels, with increasing abrading time, the ability of the BP or SS
machine to differentiate hardness within and between classes
increased. Obuchowski and Bushuk (1980) compared three meth-
ods, particle size index, Brabender hardness tester, and BP for
wheat hardness measurement and the ability to differentiate culti-
vars across wheat classes, and also found that the moisture con-
tent affected not only results of all methods for hardness evaluation
but also the maximum ability of methods to differentiate cultivars
across the wheat groups.

Because moisture levels affected hardness values measured by
the three instruments, and because the values among each wheat
group had very small variation for some cultivars (in some cases,
not significantly different from each other, as shown in Table II),
the moisture level also had effects on ranking order of hardness
values within each wheat group (Table IV). For samples with the
same moisture range, measured by the same type of instrument
(either BP or SS), the ranking order in hardness within a wheat
group changed with the abrading time. This observation on change
of ranking order within a wheat class, true for any hardness
measuring instrument tested, including BP, SS, and SKCS, would
frustrate researchers who try to compare hardness of cer-
tain wheat samples. However, the ability of the BP, SS, and SKCS
instruments to differentiate variation between the soft and hard
wheat groups remained unchanged, as indicated by positive values
in relative difference in hardness between the groups (Table III).

<table>
<thead>
<tr>
<th>Index</th>
<th>Moisture %</th>
<th>SKCS HI</th>
<th>BP30 ARI</th>
<th>BP60 ARI</th>
<th>BP90 ARI</th>
<th>BP120 ARI</th>
<th>SS20 ARI</th>
<th>SS40 ARI</th>
<th>SS60 ARI</th>
<th>SS80 ARI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean of soft wheat group</td>
<td>10–11</td>
<td>70.39b</td>
<td>43.65b</td>
<td>22.00b</td>
<td>9.12b</td>
<td>71.68b</td>
<td>51.52b</td>
<td>38.14b</td>
<td>29.24b</td>
<td></td>
</tr>
<tr>
<td>Mean of hard wheat group</td>
<td>13–14</td>
<td>73.70a</td>
<td>52.87a</td>
<td>32.68a</td>
<td>17.76a</td>
<td>79.36a</td>
<td>59.91a</td>
<td>45.74a</td>
<td>35.52a</td>
<td></td>
</tr>
<tr>
<td>Total sample</td>
<td>13–14</td>
<td>82.71a</td>
<td>67.31a</td>
<td>42.36a</td>
<td>31.52a</td>
<td>84.93a</td>
<td>72.28a</td>
<td>62.65a</td>
<td>54.81a</td>
<td></td>
</tr>
<tr>
<td>mean</td>
<td>13–14</td>
<td>74.71a</td>
<td>62.15a</td>
<td>33.68a</td>
<td>28.96a</td>
<td>82.96a</td>
<td>67.91a</td>
<td>56.68a</td>
<td>48.00a</td>
<td></td>
</tr>
<tr>
<td>Rel sample range of soft wheat group (%)</td>
<td>10–11</td>
<td>11.94a</td>
<td>26.92a</td>
<td>67.84a</td>
<td>118.96a</td>
<td>12.07</td>
<td>16.16</td>
<td>21.11</td>
<td>25.57</td>
<td></td>
</tr>
<tr>
<td>Rel sample range of hard wheat group (%)</td>
<td>10–11</td>
<td>8.97a</td>
<td>18.26a</td>
<td>31.52a</td>
<td>54.12a</td>
<td>6.37</td>
<td>11.70</td>
<td>15.67</td>
<td>22.87</td>
<td></td>
</tr>
<tr>
<td>Rel diff between min &amp; soft max (%)</td>
<td>13–14</td>
<td>1.37</td>
<td>15.44</td>
<td>28.21</td>
<td>-3.31</td>
<td>2.06</td>
<td>9.92</td>
<td>15.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rel diff between hard &amp; soft mean (%)</td>
<td>13–14</td>
<td>38.12</td>
<td>73.09</td>
<td>106.46</td>
<td>13.14</td>
<td>28.40</td>
<td>42.00</td>
<td>52.96</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Values in the same column with different letters were significant at P < 0.05. HI, hardness index; ARI, abrasion resistance index; SKCS, single kernel characteri-
  zation system; BP, barley pearler; SS, seed scarifier. Numbers after BP or SS are runtime (sec).
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CONCLUSIONS AND RECOMMENDATIONS

Wheat hardness can be measured empirically with seed scarifiers (SS). Like BP, SS is based on an abrasive dehulling action. The hardness value measured by both instruments reflected resistance of samples to abrasion under a given procedure.

Many factors affect BP and SS performance with respect to hardness values obtained and ability of the instruments to differentiate variation within and between soft and hard wheat groups. These include type of instrument, running time, levels of surface removal, and moisture levels. Thus, different instruments as well as different measuring conditions (parameters) of the same instrument gave different hardness values for the same samples. Additional factors such as sample charge size and seed kernel size, etc., may also affect hardness measurement. However, they were not within the scope of this study.

For a given method, although differences in measured hardness values of individual samples within a wheat group exist and can sometimes be statistically significant, they are very much method-dependent and thus any ranking order based on them can be misleading. This is true for methods based on all instruments used in this study, including SS, BP, and SKCS. However, all the methods do have the ability to differentiate variation between soft or hard groups. It is this ability that wheat textural measurement has been and should be based on. Any attempt to differentiate variation and then rank samples in hardness within a soft or hard wheat group should be made with caution.

Early researchers reported concerns or inadequacies for the methods based on the abrasive action such as BP-based methods, as described above. This study addressed some, if not all of these concerns. Recommendations included 1) defining hardness values as abrasion resistance index and expressed as % of kernel remaining after a given time of abrading; and 2) choosing a combination of parameters that produces ARI values in the range of 80–20. By doing so, although the range of ARI from the hardest to the softest wheat was still relatively narrower than that of SKCS or NIR, the ARI data generated by SS or BP were able to differentiate the hardness classes of soft and hard wheat. Because of this ability and because of their low cost, availability, durability, methodological simplicity, and repeatability, abrasion methods based on BP or SS can still be useful for wheat hardness measurement, particularly when or where the instruments for contemporary methods such as SKCS and NIR are not readily available.

However, unlike SKCS and NIR instruments, which have electronic control systems for standardization and calibration, there is a lack of standardization and calibration systems for BP or SS methods. This makes it difficult to compare results among laboratories because so many factors affect hardness measurement. Furthermore, unlike the SKCS and NIR methods, which not only give a hardness value, but also classify a sample as “hard”, “soft”, or “mixed”, the abrasion methods are unable to distinguish the mixed type (such as a hard and soft wheat blend). Therefore, to improve performance of SS and BP machines for textural measurement, it is also recommended to first run a set of reference material such as the one used in this study (RM 8441a) for a given procedure. This provides bench marks on ARI values for each type of wheat and then, based on the bench marks, to determine which samples belong to which type. Hopefully, this study will stimulate some interest in modifying the machines and developing systems or procedures for standardization and calibration so that abrasion methods can be as useful as SKCS and NIR methods for application in the commercial milling industry.

ACKNOWLEDGMENTS

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LITERATURE CITED


