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Effects of kernel hardness and moisture content on wheat breakage in the single kernel characterisation system

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Abstract

The particle size distribution (psd) produced by breakage of wheat in the Perten Single Kernel Characterisation System (SKCS) was measured using sonic sifting, for a range of wheat varieties, kernel sizes and moisture contents. At moisture contents of 16% wb, the psd produced by the SKCS was very evenly spread over the range 106–3350 μm, with the average particle size much greater than would result from roller milling. Hard wheats gave slightly smaller average particle sizes in the broken material (this was unexpected and contrasts with First Break roller milling, for which hard wheats give larger output particles than soft wheats), but the variation in psd among different wheat varieties was surprisingly small. This indicates that the SKCS exerts a very positive breakage action on wheat grains, giving similar degrees of breakage to kernels of different hardness. The reported hardness index therefore depends primarily on the crushing force profile or energy to grind, and is not confounded by differences in the extent of breakage achieved. Kernel size similarly gave little difference in the output psd. The effect of increasing the moisture content from 9 to 17% wb was to increase the average output particle size greatly; moist kernels do not break so readily in the SKCS.

Keywords: Wheat; Hardness; Breakage; Roller milling; SKCS; Particle size distribution; Sonic sifting; Flour

Industrial relevance: There is an emerging trend towards single kernel characterization in wheat quality testing to also gain insights on genetic and environmental influences as well as on moisture distribution. Several attempts have been made to approximate hardness as a key quality criterion. However, no universally accepted definition of hardness exists. This paper is based on the notion that during First Break roller milling, kernels break independently according to their individual properties. Meaning if the distribution of kernel properties in a sample is known predictions for the breakage behavior of grain mixtures should be possible. Interestingly it could be shown that hardness was independent of moisture content (9–17%). Hardness measurement under the given conditions related primarily to the energy required to crush the kernels. This work clearly addresses the industrial need for a fundamental definition of wheat hardness.

1. Introduction

In recent years, wheat quality testing has started to move from bulk methods to single kernel methods, in which the distributions of quality parameters of individual grains in a sample are measured. This emerging trend gives additional information about the distribution of parameters and allows correlations between single kernel parameters and processing performance to be identified. Several innovative techniques have been investigated in order to provide accurate, rapid, convenient and informative methods of measuring and predicting quality from tests on single kernels (Regnér, 1995; Evers, 1996). The Single Kernel Characterisation System (SKCS) developed by the USDA Research Centre at Beltsville, MD and commercialised by Perten Instruments, Sweden, is the most well developed system for evaluating the quality characteristics of individual wheat kernels (Martin, Rousser & Brabec, 1993; Psotka, 1995; Gaines, Finney, Fleege & Andrews, 1996; Osborne et al., 1997; Sissons, Osborne, Hare, Sissons & Jackson, 2000). The SKCS measures the weight, diameter, hardness and moisture of (usually) 300 individual kernels within 5 min, and provides information in the form of means and distributions.

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Hardness is a widely used measure of wheat breakage patterns, and is one of the key parameters reported by the SKCS. During roller milling, hard and soft wheats behave differently; hard wheats initially shatter into large angular pieces and few fine particles are released, whereas in soft wheats, fractures occur through the contents of the endosperm cells (Hoseney, Wade & Finley, 1988; Pomeranz, Martin, Rousser, Brabec & Lai, 1988). Moisture content affects wheat endosperm hardness, which is in part the reason for conditioning treatments prior to milling. In a comprehensive study comparing the effect of moisture on five different methods of measuring hardness, Obuchowski and Bushuk (1980) showed that moisture content affects different hardness tests and different cultivars to differing extents, but increasing moisture generally led to reduced hardness. Hsieh, Martin, Black and Tipples (1980) investigated the effect of moisture content on the First Break grinding of Canadian wheat, with respect to the ash and protein contents of the product streams and starch damage of the flour. Their results showed that increasing the moisture contents of wheat from 14.5 to 15.5% through tempering resulted in higher break releases (many smaller particles being produced). Glenn, Younce and Pitts (1991) studied the compressive hardness of wheat endosperm and found that beyond 17.5% moisture, textural changes occur causing wheat to become too mellow to fracture and mill properly.

Hardness has been measured previously using a range of approaches and instruments. The principle of hardness measurement may be based on crushing force (Pomeranz et al., 1988), time to grind (Stenvert, 1974; Williams, Kilborn, Voisey & Kloek, 1987; Wu & Nelson, 1991) or particle size produced (Cutler & Brinson, 1935; Symes, 1961; Williams, Sobering, Knight & Psotka, 1998). However, the basis of hardness measurement in the SKCS has not been precisely defined previously. In an ideal system for measuring wheat hardness, either the degree of breakage will be kept constant (constant output particle size distribution) and the energy required to achieve this measured, or a constant energy input will be applied, and the resulting degree of breakage measured. In most actual systems used for measuring wheat hardness, neither the energy input nor the extent of breakage is kept constant, compromising the meaningfulness and interpretation of the results. The SKCS clearly measures the crushing force during breakage (related to the energy input), but in previous studies the resulting particle size distribution (indicating the extent of breakage) has not been measured as well. It is therefore, unresolved as to whether the hardness index reported by the SKCS is related to a combination of both the energy to break and the extent of breakage, or if in practice one of these is relatively constant and the other is measured relatively unambiguously.

Despite this uncertainty, numerous workers have applied the SKCS to a range of studies and have concluded that it gives useful results. Morris, DeMacon and Giroux (1999) found that the SKCS provided the best discriminating measure of genetically different wheat hardnesses. Other workers have measured wheat properties with the SKCS and compared the results with conventional methods (Satumbaga, Martin, Eustace & Deyoe, 1995; Gaines et al., 1996). Osborne et al. (1997) reported on the use of SKCS data for prediction of wheat milling performance, in particular flour yield and starch damage quality. They concluded that the SKCS generates information on sample uniformity not otherwise available, and that data on the uniformity of hardness could be interpreted in terms of the potential for consistent milling performance. The raw SKCS data also offer the potential to screen early generation plant breeding lines for milling and flour quality (Sissons et al., 2000). Furthermore, the distribution of moisture contents from SKCS measurement provides additional information about a sample's potential storage stability (Osborne et al., 1997). Ohm, Chung and Deyoe (1998) investigated the relationship of wheat single kernel characteristics with end-use properties and found significant correlation between SKCS data and milling and baking quality.

Hardness is not clearly defined in a fundamental sense, such that relating hardness measurements to genetic and environmental influences and to milling performance is not straightforward. Wheat hardness is complex and dependent upon a number of kernel properties. However, no universally accepted definition of hardness exists (Simmonds, 1974; Wu, Stringfellow & Bietz, 1990), and the hardness index reported by the SKCS itself is an arbitrary indicator, nominally varying from 0 to 100, with no units. Also, in addition to hardness, several other single kernel parameters, including weight, size, shape, moisture content and density are believed to affect milling (Williams et al., 1987; Pomeranz et al., 1988).

Recent studies have demonstrated that during First Break roller milling, grains break independently, i.e. each kernel breaks according to its own physico–chemical properties, independent of the mixture of kernels surrounding it (Campbell & Webb, 2001). This means that if the distribution of kernel properties in a sample is known, and if predictive equations of breakage of individual kernels in terms of their physico–chemical properties exist, then it is feasible to predict the breakage of the mixture based on the distributions of single kernel properties. Thus, it is possible, in principle, to predict wheat breakage during roller milling directly from SKCS parameters. As a step towards this goal, the objective of the current work was to determine the breakage produced in the SKCS itself. This would help in identifying the basis of the hardness index reported by the SKCS

Table 1
Average kernel properties of wheat samples measured by the SKCS

Variety	Weight (mg)	Diameter (mm)	Hardness Index	Moisture content (%)
Drake	45.45	2.73	25.7	16.14
Consort	46.47	2.85	26.3	16.08
Riband	50.19	2.97	28.1	16.01
Crofter	49.23	2.80	45.4	16.31
Soissons	43.41	2.68	54.1	15.81
Avalon	46.70	2.80	62.0	16.05
Haven	50.59	3.12	62.0	16.39
Abbot	44.90	2.80	62.1	16.12
Buster	45.08	2.96	64.1	15.84
Charger	42.58	2.74	64.7	16.05
Raleigh	44.67	2.87	65.8	16.08
Caxton	46.90	2.98	66.4	15.73
Rialto	47.79	2.94	68.4	15.65
Brigadier	46.35	2.76	68.9	15.88
Mercia	45.22	2.84	71.1	16.07
Cadenza	52.69	3.10	71.9	15.79
Spark	37.17	2.64	79.1	16.15

and thus interpreting the physical significance, and in relating SKCS parameters to breakage during industrial roller milling.

2. Materials and methods

Investigations were performed on the effects of kernel hardness, size and moisture content on breakage in the SKCS Model 4100 (Perten Instruments AB, Sweden), as measured by the resulting particle size distribution of the broken kernels.

2.1. Effect of wheat hardness on breakage in the SKCS

Seventeen winter wheat cultivars from the year 2000 harvest, covering a range of hardness values, were obtained for this study from ADAS (Rosemaund, UK). The samples were conditioned overnight in 100 g batches to a moisture content of 16% (wb). Table 1 reports the average properties of the 17 varieties of wheat measured in the SKCS after conditioning, showing the wide range of hardness values. Conditioned samples were loaded into the Perten SKCS (Perten Instrument AB, Sweden) and tested according to the operating manual procedure (Single Kernel Characterisation System 4100 Manual, 1995). After testing of 300 kernels was completed, the broken material was collected and kept in individual sealed polyethylene bags for further analysis. Five replicates were performed for each wheat sample, resulting in approximately 15–20 g of broken material from each run.

The particle size distribution (psd) of the broken material was measured by sonic sifting using a GilSonic Autosiever (Gilson Company, Worthington, Ohio). The Autosiever can take seven sieves, so two sets of sieves were used to allow the particle size distribution to be measured accurately over a wide size range. The coarse set of sieves consisted of the following aperture sizes: 3350, 2800, 2360, 2000, 1700, 1400 and 1000 μm. The fine set comprised 850, 600, 300, 250, 180, 125 and 106 μm sieves. The sieves were placed in the stack with the largest aperture size on top, and samples loaded onto the top sieve. Sieving was carried out according to the operating manual (Gilson Company, Worthington, Ohio). The total sieving time was set at 5 min, and included both vertical and horizontal tapping and sonic pulsing. Sonic pulsing consisted of 3600 pulses/min (60 Hz), and the amplitude of the pulse was adjusted to allow the samples to flow freely on the sieves. The amount of power used for both sets was 97% of full power. After the process was completed, a balance accurate to 0.01 g (Ohaus Corporation, Florham Park, NJ) was used to weigh the material remaining on each sieve and in the fines collector. Material collected in the fines collector following sieving using the coarse sieve set was then analysed using the fine sieve set, to give a total of 15 fractions.

2.2. Investigation of the effect of kernel moisture content on breakage in the SKCS

From the 17 varieties, four selected varieties representing the range of hardness values (79.1, 54.1, 45.4 and 26.3) were prepared in 100 g batches and conditioned to four different tempering moistures: 13, 14, 15 and 16% (wet basis, wb) to investigate the effect of moisture on breakage in the SKCS. In addition, wheat of the cultivar Soissons was conditioned to nine different tempering moistures: 9, 10, 11, 12, 13, 14, 15, 16 and 17% (wb). Tempering wheat to moisture contents lower than 14% was achieved by oven-drying kernels overnight at 60 °C to reduce initial moisture content; the target tempering moisture was then achieved by adding appropriate amounts of water and allowing the samples to temper overnight. The tempered samples were then broken in the SKCS and analysed in the sonic sifter as described above.

3. Results and discussions

Fig. 1 shows an example of the probability density function, $\rho(x)$, and the cumulative psd, $P(x)$, obtained for conditioned Drake wheat at 16% moisture. The probability density describing particle size distributions was approximated by dividing the mass fraction of particles staying on each sieve in the stack by the difference between the aperture size of the sieve and that of the adjacent larger sieve. The probability density was relatively consistent over the particle size range, indicating that breakage in the SKCS produces a wide and evenly distributed range of particle sizes. The cumulative percentage of undersize particles was also

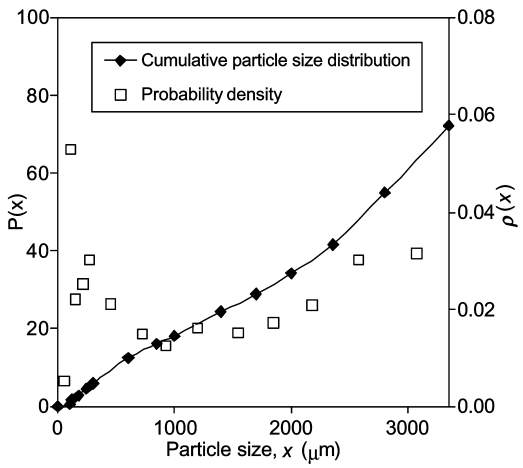

Fig. 1. Cumulative particle size distribution and probability density function resulting from milling sample of Drake (a soft wheat) conditioned to 16% moisture.

calculated, from which the average particle size, x_{50}, and the particle sizes below which 25 and 75% of material fell, x_{25} and x_{75}, respectively, were determined by linear interpolation. For the Drake sample shown in Fig. 1, the x_{25} and x_{50} were 1438 and 2635 μm, respectively, while x_{75}, just beyond the particle size range measured, was estimated to be 3434 μm. These particle sizes are much larger than would be expected from First Break roller milling, for which the x_{50} is typically in the range 500–1500 μm (Fang & Campbell, 2003a). This suggests that the mechanism of breakage in the SKCS is primarily compression, which tends to produce larger particles, in contrast to roller milling in which shear contributes significantly, as well as compression, the relative contributions depending on roll disposition (Fang & Campbell, 2002a,b, 2003a). The large particles also reflect the relatively large final gap of 0.89 mm between the rotor and crescent in the SKCS (Martin & Steele, 1996).

3.1. Effect of wheat hardness

Fig. 2 shows the variation in x_{25}, x_{50} and x_{75} with kernel hardness for all 17 varieties. (N.B. Data points for cumulative psd's and the x_P values derived from them are averages of five replicates; error bars were smaller than the symbols used in the graphs, so are not shown.) At the smaller end of the particle size range, the size below which 25% of the broken material fell varied very little with kernel hardness. The x_{50} and x_{75}, however, decreased slightly with increasing kernel hardness. This indicates that harder kernels gave, on average, slightly smaller output particles. This is counter-intuitive, as hard wheats might be expected to be harder to break and therefore to give larger output particles, as indeed has been reported for First Break roller milling (Hoseney et al., 1988; Campbell, Bunn, Webb & Hook, 2001; Bunn, Campbell, Fang & Hook, 2001). This indicates that the predominant mechanisms of breakage in the SKCS differ from those operating during roller milling. However, the variation in output particle size with hardness is surprisingly small. None of the R^2 values shown on Fig. 2 are significant (although this is primarily due to the two apparent outliers—if these are removed, the relationships appear much tighter and, for x_{50} and x_{75}, achieve R^2 values that are just significant at the 5% level. Nevertheless, even if statistically significant, the effect of hardness on the particle size distribution is not great). This indicates that the SKCS exerts a very positive crushing action on the wheat kernels, giving similar degrees of breakage to kernels of different hardness. The reported hardness index therefore depends primarily on the crushing force profile and is not confounded by large differences in the extent of breakage achieved. In other words, hardness measurement of the SKCS relates primarily to the energy required to crush the kernels.

Martin and Steele (1996) reported investigations of different SKCS rotor designs, concluding that a rotor with a sawtooth pattern gave the best hardness discrimination. It would be worthwhile to revisit the issue of rotor design from the point of view of output particle size; if a particular design proved to give an even more consistent particle size, it would make the reported hardness values even more unambiguous and easier to interpret. It might even be possible to define the measured hardness in fundamental units such as energy required per unit area of new surface produced.

3.2. Effect of moisture content

Fig. 3 shows the cumulative particle size distributions at 16% moisture for the four samples selected for

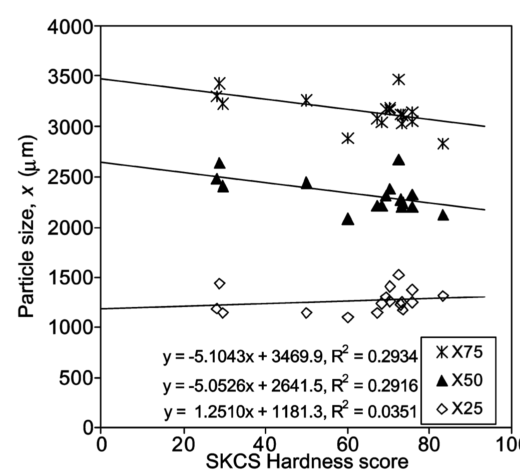

Fig. 2. x_{25}, x_{50} and x_{75} vs. SKCS hardness of seventeen wheat varieties conditioned to 16% moisture.

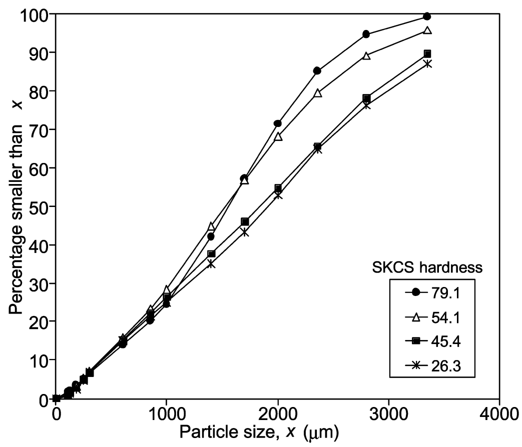

Fig. 3. Cumulative size distribution of wheats of different hardness at a tempering moisture of 16%.

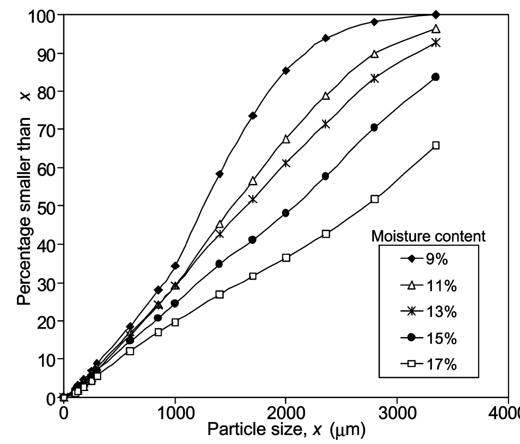

Fig. 5. Cumulative size distribution of Soissons wheat at different tempering moistures.

investigating the effect of moisture. Fig. 3 confirms that the differences in particle size distribution with hardness were more evident at the larger end of the range. Fig. 4 shows the x_{50} for the four wheats at different moisture contents. Clearly, increasing the moisture content increased the average output particle size, but the difference in breakage between the wheat samples was preserved, i.e. there was no strong hardness-moisture interaction. Similar studies using Hereward and Consort samples separated into narrow size fractions and tempered to different moisture contents confirmed this effect, and also showed that kernel size has a negligible effect on breakage in the SKCS (results not shown).

The effect of moisture on breakage was studied in more detail for a single variety, Soissons, conditioned to 9, 10, 11, 12, 13, 14, 15, 16 and 17% moisture. Fig. 5 shows the cumulative particle size distributions for five of these moisture contents, for clarity, illustrating that, like hardness, the effect of moisture is greater at the larger end of the particle size range. This is confirmed in Fig. 6, which shows a small effect of moisture on x_{25}, but larger effects on x_{50} and x_{75}, especially at moisture contents above 14%. Increasing moisture content increases the average particle size, primarily by increasing the size of the larger, more branny particles, as moisture toughens bran. Increasing moisture also softens endosperm, facilitating breakage (Obuchowski & Bushuk, 1980), but this is not reflected in a greater number of particles at the small end of the range. This is in contrast to the effect of moisture on breakage during roller milling, for which increasing the moisture content increases the numbers of both small and large particles, giving fewer in the mid-size range (Fang & Campbell, 2003b). Similarly Hsieh et al. (1980) found that increasing the moisture content gave a greater proportion of smaller particles. This again reflects that the mechanisms of breakage in the SKCS are somewhat different to those operating during roller milling. This may imply that relating SKCS hardness to breakage

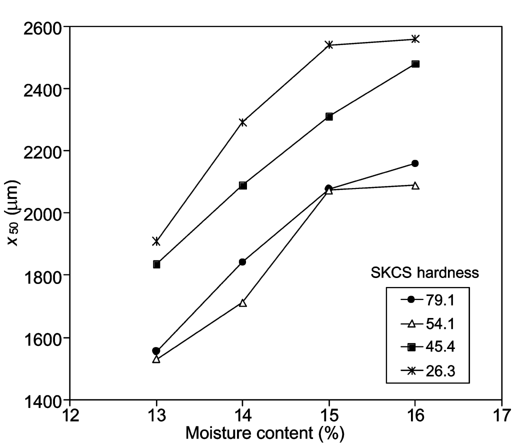

Fig. 4. Average particle size, x_{50} of wheats of different hardness at various tempering moistures.

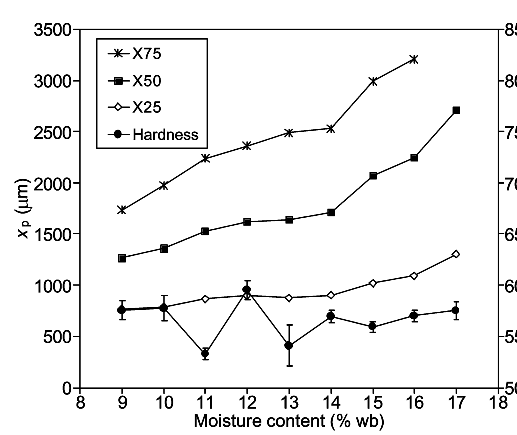

Fig. 6. x_{25}, x_{50} and x_{75} and hardness at different tempering moistures of Soissons wheat.

during industrial roller milling could be problematic; equally, the finding that the SKCS hardness relates primarily to the energy of grinding may facilitate making this link. Indeed Fang and Campbell (2002c) demonstrate that the output particle size distribution from First Break roller milling of wheat can be predicted from SKCS size and hardness data.

Fig. 5 also shows the reported hardness of the wheat samples at different moisture contents, averaged from three replicate samples. While some variation is apparent, analysis of variance confirmed that the reported hardness is independent of moisture content ($P < 1\times10^{-4}$), as reported by Psotka (1997). It should also be noted that the SKCS only reports moisture contents accurately in the range 9–15% according to the operating manual (Perten Instruments, 1995), although the hardness values returned for samples outside this range were in agreement with the other samples.

The above work addresses the industrial need for a fundamental and unambiguous definition of wheat hardness that can be related quantitatively to breakage during roller milling. The SKCS potentially provides a definition of hardness that is evidently based on the energy required to achieve an approximately constant degree of breakage, such that hardness could be defined in fundamental engineering units for robust prediction of the breakage of mixtures of wheat kernels during First Break roller milling.

4. Conclusions

The output particle size distribution from the SKCS has been measured, as a basis for determining the physical significance of hardness values reported by the SKCS. Greater kernel hardness gave slightly smaller particles on breakage, in contrast with First Break roller milling in which harder kernels result in larger output particles. However, the effect of hardness on the output particle size distribution was small, implying that SKCS hardness values depend primarily on the energy to grind. Increasing moisture content gave larger output particles, especially at the larger end of the particle size range where the particles are predominantly bran. These findings may help in relating SKCS characteristics to wheat breakage during roller milling.

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