



On Predicting Roller Milling Performance V: Effect of Moisture Content on the Particle Size Distribution from First Break Milling of Wheat

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Abstract

Extended breakage functions incorporating both single kernel size and moisture content were determined for First Break milling of hard and soft wheats under a sharp-to-sharp disposition. A moisture correction function was constructed by milling narrow size fractions of wheat tempered to different moisture contents, and subtracting the breakage function at a base moisture content of 16% from that at other moisture contents. The effect of adding moisture was to change an initially inverted U-shaped distribution at low moisture contents to a linear distribution at 16% moisture, then to a U-shaped distribution at higher moisture contents, reminiscent of the particle size distributions produced by dull-to-dull milling. The extended breakage functions were used to predict milling of unseparated feed samples at different roll gaps and moisture contents. In addition, mixtures of hard wheat at 14% moisture and soft wheat at 20% moisture, mixed in different proportions, were milled and the resulting particle size distributions compared with predictions. Excellent predictions were obtained in all cases. This confirms the independent breakage of kernels during First Break milling, and demonstrates the potential of the breakage function approach for interpreting single kernel data in terms of predictions of milling performance.

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INTRODUCTION

Previous papers in this series have introduced the breakage equation that describes roller milling of wheat grains¹; derived the form of the breakage function that describes the particle size distribution resulting from breakage of an individual wheat kernel as a function of kernel size and roll gap²; demonstrated that this form of the breakage function applies for a wide range of wheat varieties³, and investigated the effect of roll disposition on the breakage function⁴. This work has demonstrated

that, knowing the form of the breakage function, the particle size distribution resulting from First Break milling of wheat can be predicted for any inlet size distribution and any roll gap. This allows the inlet and outlet streams from First Break roller milling to be linked mathematically, and forms a sound basis for predicting roller milling performance from measured distributions of single kernel parameters. The objective of the current work was to add moisture content to the breakage function, to allow the effect of moisture content on First Break milling of wheat to be predicted.

The three parts of the wheat kernel, bran, germ and endosperm, differ in relative toughness and friability, giving different breakage patterns on roller

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milling. These differences are exaggerated by adding water to the wheat prior to milling, in a process known as conditioning or tempering. Conditioning has five purposes⁵⁻⁷:

- (i) to toughen the bran, reducing formation of bran powder;
- (ii) to soften the endosperm, enhancing its millability and reducing the power consumed by the reduction rolls;
- (iii) to facilitate separation of bran from endosperm, reducing the power consumption of the break rolls and consequently reducing evaporative losses;
- (iv) to ensure easy and accurate sifting of stocks; and
- (v) to ensure the endosperm moisture content is sufficient to give a final flour moisture content of around 14–15%.

However, the amount of water added and the timescale over which it is allowed to penetrate into the kernel vary widely in practice, with no conditioning regime universally appropriate for all wheat types and milling systems. Typically soft wheats are conditioned to 15–15.5% moisture and hard wheats to 16–16.5% wb.

Research into wheat conditioning has encompassed studies on wheat physical properties as affected by moisture content⁸⁻¹⁴; rates of water uptake^{15,16} and moisture distribution in the grain¹⁷; the effect of moisture on breakage during roller milling¹⁸⁻²⁰; comparison and evaluation of conditioning regimes^{21,22}, including accelerated conditioning²³⁻²⁵, and the effect of conditioning on flour properties and performance^{20,22,26-30}. Conditioning studies have also been reported for other grains, including oats³¹, barley³² and sorghum³³.

Zoerb and Hall⁸ concluded that moisture greatly affects mechanical properties of grains, and that all strength properties of grains decrease in magnitude with increasing moisture contents. However the nature and extent of the decrease differs between bran and endosperm. Glenn *et al.*¹¹ showed that as the moisture content of wheat endosperm increases, the compressive strength, elasticity and energy to compressive failure all decrease, with hard wheats giving greater decreases. By contrast, the elasticity and plasticity of bran increase with increasing moisture content^{12,13}. This renders the bran capable of deforming without breaking to a degree far beyond that of the endosperm. Thus, adding moisture to wheat prior to milling facilitates breakage of

endosperm while making bran more resistant to breakage.

While numerous papers have investigated the effect of moisture on the mechanical properties of the components of the wheat kernel, fewer studies have quantified the effect on the particle size distribution resulting from milling. Hsieh *et al.*¹⁹ studied the effect of moisture content after tempering on the First Break release of a Canadian spring wheat. In their study break release was defined as the proportion by mass of broken particles smaller than 730 μm . They found that over the range of tempering moisture contents from 14.5 to 17.5%, First Break release increased with increasing moisture content. This is as expected from the knowledge of the effect of moisture on endosperm properties, and confirms similar results by Anderson¹⁸. Dexter and Martin's²⁰ results showed little influence of wheat moisture content over the range 10–25% on break release through 980 μm from First and Second Break rolls, although break release from Third and Fourth Break rolls declined dramatically with increasing wheat moisture content.

In the present study the breakage function derived previously was extended to include the effect of moisture content in predictions of the particle size distribution resulting from First Break milling of wheat.

THEORY

The breakage equation for roller milling, expressed in its cumulative form, is

$$P(x) = \int_0^{\infty} B(x, D) \rho_1(D) dD \quad (1)$$

where D is the size of a feed particle, x is the size of an outlet particle, $\rho_1(D)$ is the probability density function describing the particle size distribution of the feed material, $P(x)$ is the proportion by mass of material smaller than x in the outlet stream, and $B(x, D)$ is the cumulative breakage function describing the proportion of material smaller than x produced on breakage of a feed particle initially of size D . In this work D is measured as the third longest dimension (thickness) of a wheat kernel, while x is measured as the sieve diameter of milled material. Equation (1) allows the particle size distribution resulting from milling a mixture of feed particle sizes to be predicted.

Wheat kernels are heterogeneous in more than just size, a fact underlined by the introduction of the Single Kernel Characterisation System, which measures the distributions of mass, diameter, moisture content and hardness of kernels in a sample^{34,35}. In principle equation (1) can be extended to encompass distributions of other kernel properties in the feed. The current paper aims to demonstrate this with respect to moisture content. Shellenberger⁶ notes that kernel moisture can vary by 5 percentage points within a sample both before and after conditioning, and that the time required for kernels differing in moisture content to approach equilibrium can be several months. Therefore although the average kernel moisture content might be optimal, some kernels are too wet and others too dry to give optimum flour yield. This variability in kernel moisture may be exacerbated by the practice of mixing wet and dry wheat together to preserve wet wheat and add moisture to dry wheat³⁶.

Equation (1) can be extended to account for moisture content distribution as follows:

$$P(x) = \int_0^{m_{\max}} \int_0^{\infty} B(x, D, m) \rho_1(D) \rho_2(m) dD dm \quad (2)$$

where m is the moisture content of an individual kernel, and $\rho_2(m)$ is the probability density function describing the distribution of individual kernel moisture contents in the sample. Equation (2) assumes that the size distribution and moisture distribution in a sample are independent, i.e. that large kernels have the same moisture distribution as small kernels (or, equivalently, that wetter kernels have the same size distribution as drier kernels). Thus, if the extended cumulative breakage function $B(x, D, m)$ is known, then the outlet particle size distribution could be predicted for any size distribution and moisture distribution of a given wheat sample.

If it is assumed that the effect of moisture content on breakage is approximately independent of kernel size, then the cumulative breakage function can be simplified by separating it into two components, the cumulative breakage function at a nominal moisture content m_0 (say 16%), and a correction term to account for the variation in breakage that occurs at moisture contents other than 16%:

$$B(x, D, m) \approx B(x, D)_{m_0} + K(x, m - m_0) \quad (3)$$

Then equation (2) becomes

$$\begin{aligned} P(x)_m &= \int_0^{m_{\max}} \int_0^{\infty} [B(x, D)_{m_0} + K(x, m - m_0)] \\ &\quad \times \rho_1(D) \rho_2(m) dD dm \\ &= P(x)_{m_0} + \int_0^{m_{\max}} K(x, m - m_0) \rho_2(m) dm \end{aligned} \quad (4)$$

In equation (4), the cumulative breakage function $B(x, D)_{m_0}$ can be found by milling narrow size fractions of wheat conditioned to 16%, as described previously²⁻⁴. The moisture correction function, $K(x, m - m_0)$ can be found similarly by milling samples tempered to different moisture contents and subtracting the proportion of material smaller than size x at the base moisture content m_0 from the corresponding proportion at moisture contents m .

If the samples prepared to different moisture contents are also separated into narrow size fractions, the assumption that the effect of moisture content on breakage is approximately independent of kernel size could be tested. In practice, previous work has demonstrated that the relevant parameter related to size is the milling ratio, G/D , where G is the roll gap²⁻⁴. Milling at different roll gaps is equivalent to milling different size fractions. In this paper combinations of size fractions and roll gaps were used to cover a range of milling ratios.

If the moisture distribution in a sample is very narrow, such that $\rho_2(m)$ approximates a Dirac delta function, or if only the average moisture content is available, then equation (4) can be used in the form

$$P(x)_m = P(x)_{m_0} + K(x, m - m_0) \quad (5)$$

where m is the average moisture content of kernels in the sample. In its non-cumulative form, equation (5) becomes

$$\rho_2(x)_m = \rho_2(x) + k(x, m - m_0) \quad (6)$$

where

$$k(x, m - m_0) = \frac{d}{dx} K(x, m - m_0) \quad (7)$$

MATERIALS AND METHODS

Construction of the moisture correction function

Hereward, a hard wheat (bulk density 79.4 kg/hl, protein content 14.6% db, moisture content 14.16% wb), and Consort, a soft wheat (bulk density 74.2 kg/hl, protein content 10.63% db, moisture content 13.97% wb), both from the 1999 UK harvest, were separated by thickness into narrow size fractions as described previously^{2,4}. Table I gives the size fractions and roll gaps used to give a range of milling ratios.

The separated fractions were then dried for 24 h at 40 °C in an incubator, after which the moisture content of the Hereward had reduced to 8.8% and that of the Consort to 9.3%, as measured by an oven drying method³⁷. Each dried fraction was then separated into seven batches, to which were added different amounts of water using a pipette, to give nominal moisture contents of 10, 12, 14, 16, 18 and 20% plus the original dried moisture content for each variety. Samples were left overnight to temper and then separated into five samples of 100 g each, one for each milling ratio listed in Table I. A total of 70 samples were prepared. Each 100 g sample was then milled at the appropriate milling ratio on the Satake STR-100 test roller mill using 10.5 flutes per inch (4.13 flutes per cm) First Break rolls operated under a sharp-to-sharp disposition. Milling and subsequent sieve analysis were performed as described previously^{4,38}.

The mean diameter of each fraction following moisture addition and tempering was measured using the Perten SKCS (Perten Instruments AB, Sweden) to ensure that the addition of moisture had not altered the size of grains substantially.

Table I Size fraction and roll gap combinations used to mill wheat samples at a range of milling ratios

Size D (mm)	Roll gap G (mm)	G/D
<i>Hereward</i>		
3.00–3.25	0.3	0.096
	0.4	0.128
	0.5	0.160
	0.6	0.192
	0.7	0.224
<i>Consort</i>		
3.00–3.25	0.3	0.096
2.75–3.00	0.4	0.139
	0.5	0.174
2.50–2.75	0.6	0.229
	0.7	0.267

The difference in diameter between the lowest and highest moisture contents was less than 2% and could be neglected compared with the intervals between the different milling ratios used.

The moisture correction function was calculated by subtracting the percentage of material by mass smaller than x at a moisture content of 16% from the corresponding percentage at other moisture contents. The breakage function reported previously⁴ for the two wheat varieties milled at 16% moisture was used as the base from which the moisture correction function was derived, as it had been evaluated using a greater number of samples than was used here for each moisture content and was thus more accurate.

Prediction of milling of whole wheat samples and of mixtures of wheats

To enable evaluation of the combined breakage and moisture correction functions in terms of prediction, two further sets of milling trials were performed. In the first, native (unseparated) samples of Hereward and Consort were prepared to different moisture contents (10, 12, 14, 16, 18 and 20%) and milled at roll gaps of 0.4 and 0.6 mm. The moisture distribution of each sample was measured using the SKCS. Figure 1 shows the measured moisture distributions for each sample. Note that the SKCS is capable of measuring moisture content accurately only up to 15%³⁹. Nevertheless, the measured moisture distributions were used in equation (4) to predict the output particle size distribution for each sample at each milling ratio.

In the second trial, samples of Hereward at 14% moisture and Consort at 20% moisture were mixed in the ratios 100 : 0, 75 : 25, 50 : 50, 25 : 75 and 0 : 100 Hereward : Consort, and milled at a roll gap of 0.6 mm, to demonstrate the ability to predict milling of mixtures of different wheats. For both trials three replicate 100 g samples were milled for each condition and compared with predictions based on proportional addition of the individual predictions for each variety.

RESULTS AND DISCUSSION

Construction of the moisture correction function

Figure 2 shows the proportion of milled material smaller than a given sieve aperture x as a function

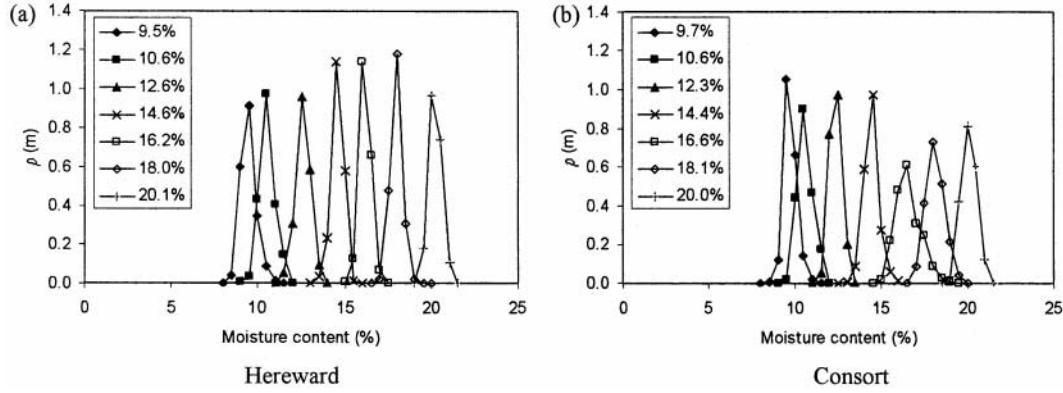


Figure 1 Moisture distributions of (a) Hereward and (b) Consort after conditioning.

of milling ratio for each value of x and for each moisture content, for the Hereward sample. The approximate parallelism of the lines for different moisture contents at each value of x justifies the simplifying assumption that the effect of moisture content on breakage is independent of milling ratio. Similar results (not shown) were obtained for the Consort. The function $B(x, D, m)$ was fitted to the data using Microsoft Excel (Microsoft Corporation, USA). From these curves, the average $K(x, D, m - 16\%)$ was calculated as

$$\begin{aligned} K(x, m - 16\%) &= \frac{1}{N} \sum_D K(x, D, m - 16\%) \\ &= \frac{1}{N} \sum_D B(x, D, m) - B(x, D, 16\%) \end{aligned} \quad (8)$$

where N is the number of milling ratios at which samples were milled. An equation cubic in x and quadratic in $(m - 16\%)$ was fitted to the data:

$$\begin{aligned} K(m - 16\%, x) &= (a_1 + b_1x + c_1x^2 + d_1x^3)(m - 16\%) \\ &\quad + (a_2 + b_2x + c_2x^2 + d_2x^3)(m - 16\%)^2 \end{aligned} \quad (9)$$

Table II lists the coefficients of equation (9) fitted for both wheat samples, along with the coefficients of determination, which indicate a good description of the data for both samples.

The derivative of equation (9) with respect to x is a quadratic in x , indicating that the effect of changing the moisture content is to change the initially linear breakage function obtained under sharp-to-sharp

Table II Coefficients of the moisture correction function for Hereward and Consort

	a	b	c	d
<i>Hereward</i>				
1	-72.3	0.652	-8.09E-04	2.39E-07
2	1702	-12.818	7.56E-03	-9.7E-07
R^2			0.933	
<i>Consort</i>				
1	-40.7	0.406	-7.03E-04	2.27E-07
2	93.6	-5.685	3.70E-03	-7.6E-07
R^2			0.952	

milling to the more U-shaped distribution found for other dispositions.

Figures 3 and 4 show the particle size distributions (non-cumulative) obtained on milling of fractions at different moisture contents and milling ratios for Hereward and Consort, respectively. These figures also show the actual average moisture contents achieved, as measured by the SKCS. As indicated above, the effect of moisture content is to change the approximately linear particle size distributions observed under sharp-to-sharp milling of samples at 16% moisture to more U-shaped distributions. At low moisture contents the U is inverted; fewer particles are generated at the large and small ends of the distribution, and more particles are seen in the mid-size range, pushing the centre of the distribution up. As moisture content increases, the U inverts, such that at high moisture contents large numbers of smaller and larger particles are seen, with fewer in the mid-size range, reminiscent of the shapes of distributions seen under dull-to-dull milling⁴. This effect is most clearly demonstrated by the data in Figure 4(d) and (e), for Consort milled at milling ratios of 0.192 and 0.224.

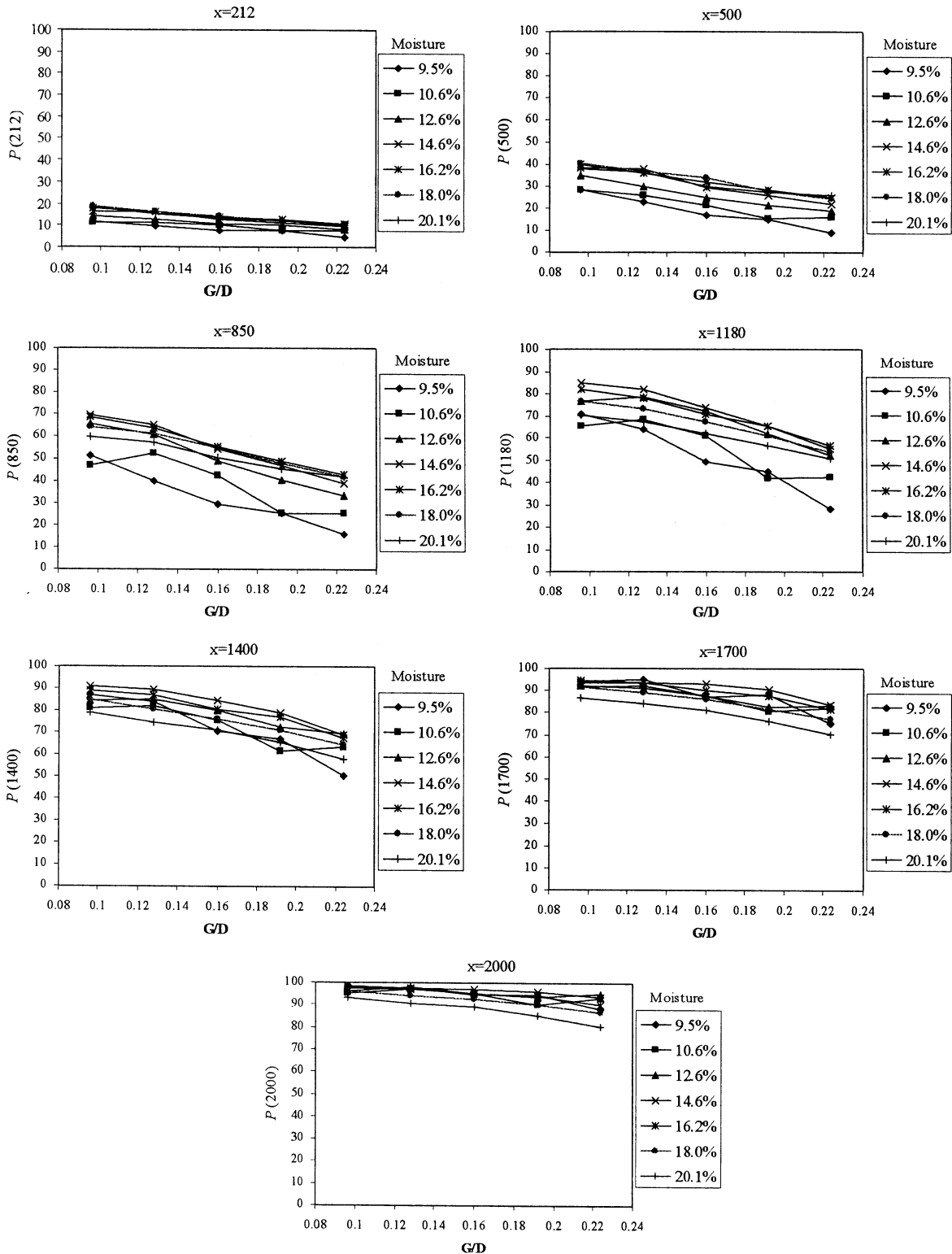


Figure 2 Proportion of milled material smaller than sieve aperture size x vs milling ratio for Hereward (hard) wheat fractions tempered to different moisture contents.

Prediction of milling of whole wheat samples and of mixtures of wheats

The moisture correction functions derived above were used to predict the milling of native (unseparated) samples. Figures 5 and 6 compare predicted

cumulative particle size distributions with experimental data for both wheats tempered to different moisture contents and milled at roll gaps of 0.4 and 0.6 mm. Clearly the agreement is excellent, as indicated by the R^2 values shown in the figure captions. Figure 7 similarly shows the predictions

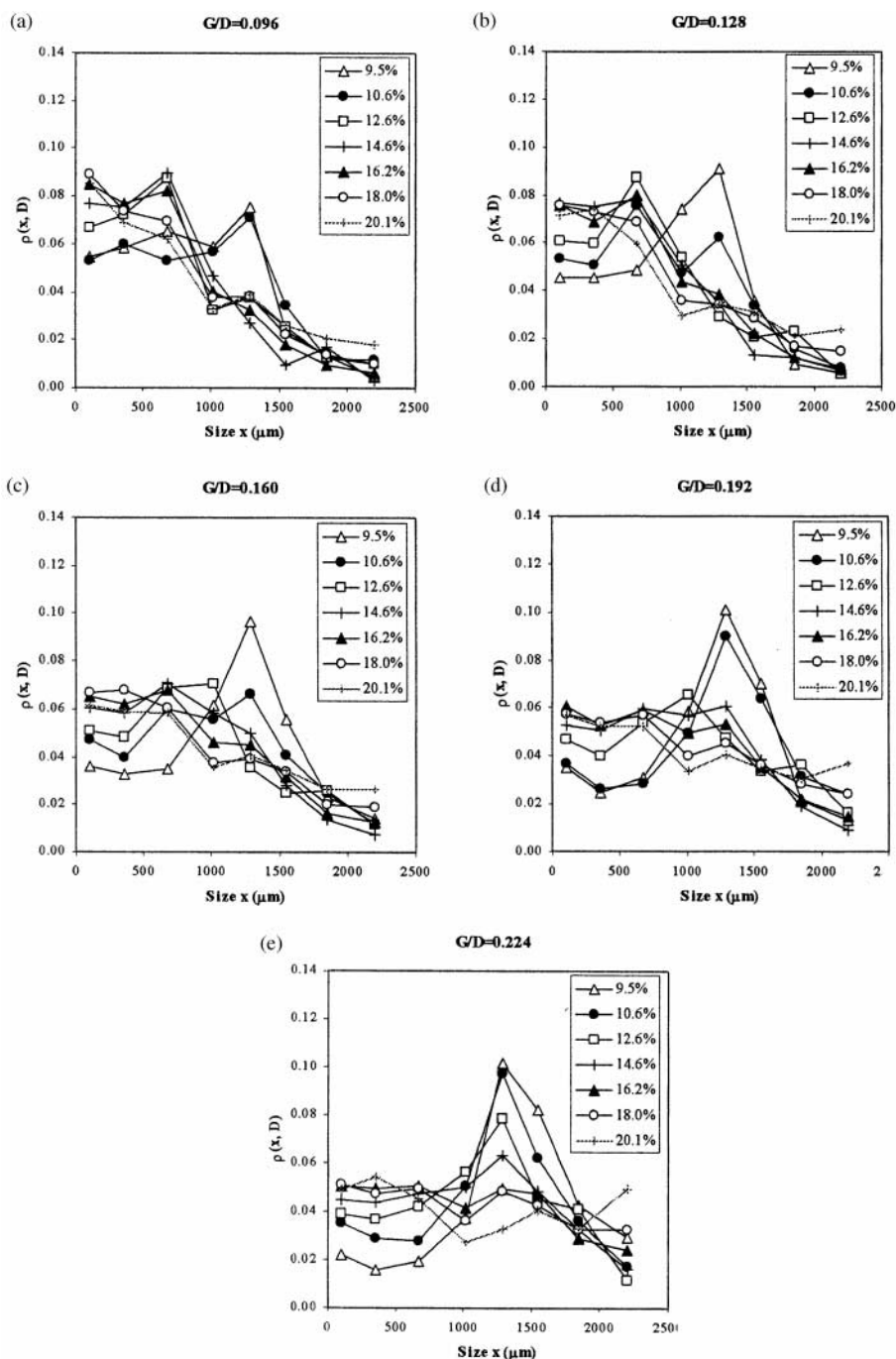


Figure 3 Size distribution of stocks from First Break milling at different milling ratios of Hereward (hard) wheat tempered to different moisture contents.

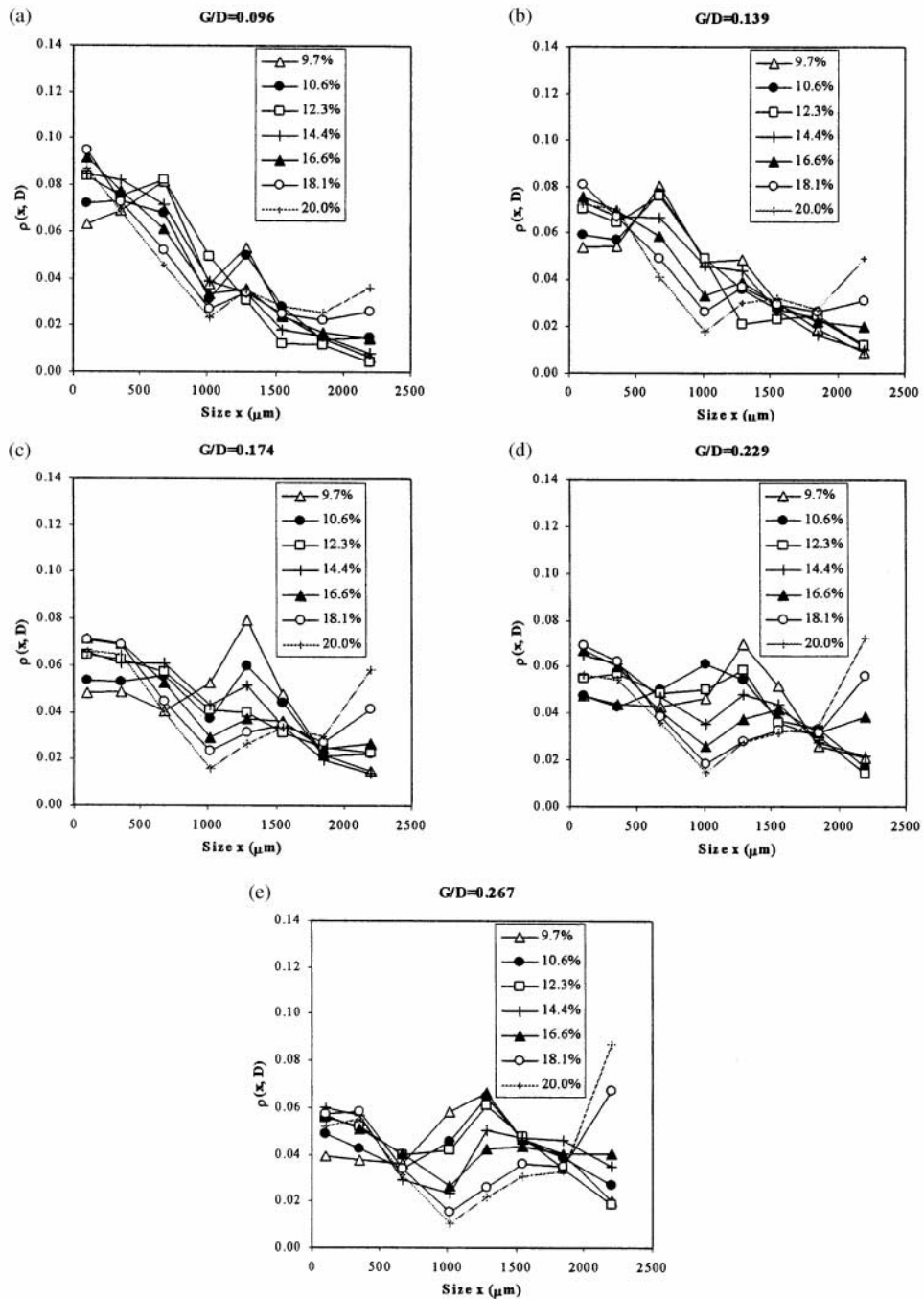


Figure 4 Size distribution of stocks from First Break milling at different milling ratios of Consort (soft) wheat tempered to different moisture contents.

when Hereward at 14% moisture and Consort at 20% moisture are mixed in different ratios and milled together. The excellent agreement confirms that the breakage function approach is able to predict milling of mixtures of wheats, and supports

the underlying assumption that kernels mill independently during First Break roller milling. While it is understood that this is an unlikely mixture to be created in practice, it demonstrates the accuracy and potential of the breakage function approach.

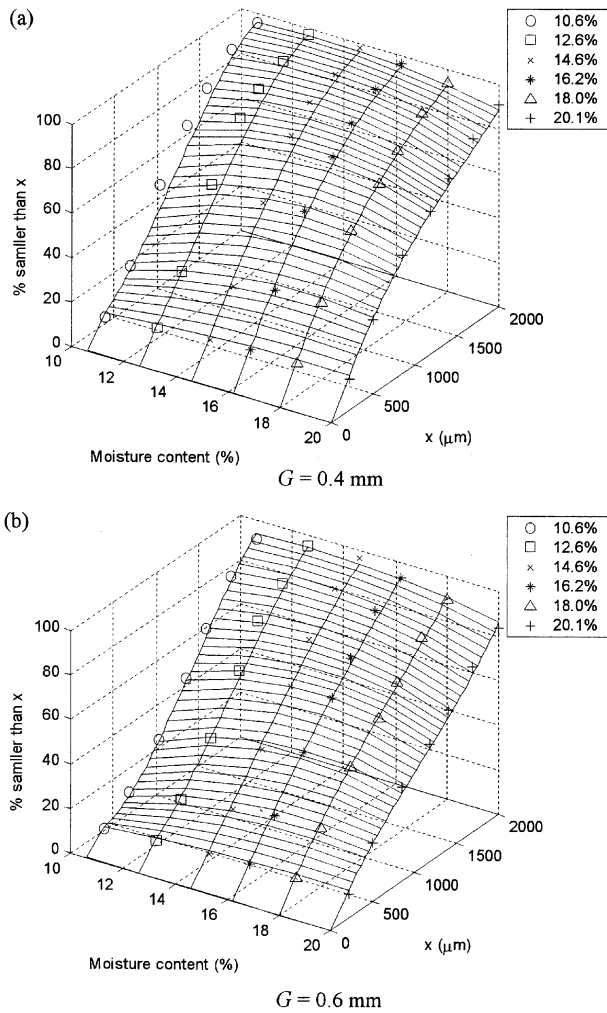


Figure 5 Comparison of predicted and experimental particle size distributions from First Break milling of Hereward wheat at roll gaps of (a) 0.4 mm ($R^2 = 0.985$); and (b) 0.6 mm ($R^2 = 0.992$). Solid lines are predictions based on Equations (5) and (9), and symbols are experimental data averaged from three replicate samples.

(Note that predictions based on Equation (5), the simplified equation that considers only the average moisture content and not its distribution, gave virtually identical predictions. This is because of the narrow distribution of single kernel moisture contents actually achieved in these samples, as indicated by Figure 1. Note too that good predictions are obtained despite some moisture contents being above the upper limit of 15% for which the SKCS is considered to give accurate moisture results.)

Interestingly, the effect of adding moisture to wheat is similar to the effect of milling under a dull-to-dull disposition. Both favour the creation of large and small particles with few in the mid-size

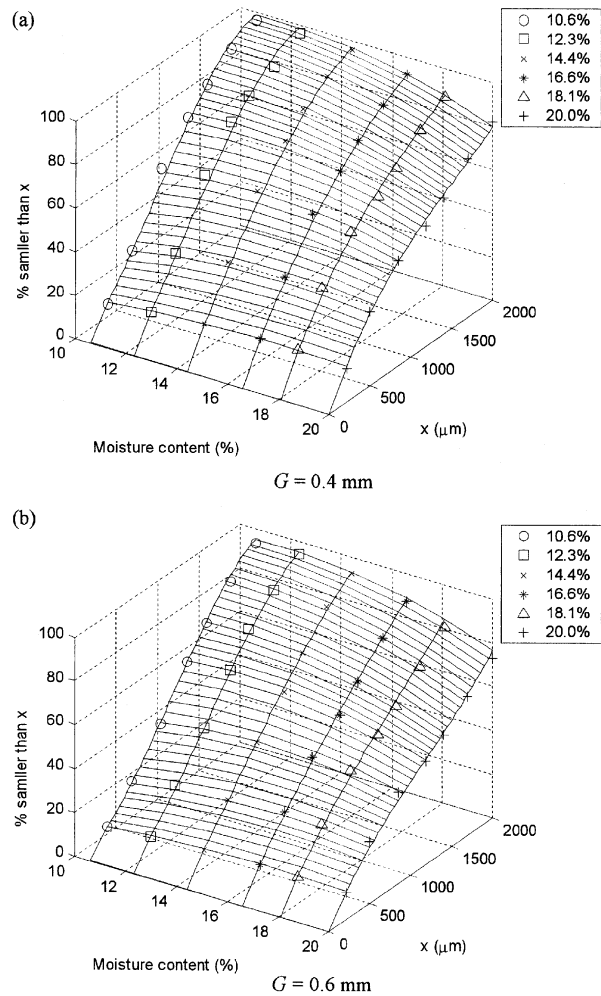


Figure 6 Comparison of predicted and experimental particle size distributions from First Break milling of Consort wheat at roll gaps of (a) 0.4 mm ($R^2 = 0.991$); and (b) 0.6 mm ($R^2 = 0.996$). Solid lines are predictions and symbols are experimental data.

range, thus facilitating separation of the large branny particles from the smaller endosperm particles. This undoubtedly explains in part the preferred practice of millers to add moisture to wheat and then mill it under a dull-to-dull disposition at First Break.

CONCLUSIONS

Extended breakage functions have been constructed to describe First Break milling of wheat kernels as functions of single kernel size and moisture content. The ability of these functions to predict milling of polydisperse feeds at different moisture contents and of mixtures of different wheats has been demonstrated. This confirms the independent breakage of wheat kernels during First Break milling, and

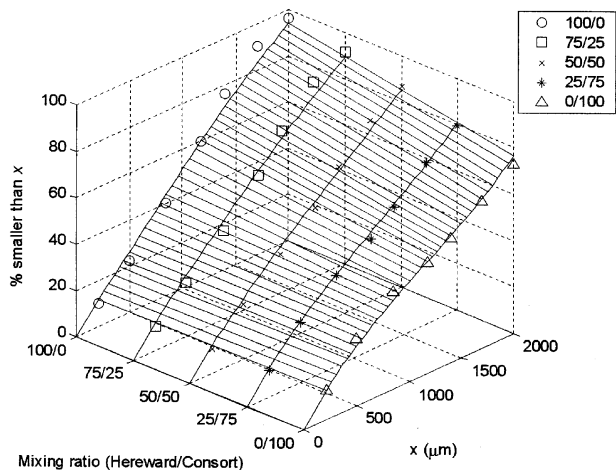


Figure 7 Comparison of predicted and experimental particle size distributions from First Break milling of mixtures of Hereward at 14% moisture and Consort at 20% moisture at a roll gap of 0.6 mm ($R^2 = 0.987$). Solid lines are predictions and symbols are experimental data.

demonstrates the potential of the breakage function approach for linking distributions of single kernel measurements to milling performance. Future work needs to identify other appropriate single kernel properties such as hardness and incorporate them into a comprehensive breakage function that would allow prediction of milling performance directly from single kernel measurements.

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