Comminution Parameters for Wheat Hardness Measurement

C. J. Chung, S. J. Clark, J. C. Lindholm, R. J. McGinty, C. A. Watson
ASSOC. MEMBER ASAE   MEMBER ASAE

ABSTRACT

A SYSTEM using the Brabender Hardness Tester, strain gage transducer, amplifier, and recording system were used to make torque measurements of wheat during grinding. Comminution theory was applied to grinding process and related to wheat hardness. A Grindability Index was defined. This index is closely related to flour yield and appears to be about the best index of grain hardness.

INTRODUCTION

Grain hardness is an important property of wheat that varies with variety, moisture content, structure, and chemical composition (Charles 1957). Wheat hardness is an important consideration in milling since it affects power consumption, starch damage and milling performance of the wheat. Different mill flow diagrams and sieve openings are used for hard and soft wheats. Wheat hardness is also an important consideration in the identification and classification of wheat. Soft wheats (soft red winter, white club, etc.) are generally used for making pastries and crackers. Hard wheats (hard red winter and spring) are generally used for making bread. Durum wheat, because of its unique properties, is used primarily for making pasta.

Methods for quantitatively measuring wheat hardness include crushing, cutting, pearling, grinding, and indenting (Chung 1971; Mepplink 1966-68). A satisfactory standardized hardness measuring method has not yet been developed.

Since wheat hardness affects the milling performance of wheat, it is not surprising that attempts have been made to obtain hardness parameters from closely controlled grinding processes. The Brabender hardness tester was developed for this purpose. The tester consists of a burr mill grinding unit and a Farinograph dynamometer. The burr mill performs a single pass or open-circuit type of grinding on a prescribed charge of grain. The grinding action is classified as a combination of compression and shear. Therefore, the torque on the shaft of the burr mill, while grinding a prescribed charge of grain, should provide a qualitative measure of the rupture strength of kernels from compression and shear stress. The Farinograph dynamometer is thus used to obtain torque values during the grinding process. Grinding energy can also be determined from the Farinograph dynamometer since torque is plotted on a graph. Area under the torque-time graph represents grinding energy. A complete description of the Brabender hardness tester is given by Shuery, et al. (1972).

Comminution Terminology and Theory

Comminution is the technical term for the process of reducing a material to very small particles. Chung (1971) found that research on comminution processes can be divided into three categories: (a) Energy transformation involved in comminution, (b) Particle size characteristics of the ground product, and (c) Energy-size reduction relationships.

Maximum rupture resistance, average rupture resistance and grinding energy are hardness parameters of the categories that can be obtained directly from the Brabender hardness tester. They are obtained from the Brabender torque — time curve (described later in this paper).

The product of comminution always consists of a wide range of particle sizes with different fractions. Various methods have been used to represent characteristics of the particle size distribution. A single parameter representation such as mean particle size, a particular particle size, or surface particle area generally is inadequate to completely describe a distribution function. Particulate materials require at least two parameters to adequately describe their distribution function. Several methods have been used to obtain a mathematical description of particle size distribution. The Gaudin-Schuhmann equation (Schuhmann 1960), which follows, has provided the best fit for smaller particles of the particulate material for a wide range of wheat varieties:

$$Y = 100 \left(\frac{X}{K}\right)^{\beta}$$

where
- Y = cumulative weight percent finer than size X.
- X = particle size, mm.
- K = product size modulus.
- β = distribution modulus.

Chung (1971) modified the equation to:

$$Y = A_1 X^{\beta} \text{ or } \operatorname{Log} Y = \operatorname{Log} A_1 + \beta \operatorname{Log} X$$

for convenience purposes where

$$A_1 = \frac{100}{K^{\beta}} = \text{a modified size modulus}$$

Fig. 5 indicates the degree of fit of cumulative percent finer, Y, compared with particle size, X. Note the logarithmic scales and that A_1 is the

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The authors are: C. J. CHUNG, Associate Professor, Agricultural Engineering Dept., Seoul National University, Suwon, Korea; S. J. CLARK, Agricultural Engineer, Agricultural and J. C. LINDHOLM, Mechanical Engineer, Mechanical Engineering Dept., Kansas State University, Manhattan; R. J. McGINTY, Research Agricultural Engineer, and C. A. WATSON, Research Chemist, North Central Region, ARS, USDA, Manhattan, KS.

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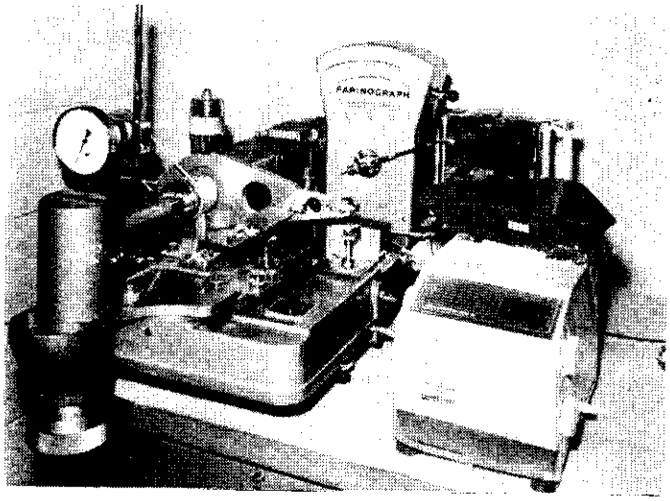

FIG. 1 The Brabender hardness tester.

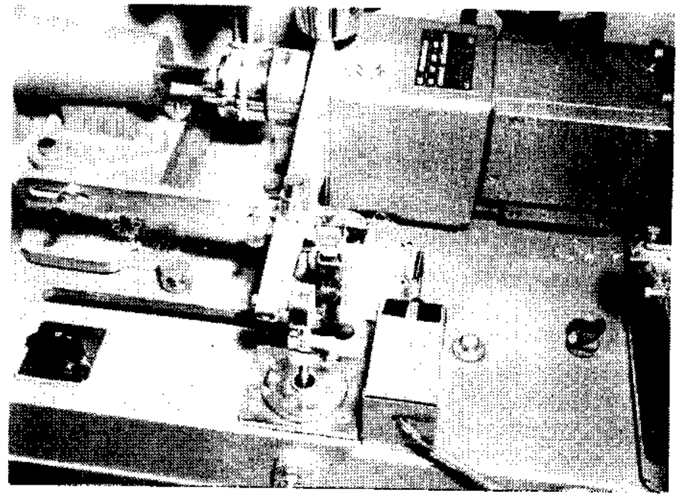

FIG. 2 The modified Brabender system with the restraining force transducer.

ordinate intercept and β is the slope.

Flour yield is another parameter that has been used by researchers (Mepplink 1966-68) to represent characteristics of the particle size distribution. It is simply the cummulative percentage of the ground product from the Brabender hardness tester that passes through the No. 100 (147 microns) Tyler screen.

Two wheat hardness parameters were obtained from energy-size reduction relationships (the third category). Rittinger's equation [1] was the basis of the first parameter, grindability index. Rittinger's equation is:

$$E = [GI] \left(\frac{1}{X_2} - \frac{1}{X_1}\right)$$

where

E = grinding energy, kg-m/g

X_2 = final average particle size, mm

X_1 = initial average particle size, mm

GI = grindability index, [(kg-m)/g] x mm

when

$$X_1 >> X_2 = X_r$$

$$E = [GI] \frac{1}{X_r}$$

As $1/X_r$ is proportional to the specific surface area (particle surface area per gram), the grindability index may be considered as the grinding energy divided by specific surface.

The second energy-size reduction parameter, toughness index, is defined by Chung's (1971) equation:

$$E = [TI] X_r^{-\beta}$$

where

E = grinding energy, (kg-m)/g

X_r = particle size, mm

β = distribution modulus

TI = the toughness index [(kg-m)/g] x mm$^{\beta}$

Experimental Equipment* and Materials

The Barbender system was modified for this research, the Farinograph was replaced with a strain gage transducer, amplifier and recording system for more sensitive torque measurements (Figs. 1, 2 and 4). The lever arm was locked so that motion could not be transmitted to the Farinograph recorder. The link transmitting the motion between the coupling and lever arms was replaced by a flat steel bar to restrain the reaction toqure of the drive shaft. Two strain gages were mounted on the restraining bar. To improve the bridge null-balance stability, two dummy gages were later attached to an unstrained bar, which

*Use of a company or product name does not imply approval or recommendation of the product by the US Department of Agriculture to the exclusion of others that also may be suitable.

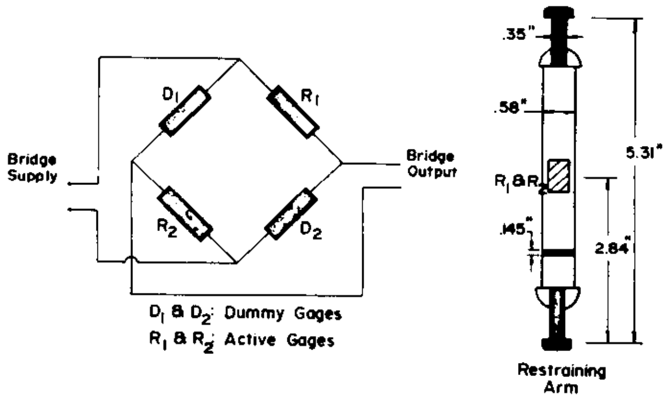

FIG. 3 Strain gage location and wiring diagram used for sensing torque in the Brabender hardness tester.

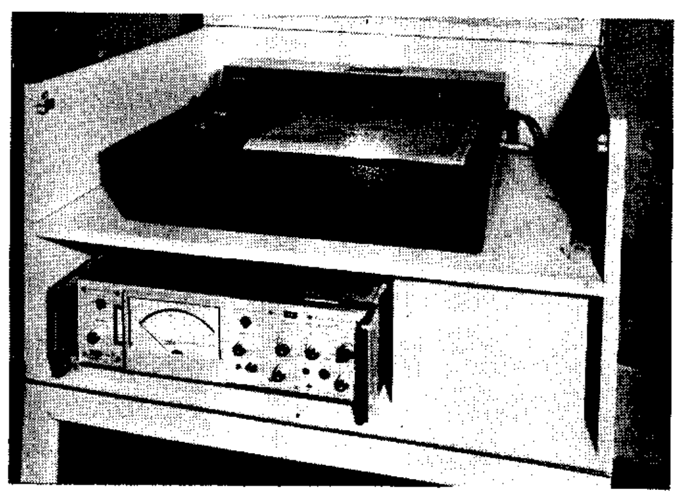

FIG. 4 The Daytronic Model 300 D transducer amplifier-indicator and the Beckman Model 100500 recorder.

TABLE 1. WHEATS TESTED IN THE BRABENDER HARDNESS TESTER

Wheat class	State grown	Number of varieties and/or locations
Soft white winter (SWW)	Washington	18
	Oregon	4
Soft red winter (SRW)	Ohio	1
Hard red winter (HRW)	Washington	4
Hard red winter (HRW)	Washington	6
	Oregon	1
	Kansas	19
	Oklahoma	2
Hard red spring (HRS)	North Dakota	11
	Montana	6
	Minnesota	2
	South Dakota	5
Durum	North Dakota	2

was placed in a shielded connector box (circuitry shown by Fig. 3).

The strain gage circuit was connected to a Daytronic Model 300 D transducer amplifier-indicator (Fig. 4). The electric signal from the Daytronic system was fed into a Beckman Model 100500 recorder, that uses a standard 10-in. cartesian coordinate recording chart. The recorder was equipped with an integrator unit.

To convert the chart values produced by the Barbender hardness tester, torque calibration points were established throughout working range. Input torques were obtained by placing different known weights on the loading arm.

Wheats used ranged widely in variety, region grown, and history of growth. They were grown in experimental plots in locations shown in Table 1.

About 400 g of wheat were used for each run. To insure that the samples for each test were uniform, the fines and foreign materials were screened out using Tyler sieves (1.65 mm opening) and shaking one minute by hand. Broken kernels remaining were then removed by hand.

For a given sample it is possible to alter particle size distribution of the product by changing the operating conditions of the Brabender burr mill. Adjustments include the clearance between the mill cone and mantle and the angular speed of grinding shaft. Clearance is related to degree of grinding; angular speed, to rate of grinding. The degree of grinding was selected to keep the amount of undersize passing through a No. 200 (74 micron) Tyler Sieve relatively small. It was therefore not necessary to use any fine particle sizing technique other than sieve analysis.

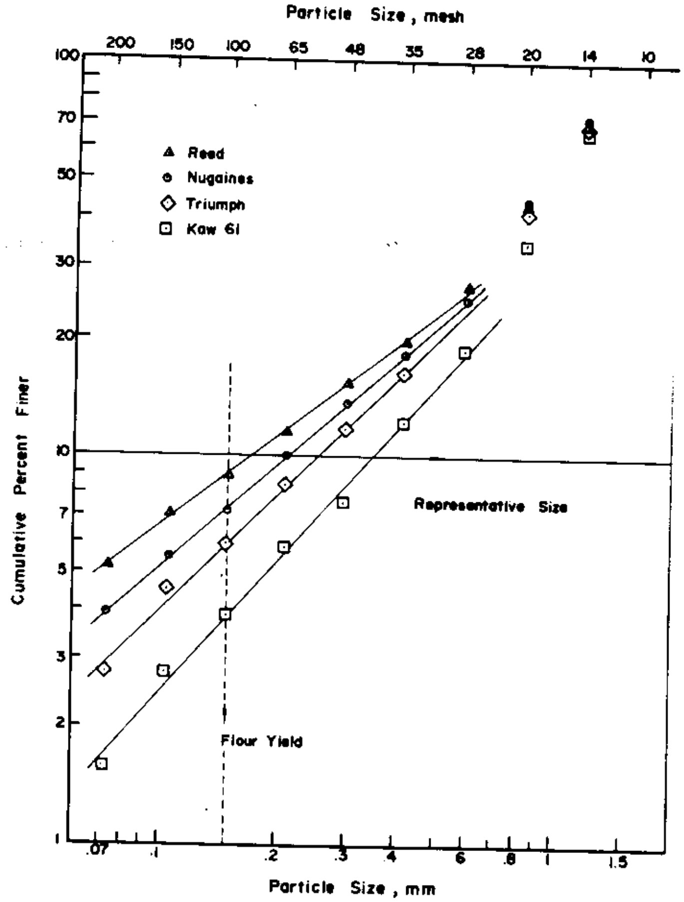

FIG. 5 Particle size distributions of ground wheats with illustrations for obtaining the representative size and flour yield.

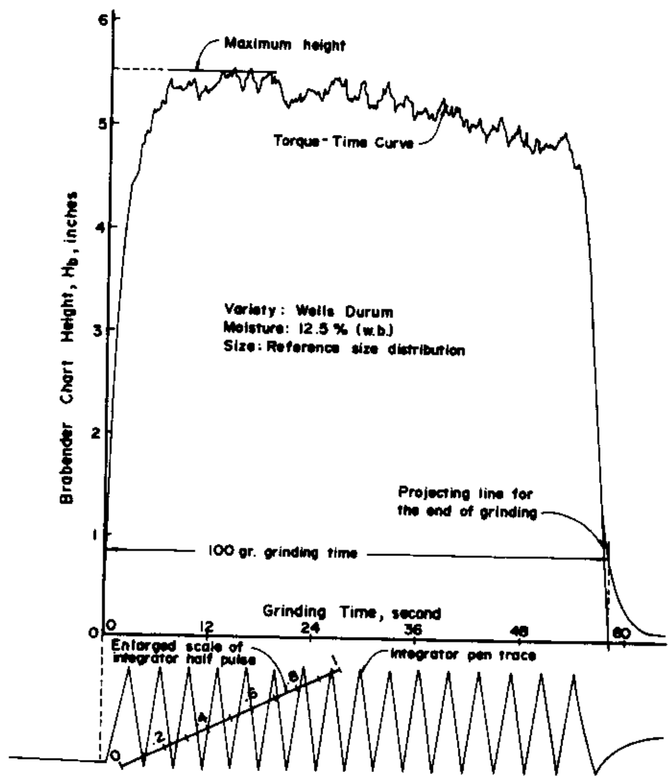

FIG. 6 A typical torque-time curve and integrator pen trace from the Brabender hardness tester.

TABLE 2. WHEAT HARDNESS PARAMETERS FROM THE BRABENDER HARDNESS TESTER

Category	Parameter	Symbol	Unit	Nature of data
1	Maximum rupture resistance	T_{BM}	kg-m	Energy or strength
	Average rupture resistance	T_{Ba}	kg-m	
	Grinding energy	E_B	kg-m/g	
2	Flour yield	FY	percent	Particle characteristics
	Modified size modulus	A_1	- -	
	Distribution modulus	β	—	
	Representative size	X_{10}	mm	
3	Grindability index	GI	$\frac{\text{kg-m}}{\text{m}}$ x mm	Energy-size reduction relationship
	Toughness index	TI	$\frac{\text{kg-m}}{\text{g}}$ x mm	

On this basis, no reason was found to change the clearance index of "9", already standardized for the Brabender hardness tester. The rate of grinding selected was a convenient mill shaft speed of 20 rpm. This speed gave a desired shape (Fig. 6) for the torque-time curve with a 100-g charge and the 5 ipm (12.7 cm/min) recorder chart/speed.

Particle analyses of the ground material obtained from the Brabender machine were made with 8-in. (20.3 cm) Tyler sieves — No. 14, 20, 28, 35, 48, 65, 100, 150, and 200 (1.19 mm, and 833, 595, 417, 295, 208, 147, 105, and 74 micron, respectively) and a Ro-Tap shaker. Total shaking time was 20 min, interrupted after 10 min to brush the undersides of the sieve to remove fine clinging particles. Experiments for the Brabender grinding and particle size analyses were replicated twice. Each point on Fig. 5 represents the average of the two replications.

Results and Discussion

Analyses of comminution parameters in the Brabender burr mill provide information on different segments of wheat properties that affect wheat hardness. For convenience, the parameters are classified into the three previously defined categories: (a) quantities from the torque-time curves, (b) those related only to particle characteristics, and (c) those obtained from the energy-size reduction relationship. The parameters are categorized in Table 2.

Definitions of the important parameters are:

Maximum rupture resistance, T_{BM}; maximum torque (kg-m) required to rotate the Brabender burr mill shaft while grinding 100 g of wheat under specified operating conditions.

Average rupture resistance, T_{BA}; average torque (kg-m) over grinding time for 100 g.

Grinding energy, E_B; energy input to the Brabender burr mill per gram of wheat ground.

Flour yield, FY; cummulative percentage of ground material obtained from the Brabender hardness tester passing through a No. 100 (147 microns) Tyler sieve.

Modified size modulus, A_1; the coefficient in the modified Gaudin-Schuhmann equation:

$$Y = A_1 X^{\beta}$$

$$A_1 = \frac{100}{K^{\beta}}$$

K = product size modulus
β = distribution modulus.

Distribution modulus, β; the exponent β in the Gaudin-Schuhmann equation, a modeling equation for the cumulative weight particle-size distribution curve.

Representative size, X_{10}; particle size corresponding to the 10 percent cummulative weight from the cummulative weight particle-size distribution curve.

Grindability index, GI; a grinding energy from Rittinger's energy-size reduction equation divided by the difference between the reciprocals of the final and initial particle sizes.

$$GI = \frac{E}{\left[\frac{1}{X_2} - \frac{1}{X_1}\right]}$$

X_2 = final particle size, mm
X_1 = initial particle size, mm
E = grinding energy, kg-m/g

Toughness index, TI; a composite parameter defining grain hardness (determined by multiplying grinding energy E by particle X_r to β (distribution modulus) power.

$$TI = E X_r^{\beta}$$

β = distribution modulus
X_r = particle size, mm
E = grinding energy, kg-m/g

All the quantities were intended to represent the common characteristic — wheat hardness. However, responses of quantities for different wheats were not the same. To show the relationship between the parameters listed in Table 2 to each coefficient, a matrix correlation was run (Table 3). In general, parameters within the same category correlated closely. Energy or strength measurements (category 1) did not correlate closely with particle characteristics (category 2). On the other hand, the parameters from the energy-size reduction relationships (category 3) in general correlated strongly with strength and particle size. These results indicate that two functional techniques, particle characteristic and energy or strength, may measure different phenomena in a rigorous sense. The quantities from energy-size reduction relationships merely compromise the two techniques. Therefore, selecting a particular technique to measure wheat hardness may depend upon which characteristics are most important for practical use.

Reasons are numerous against considering particle characteristic parameters over grinding energy parameters. Particle characteristics are indirect measures of hardness and cannot be explicitly represented by physical quantities related to strength. Additionally, no unique technique is available to satisfactorily characterize a range of particle sizes by a single parameter. The use of two or more parameters for representing wheat hardness such as A_1 and β from the Gaudin-Schuhmann equation is undesirable due to the complexity involved in obtaining the data for the parameters. Particle measurement is also susceptible to undesirable variation with grain moisture and is tedious compared with direct strength or energy measurements.

Fig. 7 shows that Brabender grinding energy is related to flour yield. Flour yields for hard and soft wheats differ widely, but flour yield correlates poorly with grinding energy (correlation coefficient = 0.68). Therefore, flour yield may be used only as a

TABLE 3. CORRELATION COEFFICIENTS FOR PARAMETERS OBTAINED FROM BRABENDER BURR MILL COMMINUTION

1	T_{BM}	1.00			−0.67	−0.61	0.58	0.63		
	T_{BA}	0.99	1.00		−0.67	−0.60	0.59	0.63		
	E_B	0.92	0.93	1.00	−0.68	−0.86	0.62	0.66		
2	F_Y				1.00					
	A_1				0.86	1.00				
	β				−0.94	−0.69	1.00			
	X_{10}				−0.98	−0.88	0.95	1.00		
3	GI	0.74	0.744	0.78	−0.96	−0.86	0.93	0.98	1.00	
	TI	0.81	0.81	0.85	−0.86	−0.92	0.74	0.88	0.93	1.00
		T_{BM}	T_{BA}	E_B	FY	A_1	β	X_{10}	GI	TI
			1			2			3	

rough estimate of wheat hardness.

Distribution and size moduli in the Gaudin-Schuhmann equation were compared to flour yield in regards to how well they correlated with the energy parameters. Neither modulus correlated with energy as well as flour yield. However, representative size, X_{10}, which is defined as the particle size corresponding to the 10 percent cummulative weight from the particle size distribution curve, combines distribution and size moduli. It generally correlated with energy about the same as flour yield. Therefore, the particle characteristic can be represented better by either flour yield or the representative size, X_{10}, than by distribution or size moduli. As flour yield is much simpler to determine, it was the best particle parameter for characterizing wheat hardness.

Comparing grindability and toughness indices with other hardness parameters showed that toughness correlated better than grindability with the energy parameters. Grindability generally correlated better than toughness with particle parameters. Correlations were high for both particle and energy parameters, so either index could be used satisfactorily to rate wheat hardness.

Data transformed from the defining equations of toughness and grindability indices vary, as shown in Fig. 8. The grinding energy and toughness index correlate well; additionally data from soft (SRW and SWW) and hard wheats differ considerably.

Another advantage of the toughness and grindbility indices is that they compensate for moisture content variations. Mepplink (1966-68) indicated that grinding energy increases as grain moisture increases. On the other hand, X_r and X_r^{β} in the defining equations of both indices apparently decrease since granulation increased with grain moisture increases. Since the two indices are the products of grinding energy and X_r or X_r^{β}, changes in moisture content should have a small effect on the indices. We did not, however, test index variations due to changes in grain moisture.

SUMMARY AND CONCLUSIONS

Comminution theory was applied to the Brabender burr mill grinding process in an effort to develop a better hardness parameter. The energy-size reduction relationship for the steady-state comminution process was presented and the toughness index was defined from that the relationship. Parameters from the Brabender system included flour yield, distribution and size moduli for the Gaudin-Schuhmann equation, representative size, maximum rupture resistance, average rupture resistance, Brabender grinding energy, grindability index, and toughness index. Experiments were performed using 82 wheats representing five classes of wheat. All parameters were compared by simple, linear correlation analysis.

1 Hardness indicating parameters derived from particle characteristics in general do not correlate well with direct measurements of strength or grinding energy.

2 Among parameters from particle characteristcs, flour yield appears best for determining the wheat hardness of hard and soft classes of wheat (not as good for intermediate varieties).

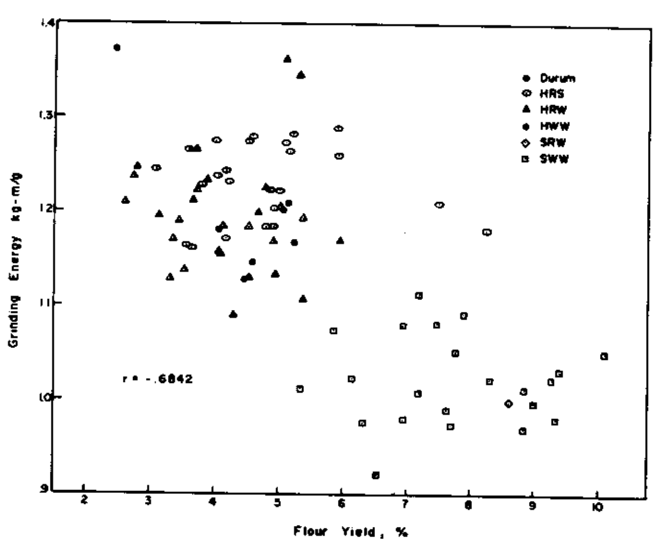

FIG. 7 A typical torque-time curve and integrator pen trace from the Brabender hardness tester.

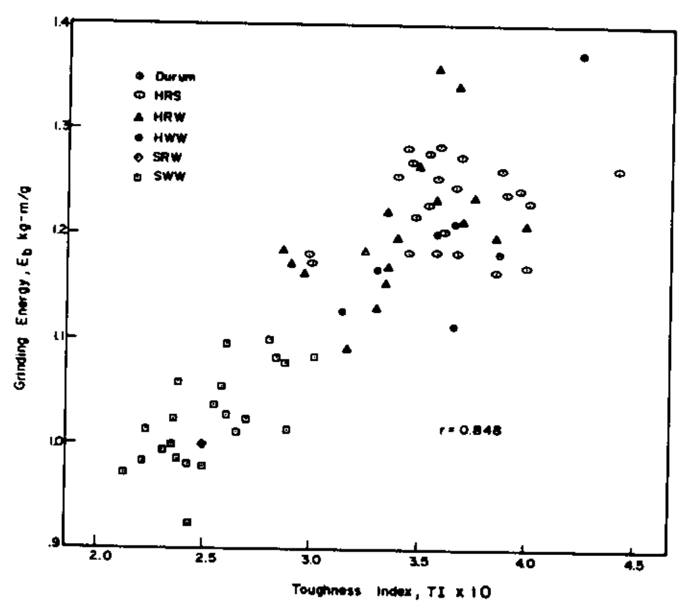

FIG. 8 The correlation between the Brabender grinding energy and flour yield for different classes of wheat.

3 The energy size reduction relationship for the Brabender burr mill (open-circuit grinding) was:

$$E = [TI]\, X_r^{-\beta}$$

where

E = grinding energy per unit weight

X_r = the particle size.

β = the distribution modulus in Gaudin-Schuhmann equation.

From this equation, the toughness index, TI, was defined.

$$TI = E\, X_r^{\beta}$$

The defining equation includes factors from both particle characteristics and grinding energy. Experimental results showed that the toughness index correlated well with both energy and particle parameters. It could, therefore, be used satisfactorily to project those two properties.

4 The defining equation of the grindability index, GI, is

$$GI = E\, X_r .$$

The equation is a transformed form of Rittinger's equation, $E \propto (1/X_2 - 1/X_1)$, when $X_1 >> X_2 = X_r$. The correlation analysis between the grindability index and the other parameters gave almost the same result as the toughness index. The grindability index correlated better than toughness with particle parameters and poorer with grinding energy.

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